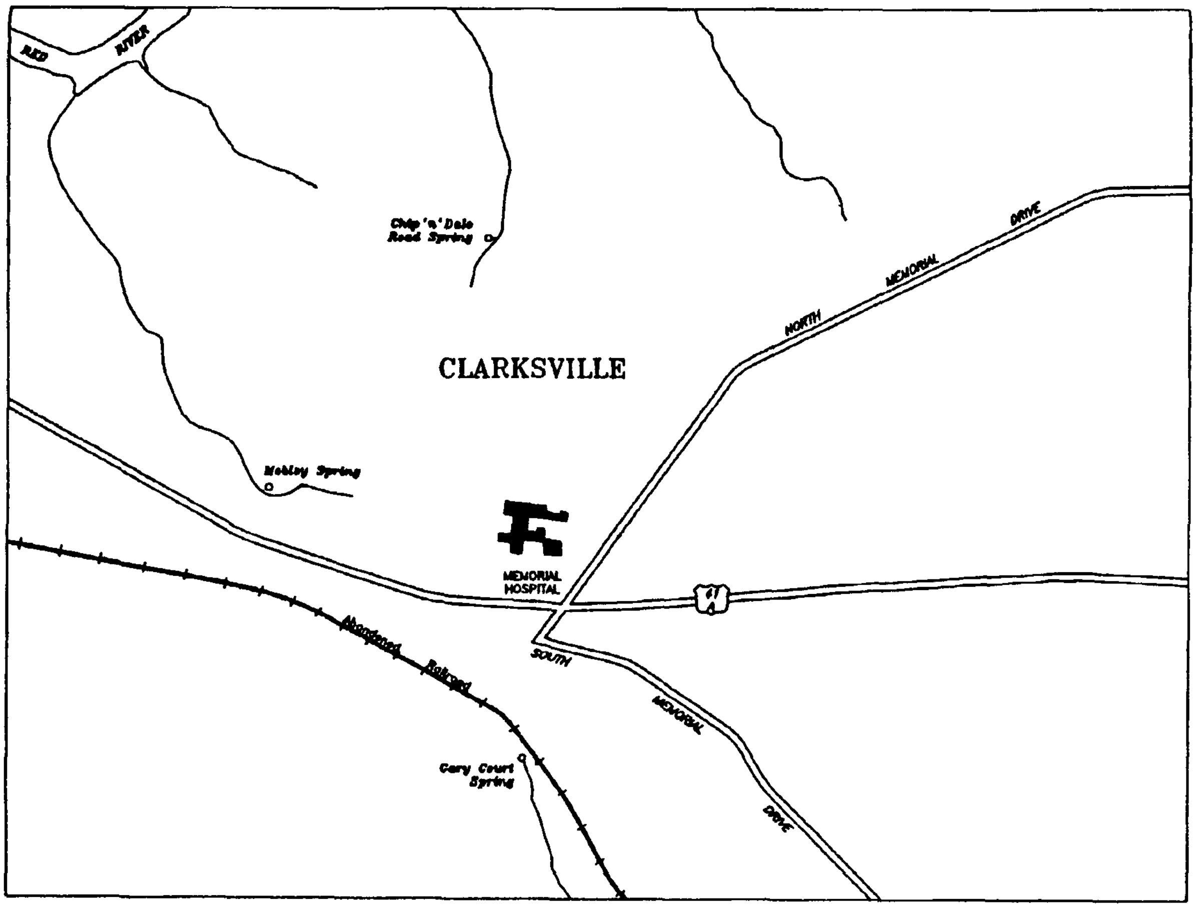
Water-Resources Investigations Report 90-4044

EFFECTS OF STORM-WATER RUNOFF ON LOCAL GROUND-WATER QUALITY, CLARKSVILLE, TENNESSEE



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Prepared by the
U.S. GEOLOGICAL SURVEY

in cooperation with the
TENNESSEE DEPARTMENT OF HEALTH AND ENVIRONMENT,
DIVISION OF CONSTRUCTION GRANTS AND LOANS

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Nashville, Tennessee
1990

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For those readers who may prefer to use metric units rather than inch-pound units, conversion factors for terms used in this report are listed below:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
cubic foot (ft^3)		cubic meter (m^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
mile per square mile (mi/mi^2)	0.621	kilometer per square kilometer (km/km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare
gallon per minute (gal/min)	0.06308	liter per second (L/s)
pound (lb)	0.4536	kilogram (kg)
ton	907.2	kilogram (kg)

Temperature in degrees Celsius (^oC) may be converted to degrees Fahrenheit (^oF) as follows:

$$^oF = 1.8 * {}^oC + 32$$

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

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EFFECTS OF STORM-WATER RUNOFF ON LOCAL GROUND-WATER QUALITY, CLARKSVILLE, TENNESSEE

By Anne B. Hoos

ABSTRACT

Storm-related water-quality data were collected at a drainage-well site and at a spring site in Clarksville, Tennessee, to define the effects of storm-water runoff on the quality of ground water in the area. A dye-trace test verified the direct hydraulic connection between the drainage well and Mobley Spring. Samples of storm runoff and spring flow were collected at these sites for nine storms during the period February to October 1988. Water samples were collected also from Mobley Spring and two other springs and two observation wells in the area during dry-weather conditions to assess the general quality of ground water in an urban karst terrain.

Evaluation of the effect of storm-water runoff on the quality of local ground water is complicated by the presence of other sources of contaminants in the area. Concentrations and loads for most major constituents were much smaller in storm-water runoff at the drainage well than in the discharge of Mobley Spring, indicating that much of the chemical constituent load discharged from the spring comes from sources other than the drainage well. However, for some of the minor constituents associated with roadway runoff (arsenic, copper, lead, organic carbon, and oil and grease), the drainage well contributed relatively large amounts of these constituents to local ground water during storms. The close correlation between concentrations of total organic carbon and concentrations of most trace metals at the drainage-well and Mobley Spring sites indicates that these constituents are transported together. Many trace metals were flushed early during each runoff event.

Mean storm loads for copper, lead, zinc, and four nutrient species (total nitrogen, ammonia nitrogen, total phosphorus, and orthophosphorus) in storm-water runoff at the drainage-well site were lower than mean storm loads predicted from an existing regression model. The overprediction by the model may be a result of the small size of the drainage area relative to the range of drainage areas used in the development of the models, or to the below-normal amounts of rainfall during the period of sampling for this investigation. Loads in storm-water runoff for 22 constituents were extrapolated from sampled storms to total loads for the period February to October 1988. Calculated loads for trace metals for the period ranged from 0.030 pounds for cadmium to 12 pounds for strontium. Loads of the primary nutrients ranged from 0.97 pounds for nitrite as nitrogen to 34 pounds of organic nitrogen.

Storm-water quality at the drainage-well and Mobley Spring sites was compared to background

water quality of the local aquifer, as characterized by dry-weather samples from three springs and two observation wells in the Clarksville area. Concentrations of total-recoverable cadmium, chromium, copper, lead, and nickel were higher in many storm-water samples from both the drainage-well and Mobley Spring sites than in samples from any other site. In addition, concentrations of total organic carbon, methylene blue active substances, and total-recoverable oil and grease were generally higher in storm-water samples from the drainage-well site than in any ground-water sample.

Densities of fecal coliform and fecal streptococcus bacteria and concentrations of total-recoverable iron, manganese, and methylene blue active substances in storm samples from the drainage-well site exceeded the maximum contaminant levels listed in Tennessee's drinking-water standards (1988) by as much as 2,500 and 5,500 colonies per 100 milliliters, and 2.7, 0.29, and 0.05 milligrams per liter, respectively. Densities of fecal coliform and fecal streptococcus bacteria and concentrations of total-recoverable iron, manganese, and lead in storm samples from Mobley Spring exceeded the maximum contaminant levels by as much as 500 and 4,500 colonies per 100 milliliters, and 18.7, 0.65, and 0.02 milligrams per liter, respectively. For iron, manganese, and bacteria, these undesirable levels are not necessarily attributable to storm-water recharge, because concentrations of these constituents also exceeded drinking-water standards in one or more of the dry-weather samples from selected springs and observation wells in the area.

INTRODUCTION

Storm-water runoff from urban areas has been recognized as a source of contamination to receiving surface- and ground-water bodies (U.S. Environmental Protection Agency, 1984). In karst areas, the direct entry of surface runoff to the underlying aquifer through surface features such as sinkholes and sinking streams, and the rapid movement of ground water through well-developed subsurface solution channels cause pulse transport of contaminants through the aquifer, which in turn may create periodic water-quality problems. These problems are compounded by the practice of constructing drainage wells to reduce flooding in areas with insufficient surface drainage. Removal of the unconsolidated material from the mouth of the sinkhole increases the peak contaminant levels in ground water following storms, and may actually increase the overall contaminant load to the system by reducing the degree to which suspended contaminants are removed, by adsorption to soil particles, from the storm water.

In November 1987, the U.S. Geological Survey, in cooperation with the Tennessee Department of Health and Environment, Division of Construction Grants and Loans, began a 15-month investigation of the effects of diverting urban storm-water runoff to drainage wells on ground-water quality. The rapidly urbanizing area of Clarksville, Tennessee (fig. 1), was selected as the site for this investigation, because of its location in a well-developed karst terrain and because a number of drainage wells are currently used in this area to reduce surface flooding.

Purpose and Scope

The purpose of this report is to document the results of an investigation to characterize the effects of urban storm-water runoff entering a drainage well in Clarksville, Tennessee, on the quality of ground water in the area. A description of the data-collection program initiated for the investigation, and preliminary data collected during February and March 1988 have been published in an earlier report (Hoos, 1988). This report includes a summary and analysis of all hydrologic data collected between February and October 1988, and estimates of loads of selected inorganic and organic constituents for the period of investigation.

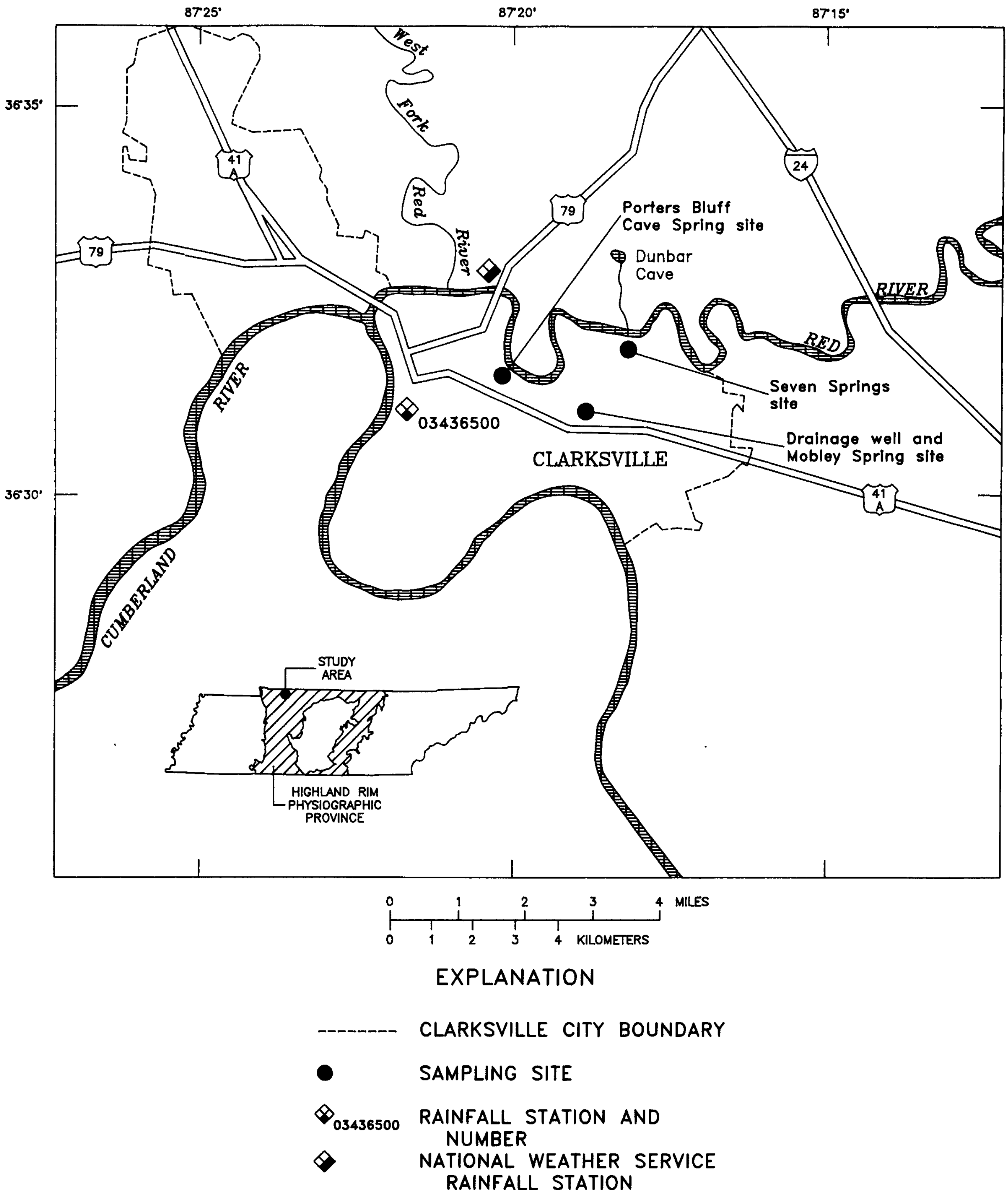


Figure 1.--Location of study area, sampling sites, and rainfall stations in Clarksville, Tennessee.

Acknowledgments

The author wishes to thank Mr. Charles Mobley, Mr. Jack Uffelman, and the Administration of the Clarksville Memorial Hospital for their permission to install hydrologic stations and instrumentation on their property. Thanks are also extended to Dr. Phillip Kemmerly of the Department of Geology and Geography, Austin Peay State University, who shared his knowledge of the hydrogeology of the Clarksville area; Mr. Jack Frazier of the Clarksville City Engineers Office, who assisted in the dye-trace investigations; Mr. Bruce Richards of the Clarksville Memorial Hospital, who assisted in storm-sample collection; and Mr. Larry Hasty of the U.S. Department of Agriculture, Soil Conservation Service, who provided extensive information concerning flooding at the Memorial Hospital sinkhole. The author also thanks the administrators of the Nonpoint Source Program of the Tennessee Division of Health and Environment, Division of Construction Grants and Loans, for their enthusiastic support and assistance in this study.

DESCRIPTION OF AREA AND SELECTION OF STUDY SITE

The city of Clarksville is located in the Western Highland Rim physiographic province, near the Tennessee-Kentucky border (fig. 1). Most of the city is situated on a moderately dissected upland surface, interrupted by the bottomland areas adjacent to the Cumberland and Red Rivers. The area is underlain by Upper Mississippian carbonate rocks; from youngest to oldest, these are the Ste. Genevieve, St. Louis and Warsaw Limestones (fig. 2), which dip gently to the west-northwest. The residual soil is a clay matrix with nodules of dense chert, ranging in thickness from 0 to 30 feet. The bedrock is deeply weathered, with numerous openings developed by solution along bedding planes (Kemmerly, 1980). The contact between the St. Louis and Warsaw Limestones is exposed in some of the tributary valleys adjacent to the Red River (fig. 2) and is the origin of several springs in the area.

Karst topography is well developed in this area, particularly in areas underlain by the St. Louis and Ste. Genevieve Limestones, and includes such features as sinkholes, disappearing streams, springs, and caves of modest dimensions (Kemmerly, 1988, p. 114). Sinkholes, or topographic depressions, result from settlement of surface materials into solution openings beneath the surface (Kemmerly, 1980). Sinkhole density is estimated to range between 5 and 40 per square mile (Kemmerly, 1980).

A sinkhole on the grounds of the Clarksville Memorial Hospital was selected as the site of this study. Two drainage wells have been installed at the bottom of the sinkhole to accelerate drainage of storm-water runoff. This site was selected on the basis of the following criteria:

- The watershed for the sinkhole is a high-density commercial and residential area.
- Watershed boundaries for the sinkhole are well defined, so that all influences to the quality of runoff can be identified.
- A spring was found downgradient from the drainage wells, which provided a sampling point for the ground water.
- Travel time of ground-water flow between the drainage wells and the ground-water sampling point was long enough to permit observation of any physical or chemical reactions modifying concentration of contaminants. However, the distance between the drainage wells and the ground-water sampling point was not so large as to allow a significant volume of recharge to enter the aquifer along the flow path and dilute the system.

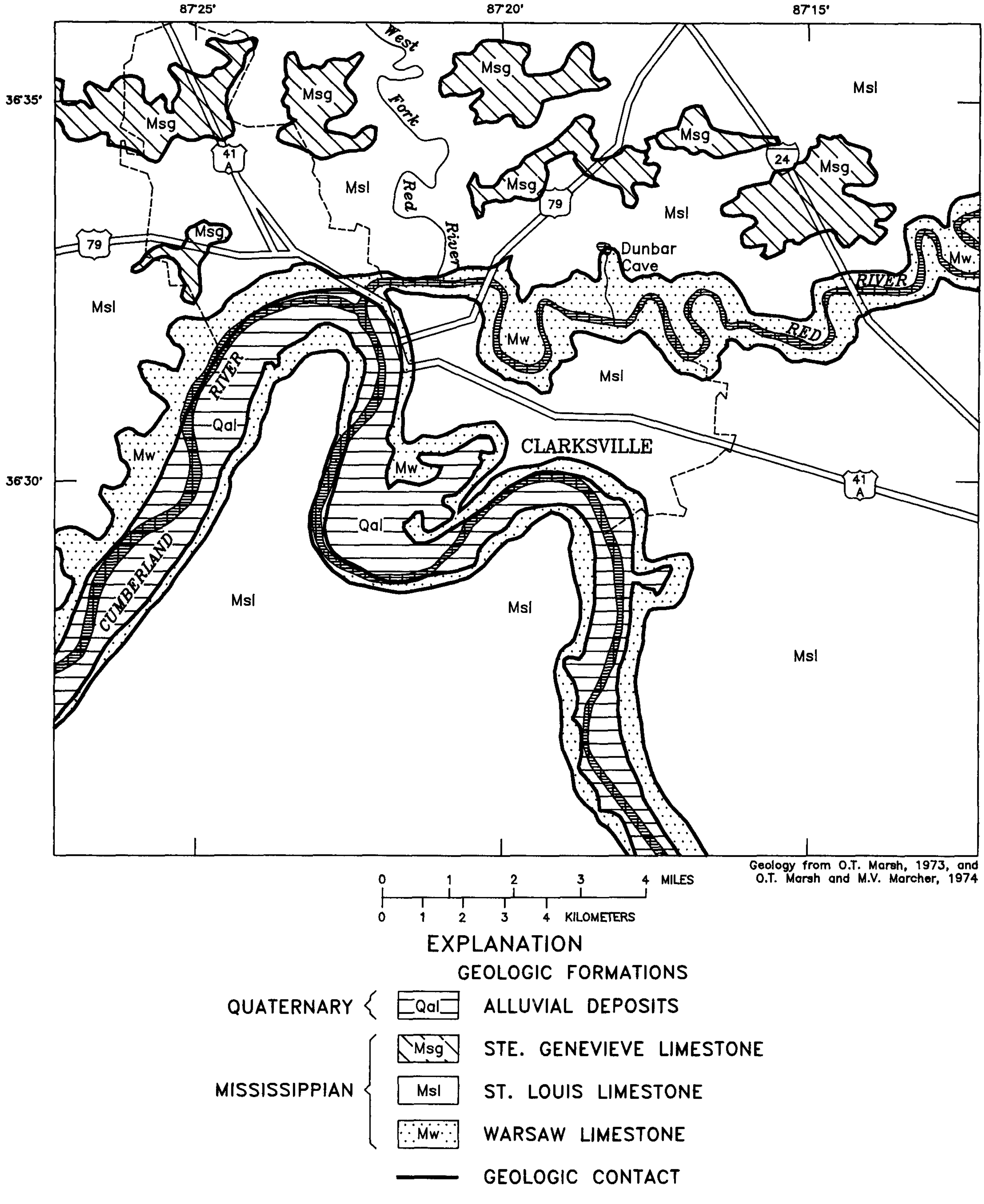


Figure 2.--Geology of the Clarksville area, Tennessee.

The selected study site and its watershed boundary are shown in figure 3. The watershed boundary was delineated by the U.S. Department of Agriculture, Soil Conservation Service (1986a). The 12-acre watershed consists of approximately 90 percent paved parking lots and rooftops of the Clarksville Memorial Hospital complex, with the remaining area residential. Two drainage wells, approximately 5 feet apart, were installed in the early 1980's at the bottom of a depression (fig. 4) and are the only outlet for runoff from the drainage area. The wells are 6 and 22 feet in depth, with corrugated-steel casing to depth and raised metal grates. Because of the proximity of the two drainage wells to each other, they can be considered to function hydraulically as a single unit, and will be referred to collectively as a single drainage well.

HYDROLOGIC SETTING

Average annual precipitation for the Clarksville area, recorded at the National Weather Service station at the Clarksville Sewage Treatment Plant (fig. 1), is 49.6 inches. The range of average monthly precipitation is from 5.92 inches in March to 2.83 inches in October.

The surface-drainage network in the Clarksville area is sparse. Network density for drainage basins in the area, calculated as the ratio of total channel length to drainage area, was estimated as 0.48 mi/mi^2. This value is low as compared to the estimated average of 2.1 mi/mi^2 for 15 drainage basins in the Highland Rim physiographic province of Tennessee (Hoos, U.S. Geological Survey, unpublished data, 1989). Drainage is principally in the subsurface through well-developed solution channels along bedding planes, joints, and fractures in the bedrock. The Cumberland and Red Rivers are the major drains in the area (Kemmerly, 1988).

The water-table aquifer is recharged through precipitation. Net annual recharge to the carbonate aquifer in the Clarksville area is estimated to range from 3 to 12 inches, with an average value of 6 inches (Hoos, U.S. Geological Survey, unpublished data, 1989). Movement of ground water through the subsurface-drainage system appears to be quite rapid. Velocities measured from dye-trace tests in the Clarksville area ranged from 600 to 3,500 feet per day (ft/d) (Kemmerly, 1984). The general direction of ground-water movement appears to be westward (Kemmerly, 1988).

Flow direction and velocities from the drainage-well site were determined through a series of fluorescein dye-trace tests. For each test, about 0.8 pound of fluorescein dye (Acid Yellow 73) was mixed with 5 gallons of water and poured into the deep 22-foot drainage well. Just prior to injection, the sinkhole was dosed with several thousands of gallons of water (the amount varied for each test, fig. 5), in order to wet the subsurface conduit surfaces (Mull and others, 1988). This dosing volume was provided either by a release from a nearby fire hydrant, at a flow rate of 480 gal/min, or, for the July 13 and 30 tests, by storm runoff. Dye-monitoring apparatus for a spring consisted of a nylon mesh bag containing activated coconut charcoal suspended in the flow below the resurgence. For an observation well, the apparatus was submerged in borehole water opposite a known water-bearing opening. The wells were not pumped during the dye-trace tests, because the objective of the tests was to determine the direction and velocity of ground-water flow in the aquifer during a storm under natural, unpumped, conditions. Dye recovery was tested by placing the exposed charcoal in a basic alcohol solution (Mull and others, 1988).

For the test conducted on January 21, 1988, three springs (Mobley, Chip'n'Dale Road, and Gary Court Springs, fig. 3) were monitored for a 7-day period for the presence of dye. These three springs were judged to be possible resurgent points for ground water flowing downgradient from the drainage-well site. Two of the springs

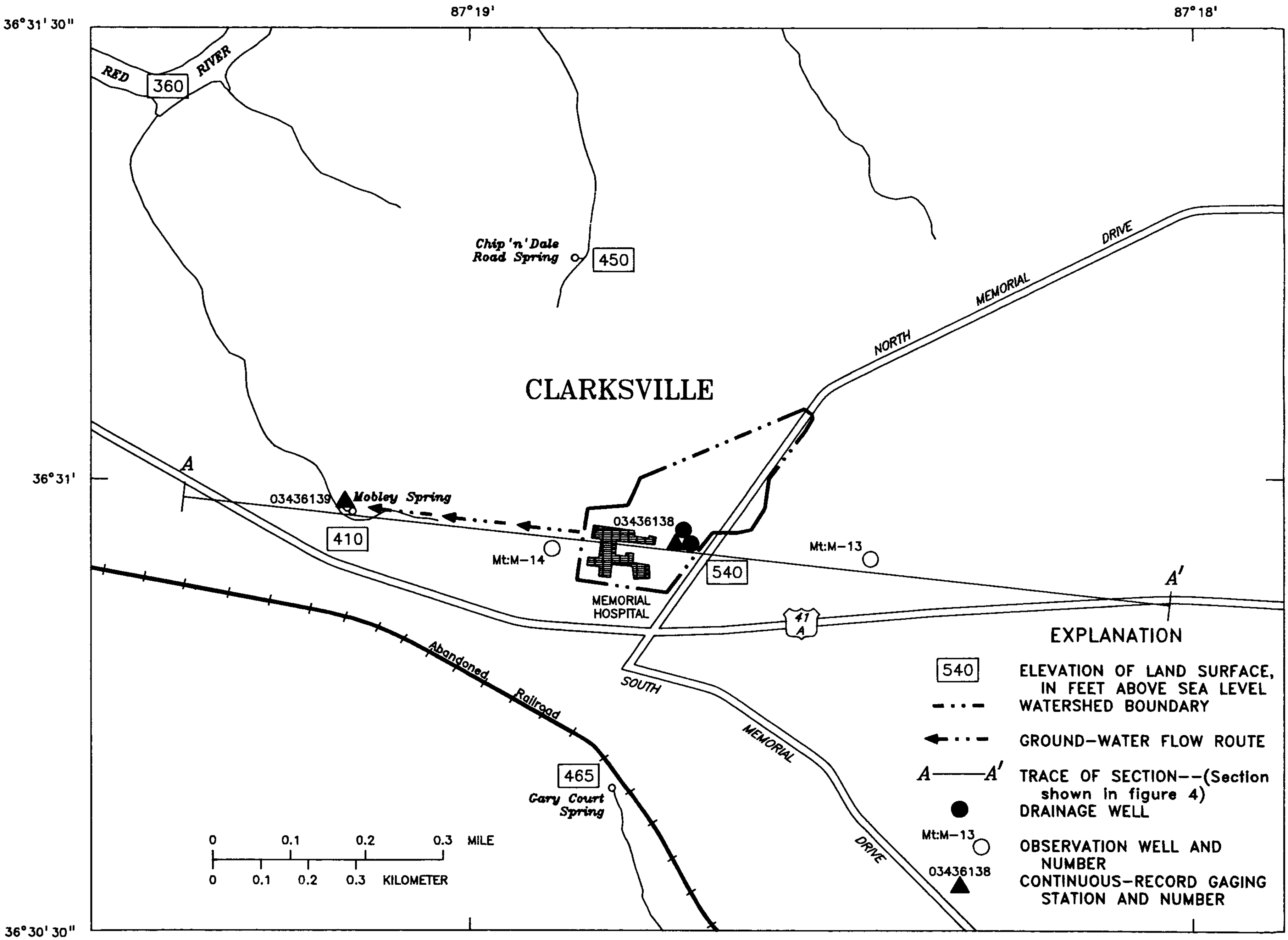


Figure 3.--Locations of drainage wells and other surface- and ground-water sites in the Mobley Spring area.

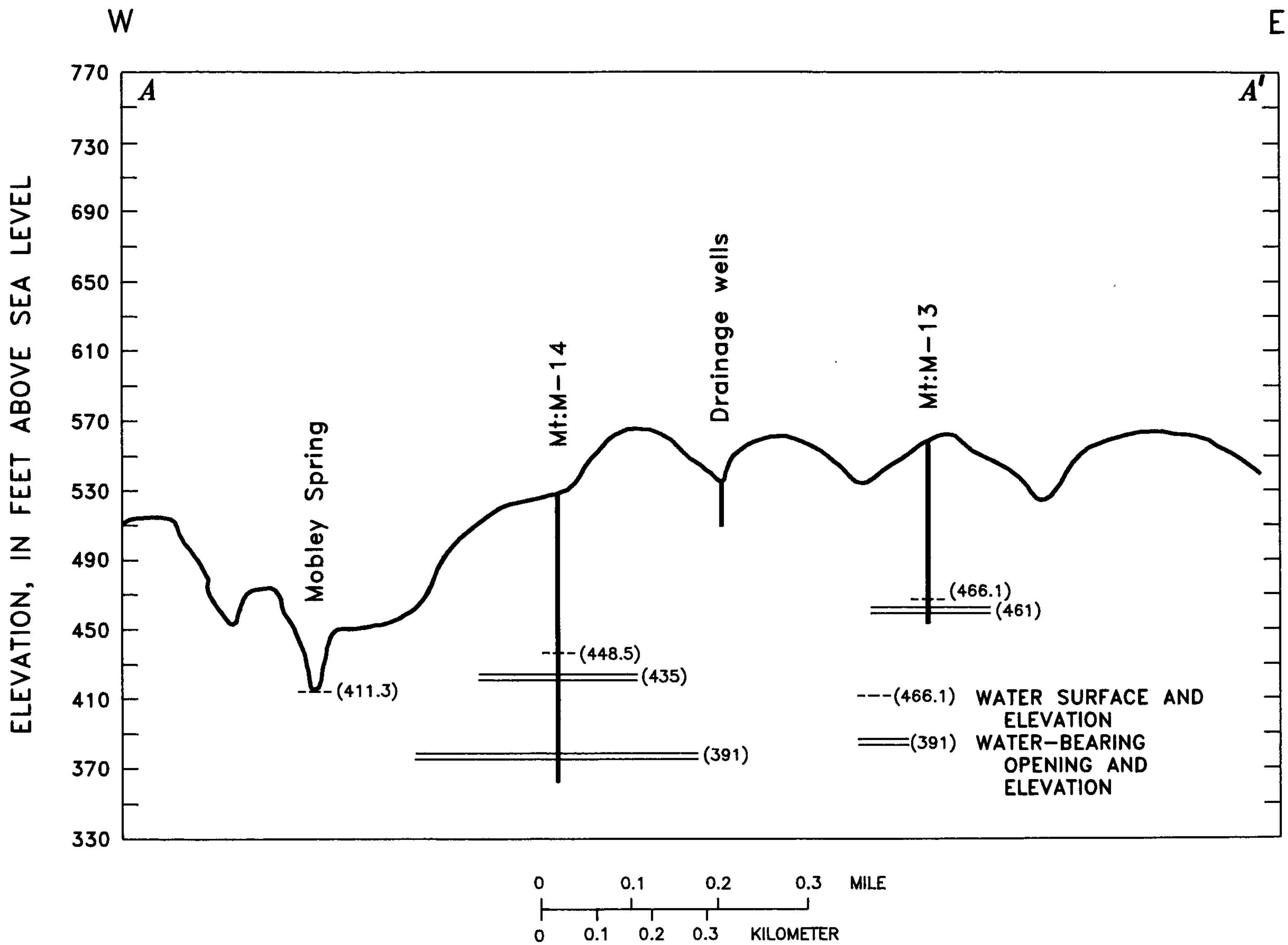


Figure 4.--Section from west to east through the Mobley Spring area showing location of wells, water-bearing openings, and elevation of water table on June 1, 1988.

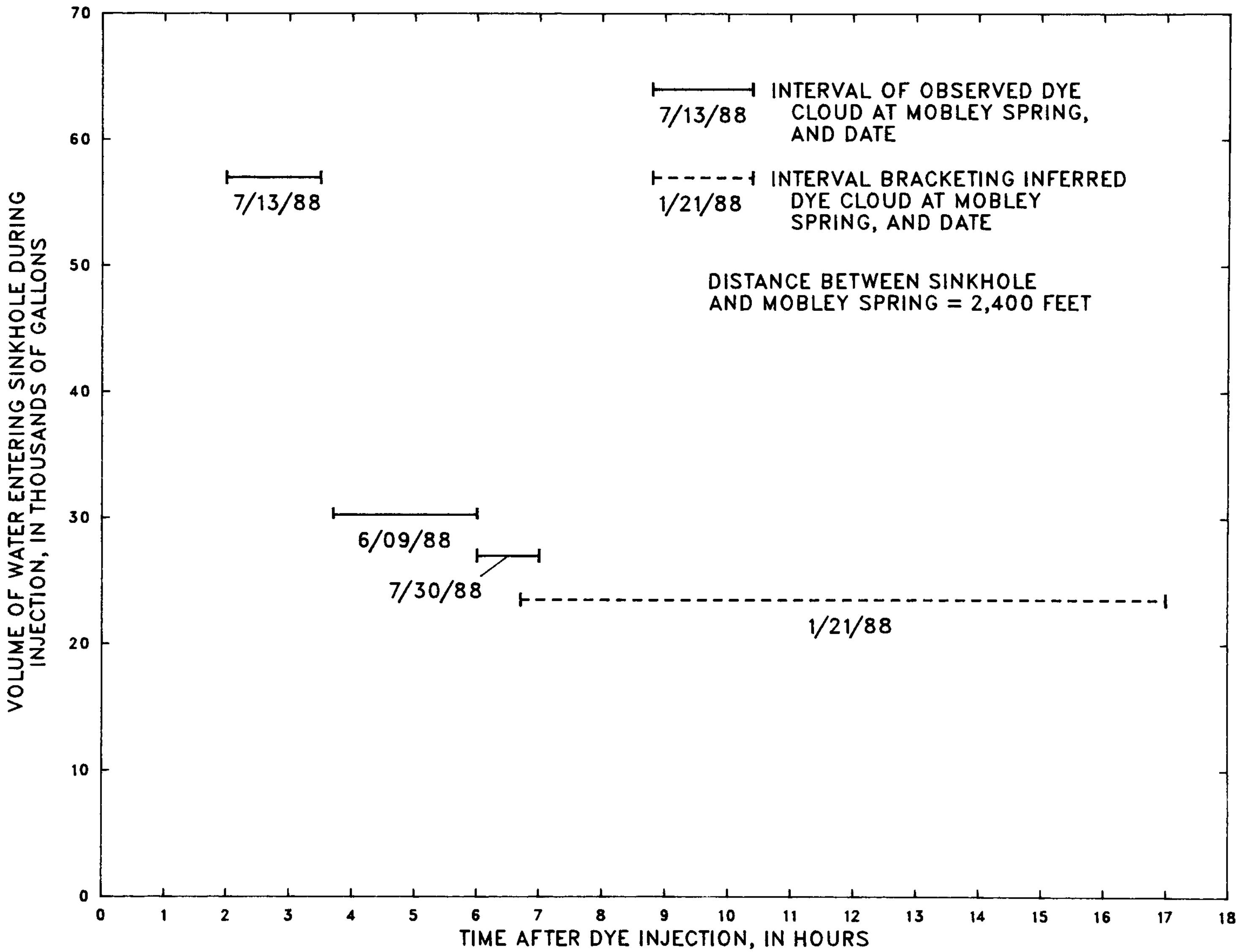


Figure 5.--Relation between travel time and dye injection volume.

(Mobley and Chip'n'Dale Road Spring) issue from the contact between the St. Louis and Warsaw Limestones. Dye was recovered below Mobley Spring, located approximately 2,400 feet west of the drainage-well site, but because the dye cloud passed this site during the night following the injection, the time of travel between the drainage-well site and Mobley Spring was estimated to range from 6.7 to 18.5 hours. No dye was detected at the other monitoring sites (Gary Court and Chip'n'Dale Road) during the 7-day period following injection.

For the three additional tests, conducted on June 9, July 13, and July 29, 1988, Mobley Spring and the observation wells Mt:M-13 and Mt:M-14 (fig. 3) were monitored for dye. Well Mt:M-13 is an abandoned domestic water-supply well located approximately 1,200 feet east of the drainage-well site, in the part of the aquifer that was initially believed to be in an upgradient direction from the drainage-well site. Well Mt:M-14 is an observation well drilled for this project with the objective of providing a downgradient ground-water sampling point between the drainage-well site and Mobley Spring.

The observed travel time between the drainage-well site and Mobley Spring varied for each dye-trace test, ranging from about 2 hours for the July 13 test, to more than 7 hours for the January 21 test. Travel time appeared to be strongly dependent on the dosing volume (fig. 5). This range in travel time corresponds to a range in ground-water velocity of less than 8,000 to 30,000 ft/d. Ground-water velocities measured in other dye-trace tests in the area range from 600 to 3,500 ft/d (Kemmerly, 1988).

The dye-trace test conducted on June 9 did not indicate that the two observations wells were connected hydraulically to the drainage-well site. However, during the storm dye-trace test conducted on July 13, dye was recovered at Mt:M-13 between 9 and 33 hours after injection at the drainage well. This hydraulic connection could not be confirmed in the July 30 test. This indicates that the connection between the drainage well and Mt:M-13 is tenuous and depends on the duration and intensity of the storm. No dye was detected at Mt:M-14 during any of the dye-trace tests. Both Mt:M-14 and Mt:M-13 were therefore judged unsuitable as storm-monitoring points. The direction of ground-water movement in the vicinity of the drainage well, as inferred from the dye-trace tests, is shown in figure 3.

Following verification of the direct connection between the drainage-well site and Mobley Spring, the two sites were instrumented to collect storm-related data to define the type and quantity of contaminants in storm-water runoff and in the receiving ground-water basin. Water samples were collected during dry-weather conditions from both observation wells, to characterize ground-water quality in parts of the aquifer not believed to be directly affected by the storm-water runoff entering the drainage well.

Water samples were collected during dry-weather conditions from Seven Springs (figs. 1, 6) and Porters Bluff Cave Spring (figs. 1, 7), to assess the general quality of ground water in an urban, karst terrain. The geologic setting of both spring sites is similar to the Mobley Spring site. At the Seven Springs site, ground water issues from several small caves near the regolith-bedrock contact close to the contact between the Warsaw and St. Louis Limestones. The spring drains a ground-water basin (as inferred from surface topography) that underlies a low-density residential area. The entrance to Porters Bluff Cave is a large opening in the bedrock near the contact between the Warsaw and St. Louis Limestones. The spring drains a ground-water basin that underlies a medium- to high-density residential and commercial area.

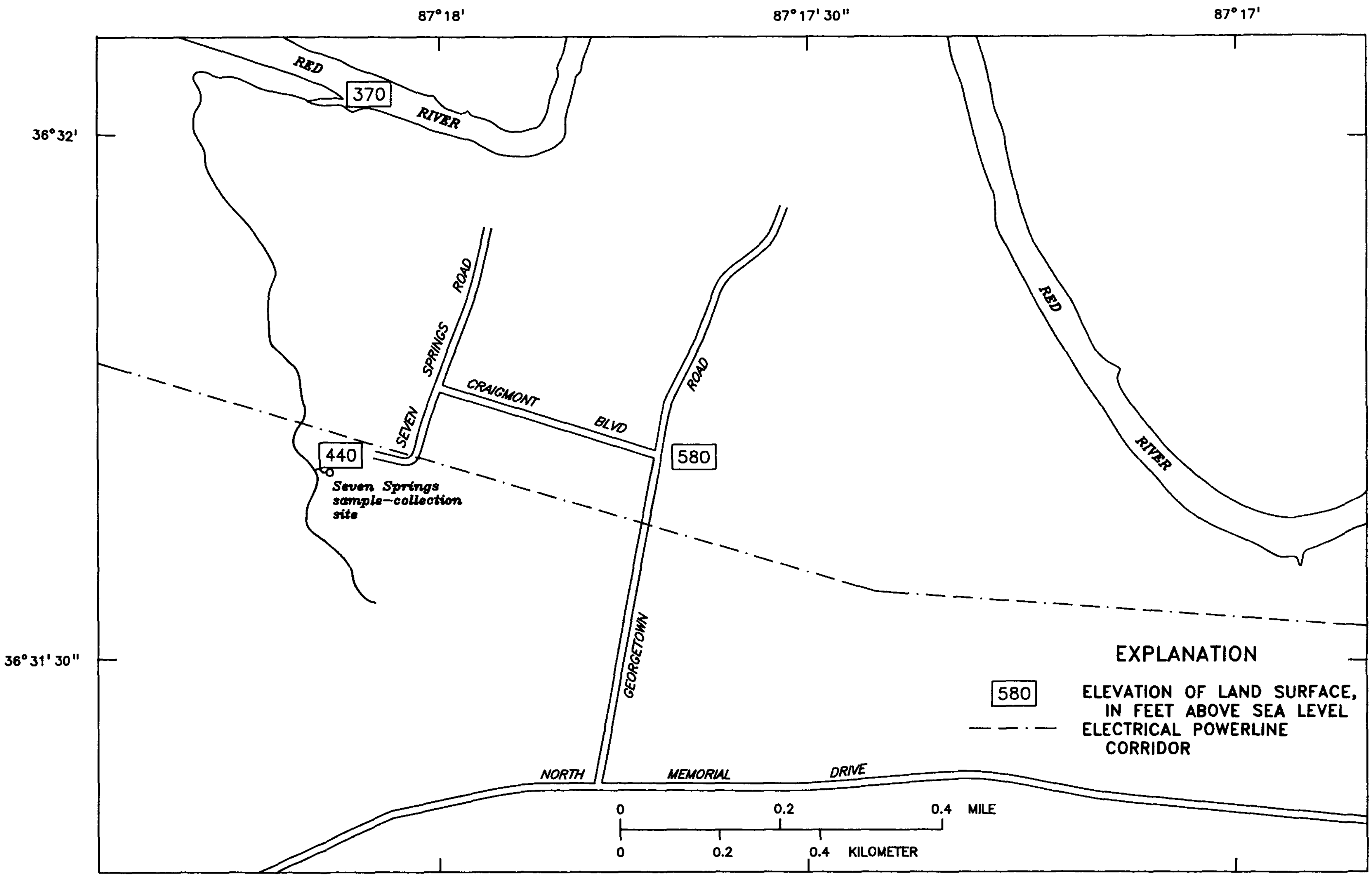


Figure 6.--Location of Seven Springs sample-collection site.

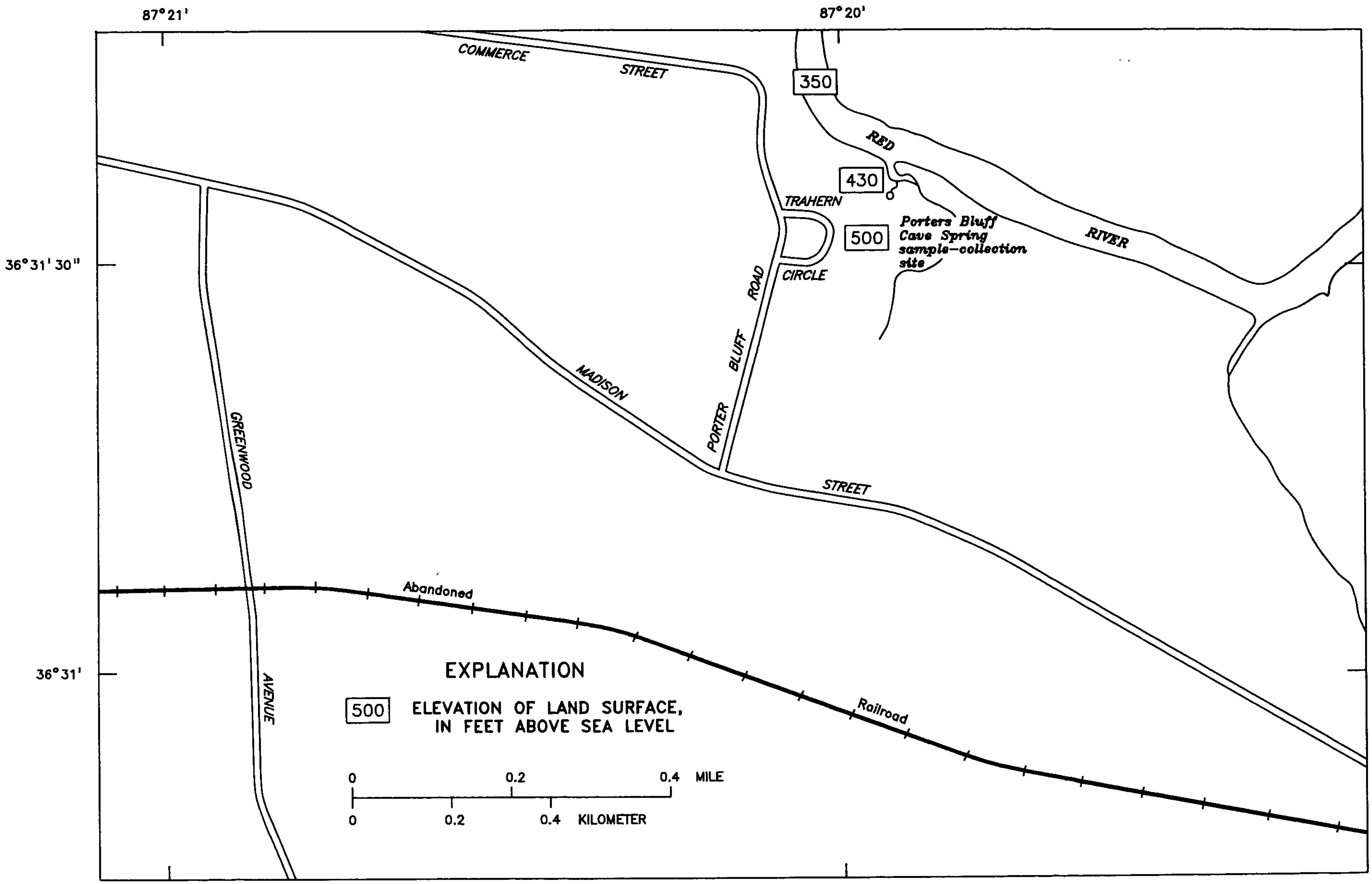


Figure 7.--Location of Porters Bluff Cave Spring sample-collection site.

DATA-COLLECTION METHODS

Stage Measurement and Discharge Rating

A continuous record of stage at the drainage-well site (station 03436138) was collected during the period February 21 to October 31, 1988. Construction of a small weir (16 feet in cross-channel width, averaging 0.5 foot in height) near the drainage well provided for interception and ponding of the sheet flow as runoff began, permitting collection of samples and measurement of stage at the beginning of the hydrograph. Discharge through the drainage wells was estimated from the stage data through a stage-discharge rating developed as follows. The sinkhole is assumed to act as a reservoir of standing water, from which water discharges through a constricted opening (the drainage well) into a conduit with either open-channel flow or full flowing without backwater influence. Under these assumptions, the discharge through the drainage well is dependent only on the stage in the sinkhole. Observed stage data were used to develop an empirical relation between stage in the sinkhole basin and discharge through the sinkhole outlet (drainage wells), by pairing each stage value on the receding limb of the stage hydrograph with the corresponding incremental volume change calculated from a stage-volume relation (Larry Hasty, U.S. Department of Agriculture, Soil Conservation Service, written commun., 1988). Only data from the receding limb, when inflow to the sinkhole from the watershed is assumed to have ceased, are used; in this way, the incremental volume change calculated by the stage-volume relation can be equated to discharge through the drainage wells.

The empirical relation (fig. 8) was fitted using a least-squares regression to the equation

$$Q = 0.5 * h^{0.9}, \qquad (1)$$

where

Q is discharge through the sinkhole outlet, in cubic feet per second; and

h is stage of the sinkhole, in feet.

Dimensions for this equation are not consistent. The model for discharge, given the assumptions described above, however, is in the form

$$Q = C * (2.*g)^{0.5} * h^{0.5}, \qquad (2)$$

where

C is a constant related to the cross-sectional area of the constricted opening, in the case of discharge into the atmosphere, or to the dimensions and roughness of the conduit, in the case of discharge into a full-flowing conduit, in feet squared; and

g is gravitational acceleration, in feet per second squared.

In the empirical model, discharge varies almost in proportion to stage in the sinkhole, whereas in the theoretical model, discharge varies in proportion to the square root of stage. This difference in predicted discharge variation between models indicates that the model of a static reservoir discharging to atmospheric conditions or to a full-flowing conduit is not valid. Flow through the sinkhole outlet therefore may be controlled by the hydraulics of saturated groundwater flow. Water-table control of discharge through the sinkhole outlet would invalidate the development of a single-valued stage-discharge relation; however, the empirical relation is used as the best approximation.

A continuous record of stage in the channel immediately downstream of Mobley Spring (station 03436139), was collected for the period February 9 to October 31, 1988. Discharge from the spring was estimated from stage data through a stage-discharge rating developed from 12 discharge measurements, using methods described by Kennedy (1984).

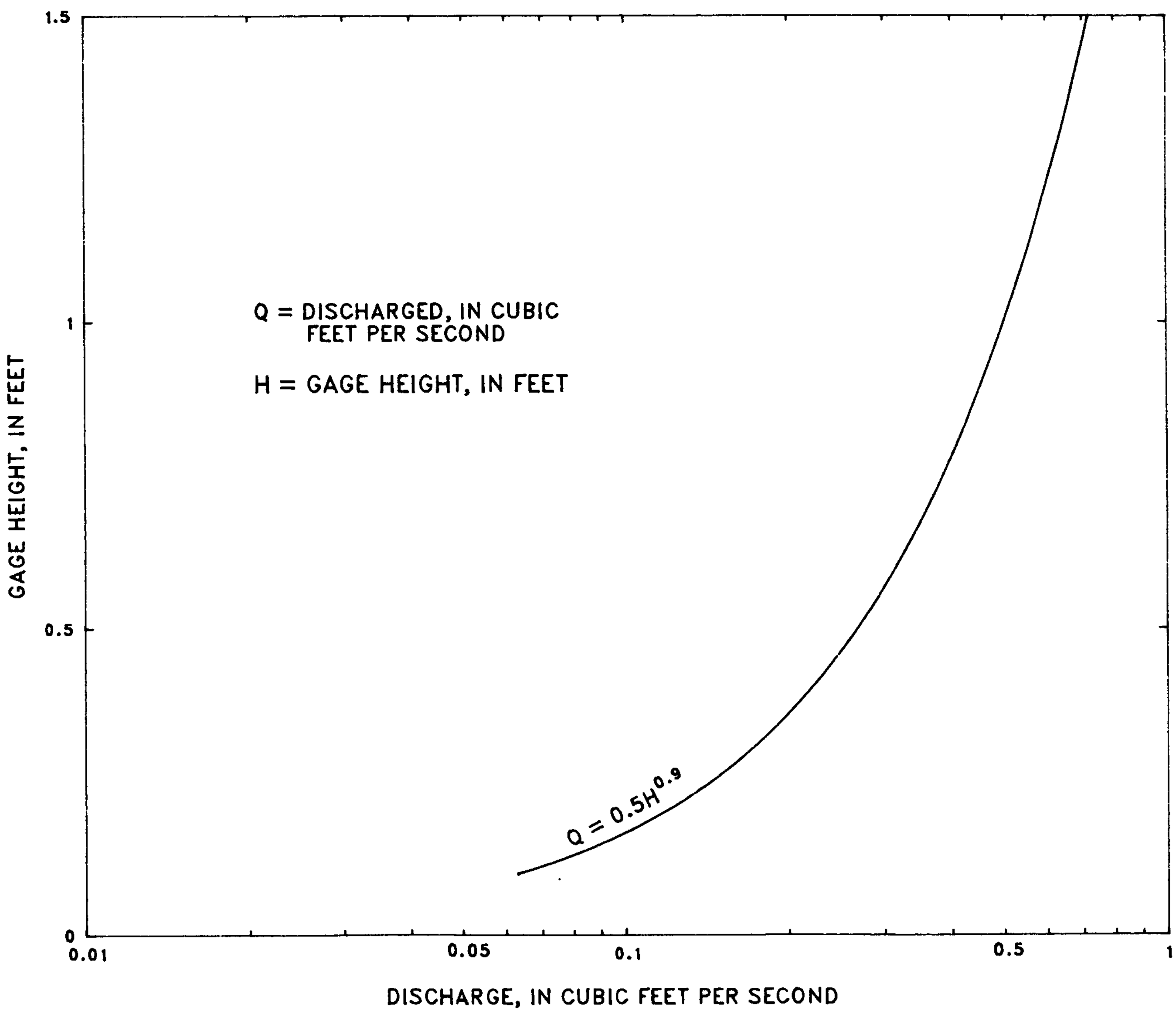


Figure 8.--Relation between stage and discharge at the drainage-well site.

Water-Quality Samples

Sample collection at the drainage-well and Mobley Spring sites was automated to permit collection of samples at the beginning of storm runoff, before monitoring personnel could reach the site. Water-quality samplers were installed at these stations to collect discrete samples at 5- and 10-minute intervals, respectively, after a specific stage was reached.

The number of samples collected and the types of analyses performed for each of the nine storms sampled are given in table 1. Samples from the storm of February 2, 1988, which predated installation of the automated sampling equipment, were collected as a single-grab sample at each site. The objective of operating the automated sampling equipment is to collect samples before, during, and after the storm-hydrograph peak at both sites. The sample sets from storms of February 14 and 19, 1988, are not complete, however, because of initial difficulty in establishing proper settings of equipment controls. At least one sample from each storm was analyzed for selected major inorganic constituents and trace metals. Analyses for total organic carbon, oil and grease, nutrients, methylene blue active substances (representing the anionic surfactant groups alkyl benzene sulfonates and linear alkyl sulfonates), fecal coliform and fecal streptococcus bacteria, priority pollutants, and scans for presence of nonpurgeable organic compounds were included for selected storms and samples. Concentrations for metals and oil and grease are reported as total recoverable, meaning that the constituents were determined from unfiltered samples that were digested by a method that results in dissolution of readily soluble substances.

Samples were retrieved from the automatic samplers and placed in insulated containers as soon as monitoring personnel could reach the site following the storm, then transported to the U.S. Geological Survey office in Nashville. Specific conductance was measured for all samples, either at the sampling site or shortly after transport to the field office. Samples were composited for laboratory analysis of all constituents except total organic carbon. Levels of total organic carbon were profiled through the entire hydrograph by analyzing every second or third discrete sample. The samples were packed with ice and sent to the U.S. Geological Survey laboratories in Arvada, Colorado, and Ocala, Florida, for analysis in accordance with procedures outlined by Skougstad and others (1979) and Wershaw and others (1987).

Samples were composited on a time-weighted basis; that is, equal volumes of samples collected at discrete times, separated by equal time increments, were composited to represent the total volume of storm water over a given time period. For the purpose of characterizing the quality of this volume of storm water, and particularly for the purpose of estimating loads, a flow-weighted composite is more appropriate. However, because the stage-discharge relation at the sinkhole was not developed until after several months of stage record had been collected, the discharge hydrograph was not available at the time the samples were collected; consequently, flow weighting of the composites could not be done.

Grab samples from Mobley Spring, Porters Bluff Cave Spring, Seven Springs stations, and wells Mt:M-13 and Mt:M-14 were collected during dry-weather conditions to obtain information on background levels of constituents in ground water (table 1). Samples were analyzed for major inorganic constituents, selected trace metals, total organic carbon, nutrients, methylene blue active substances, and volatile organic compounds. Scans for presence of nonpurgeable organic compounds were also included. Field measurements of alkalinity, pH, dissolved oxygen (for springs), and bacteriological analysis for fecal coliform and fecal streptococcus bacteria were conducted for these samples.

Table 1.—*Hydrologic conditions and types of analyses performed for each sampling event*

[S, standard analysis - major constituents (see *Supplement B*); C, total organic carbon (see *Supplement B*); T, selected trace-metal analysis (see *Supplement B*); O, oil and grease analysis (see *Supplement B*); G, gas chromatograph flame ionization screening of nonpurgeable organic compounds; GM, gas chromatograph mass spectrometric analysis of nonpurgeable organic compounds (see tables 4 and 5); V, analysis of volatile organic compounds (see tables 5 and 6); N, major nutrient analysis (see *Supplement B*); M, analysis of methylene blue active substances; B, bacteriological analysis; --, no record]

Site	Storm	Date	Rain-fall (inch)	Water level rise (feet)	Type and number of samples	Analyses
Drainage well	1	02/02/88	1.47	--	Single	S,C,T,O,G
Mobley Spring				--	Single	S,C,T,O,G
Drainage well	2	02/14/88	1.04	--	Time-composite - 1 sample[1]	T,G
Mobley Spring				0.53	Time-composite - 1 sample	T,G
Drainage well	3	02/19/88	.28	--	Time-composite - 1 sample[1]	S,C,T,O
Mobley Spring				.06	None	
Drainage well	4	03/25/88	.15	.27	Time series - 28 samples	S,C,T,O,G,GM
Mobley Spring				.04	Time series - 28 samples	S,C,T,O,G,GM
Drainage well	5	05/23/88	.20	.63	Time series - 28 samples	C,T,G
Mobley Spring				.06	Time series - 24 samples	C,T,G
Drainage well	6	07/04/88	.03	.28	Time series - 28 samples	T,C
Mobley Spring				.06	None	
Drainage well	7	07/13/88	.40	1.68	Time series - 28 samples	T
Mobley Spring				.14	Time series - 24 samples	T
Drainage well	8	10/16/88	.25	.51	Time series - 28 samples	T,C,M,N
Mobley Spring				.06	None	
Drainage well	9	10/23/88	.08	.11	Time series - 2 samples	B
Mobley Spring				.04	Time series - 3 samples	B
Mobley Spring	--	02/29/88[2]	0	0	Single	S,C,O,G
Mobley Spring	--	06/09/88[2]	0	0	Single	C,T,V
Mobley Spring	--	07/29/88[2]	0	0	Single	B,N,M
Mt:M-13	--	05/09/88[2]	0	0	Single	S,C,T,O,G
Mt:M-13	--	09/06/88[2]	0	0	Single	V,B,N,M
Mt:M-14	--	09/06/88[2]	0	0	Single	S,C,T,G,V B,N,M
Porters Bluff Spring	--	07/29/88[2]	0	0	Single	S,C,T,O,G B,N,M
Seven Springs	--	07/29/88[2]	0	0	Single	S,C,T,G,V B,N,M

[1]Insufficient volume in each sample bottle required compositing to a single sample.
[2]Samples were taken during normal flow conditions.

RAINFALL

Rainfall for the Cumberland River at Clarksville, Tenn. (station 03436500, fig. 1) for the period February to October 1988, is shown in figure 9, along with stormflow stage and springflow hydrographs for the drainage-well and Mobley Spring sites, respectively. The magnitude of sampled storms is compared with that of all storms occurring during this period. Storm and antecedent rainfall data for all storms during the period February to October 1988 from the Cumberland River at Clarksville station are summarized in the "*Supplemental Information*" section at the back of this report.

Rainfall at the Clarksville Sewage Treatment Plant, about 2.5 miles northwest of the drainage well, was about 25 percent below normal for the period February to October 1988 (National Oceanic and Atmospheric Administration, 1988). Rainfall during the months May and July at this site totaled 2.56 and 3.24 inches, respectively, and was significantly below the 30-year standard normals for these months of 4.14 and 3.81 inches, respectively.

QUANTITY OF STORM-WATER RUNOFF AND SPRING DISCHARGE

The estimated volume of storm-water runoff, peak discharge, peak water level, and other storm-related data for all storms, sampled or unsampled, during the period February to October 1988, are summarized in the "*Supplemental Information*" section at the back of this report. The volume of storm-water runoff and spring discharge at the drainage-well and Mobley Spring sites, respectively, during sampled storms was estimated by integrating the discharge hydrograph at each site. Runoff volume at the drainage-well site during unsampled storms was estimated using the rational formula,

$$V = C * I * DA, \qquad (3)$$

where

V is volume of runoff, in acre-feet;
I is total storm rainfall, in feet;
DA is drainage area, in acres; and
C is the coefficient modeling the ratio of rainfall converted to runoff.

Because of the large area of impervious surfaces in the drainage basin (90 percent of the total area), it was assumed that all of the rainfall would be converted to runoff, so that C was assigned a value of 1. This selection was verified by comparing the volume estimated using the rational formula to the volume calculated by integrating the discharge hydrograph for several storms.

The flow regime present during sampled storms was summarized by comparison with the flood-depth frequency relation for the Hospital Sinkhole station. This relation was furnished by the U.S. Department of Agriculture, Soil Conservation Service (Larry Hasty, written commun., 1988), and was obtained from rainfall-runoff modeling (using runoff curve number 95) of type II 24-hour storms. The procedure is described in Technical Release 55 of the U.S. Department of Agriculture, Soil Conservation Service (1986b). The relation is shown on an extreme log data plot in figure 10. The maximum flood depth for the period of data collection, 5.7 feet, occurred during the storm of July 19, 1988. This depth is considerably lower than the calculated flood depth (6.9 feet) having a 1-year recurrence interval.

QUALITY OF STORM-WATER RUNOFF AND SPRING DISCHARGE

Water-quality data for storm samples collected from the drainage-well and Mobley Spring sites are listed in the "*Supplemental Information*" section at the back of this report. Water-quality data for dry-weather samples collected from

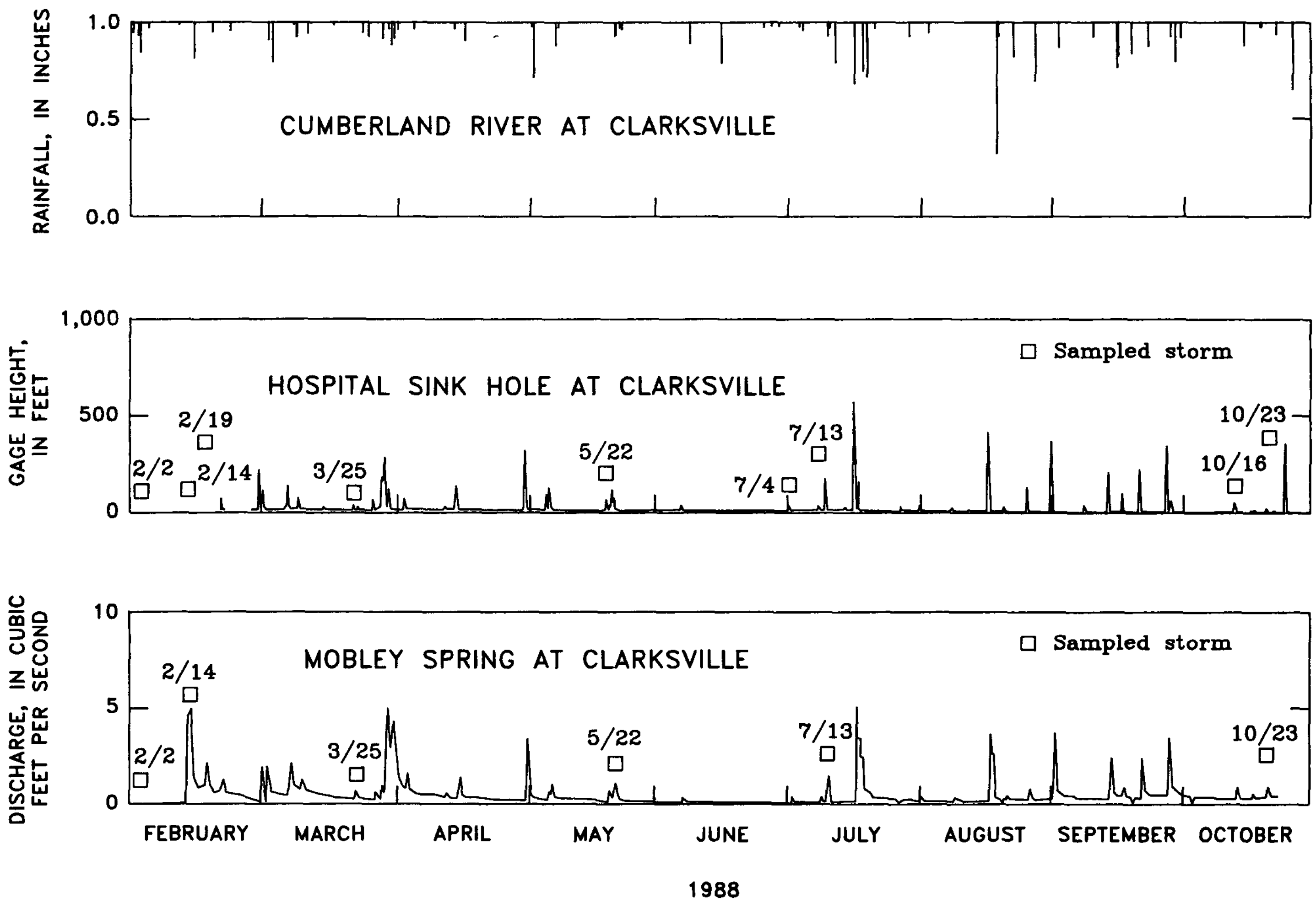


Figure 9.--Graphs showing instantaneous rainfall at Cumberland River at Clarksville, Tennessee (station 03436500), instantaneous gage height at the drainage-well site at Clarksville, Tennessee (station 03436138), and instantaneous discharge at Mobley Spring at Clarksville, Tennessee (station 03436139), February to October 1988. Rain gage (station 03436500) is a 30-minute-interval tipping-bucket rain gage operated by the U.S. Army Corps of Engineers.

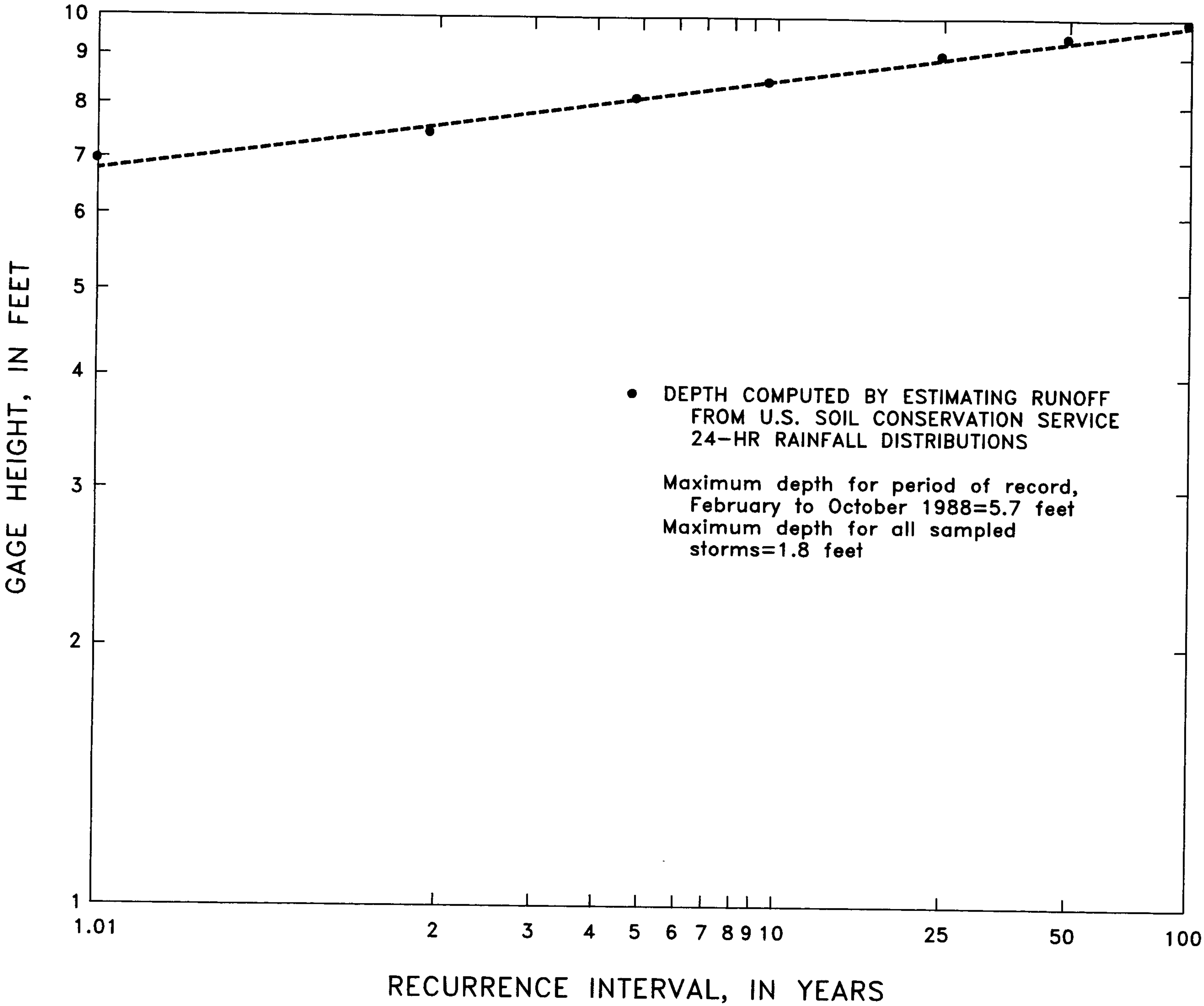


Figure 10.--Frequency of flood depth at the drainage-well site.

additional ground-water monitoring sites in the Clarksville area are also listed in the "*Supplemental Information*" section.

The storm hydrograph, concentrations for selected constituents, and values for selected properties for the storms of March 25, and October 16, 1988, are presented in the "*Supplemental Information*" section and are discussed in subsequent sections. The values and concentrations are from composite samples collected during periods separated by the dashed vertical lines below the hydrograph. Periods represented by samples for which no laboratory analyses (except for total organic carbon) were done are indicated by hachured lines. The properties and constituents included in this figure were selected to indicate as much information about the total water quality as possible. Specific-conductance values and total-organic-carbon concentrations show the timing of transport of the bulk of the dissolved, ionized constituents and organic compounds, respectively.

The variation in concentrations of all the major cations during each sampled storm were strongly and positively correlated to each other: concentrations increase and decrease concurrently during the storm hydrograph, with the correlation coefficient r^2 for an individual storm generally greater than 0.8. The pattern of variation for concentrations of each major cation is represented by concentrations of total-recoverable magnesium (*Supplements E and F*). The variation in concentration of most trace metals during each sampled storm were strongly and positively correlated to each other, with r^2 for an individual storm generally greater than 0.95. The pattern of variation for concentrations of most trace metals is represented by concentrations of total-recoverable iron (*Supplements E and F*). Concentrations of total-recoverable zinc are also shown, because transport of zinc did not always correlate positively with transport of the other trace metals. The relations among the various constituents shown in *Supplements E and F* were typical of all sampled storms.

Storm-water-runoff and spring-flow volumes, concentrations, and loads of nine selected constituents for each composite sample for the storms of March 25, July 4, and July 13, 1988, are shown for the drainage-well and Mobley Spring sites (table 2). Loading rates for the periods for which analytical results were not available were estimated by averaging concentrations in samples collected immediately before and after the unsampled period. The volumes and loads represented by each composite sample (or inferred for each unsampled period) are expressed as a percentage of total storm volumes and loads.

Totals of storm-water-runoff and spring-flow volumes and loads of selected constituents for all sampled storms from March to October 1988, are given for the drainage-well and Mobley Spring sites (table 3). Loads of the trace metals cadmium, chromium, copper, iron, lead, nickel, and zinc are of particular interest, because these metals are associated with automobile traffic, roadway maintenance, street litter, and fuel and oil additives (Dannis, 1974; Shaheen, 1975; Harrison and Lonen, 1977; Gupta and others, 1981). Nutrients are also commonly associated with roadway runoff.

The seasonal variation in storm loads and mean concentrations (calculated as the quotient of storm load and runoff volume) of selected constituents at the drainage-well site is illustrated in figure 11. The pattern of seasonal variation of storm loads for total-recoverable iron, magnesium, and zinc is representative of the pattern for total-recoverable calcium, sodium, barium, and manganese. The highest storm load occurred during the July 13, 1988, storm. It is not possible, however, to conclude that loadings for these constituents would generally be higher for summer storms, because loads for the July 4, 1988, storm were low. In contrast, mean concentrations of

Table 2.—*Percentages of total storm-water-runoff volume and loads of selected constituents represented by each composite sample at the drainage-well and Mobley Spring sites*

[NCS = no composite sample analyzed for this period - concentrations and loads, for all constituents (except total organic carbon) during this period were estimated by averaging concentrations in samples collected immediately before and after the unsampled period (discrete samples for total organic carbon were analyzed for all periods); site number: 1, Drainage well; 2, Mobley Spring; --, no data; BD, concentration in all samples below analytical detection limit]

Date of storm	Site number	Composite-sample number	Percent of total storm-water runoff volume	Percent of total storm load: Total recoverable calcium	Total recoverable magnesium	Total recoverable barium	Total recoverable copper	Total recoverable iron	Total recoverable lead	Total recoverable zinc	Total organic carbon
03/25/88	2	NCS	9	8	8	8	14	17	31[a]	13	13
		1	19	18	18	19	28	50	69[a]	28	28
		2	17	18	18	17	14	9	0[a]	15	14
		3	21	22	22	21	17	11	0[a]	15	13
		4	17	17	18	18	14	7	0[a]	15	16
		NCS	17	17	17	17	13	6	0[a]	14	16
07/04/88	1	1	30	27	24	26	BD	43	BD	33	38
		NCS	40	40	40	39	BD	40	BD	43	33
		2	9	10	11	10	BD	6	BD	9	9
		NCS	21	23	24	25	BD	11	BD	15	19
		3	0	0	0	0	BD	0	BD	0	0
07/13/88	1	1	2	2	2	4	20[a]	3	0[a]	3	--
		NCS	7	6	5	14	80[a]	13	6[a]	8	--
		2	23	8	9	22	0[a]	22	23[a]	6	--
		NCS	14	11	12	37	0[a]	13	13[a]	11	--
		3	54	73	72	24	0[a]	49	57[a]	77	--
07/13/88	2	NCS	16	18	18	23	BD	30	29	31	--
		1	8	10	11	13	BD	16	15	15	--
		NCS	33	33	33	37	BD	40	39	40	--
		2	8	7	6	5	BD	4	4	4	--
		NCS	31	28	28	20	BD	9	12	10	--
		3	4	4	3	2	BD	1	1	0	--

[a]Percentages approximate because levels in some samples from this storm were below the analytical detection limit

Table 3.—*Storm-water runoff and spring-flow volume and loads of selected constituents at the drainage-well and Mobley Spring sites during the period February to October 1988*

[Constituents shown in capital letters are the most common highway contaminants: Values are in tons x 10^{-6}, except where noted; site number: 1, Drainage well; 2, Mobley Spring; --, no data; BD, concentration in all samples below analytical detection limit]

Date of storm	Site number	Storm-water-runoff or spring-flow volume[a] (cubic feet)	Total recoverable calcium	Total recoverable magnesium	Total recoverable sodium	TOTAL ARSENIC	Total recoverable barium	Total recoverable cadmium	TOTAL RECOVERABLE CHROMIUM	TOTAL RECOVERABLE COPPER
03/25/88	1	1,172	550	35	150	--	0.98	0.035[b]	BD	1.0
	2	9,165	25,000	2,400	2,700	--	15	BD	BD	3.6
05/22-23/88	1	7,190	2,400	140	410	0.22	2.7	BD	BD	BD
	2	12,867	31,000	3,100	3,400	BD	18	BD	BD	BD
07/04/88	1	1,294	770	74	91	.055	.89	BD	BD	BD
	2[c]	--	--	--	--	--	--	--	--	--
07/13/88	1	23,015	10,700	920	41,000	--	5.1	.073[b]	BD	.65
	2	30,933	60,000	6,600	6,500	--	76	1.3[b]	16	BD
10/16/88	1	4,771	1,300	50	210	--	2.6	.44	.05[b]	3.7
	2[c]	--	--	--	--	--	--	--	--	--
10/23/88[d]	1	209	--	--	--	--	--	--	--	--
	2	10,170	--	--	--	--	--	--	--	--

Date of storm	Site number	TOTAL RECOVERABLE IRON	TOTAL RECOVERABLE LEAD	Total recoverable lithium	TOTAL RECOVERABLE NICKEL	Total recoverable manganese	Total recoverable strontium	TOTAL RECOVERABLE ZINC	Total organic carbon as C	TOTAL RECOVERABLE OIL AND GREASE
03/25/88	1	9.0	0.69	BD	BD	1.5	9.6	3.4	350	73
	2	200	1.6	2.2	BD	41	98	11	990	BD
05/22/88	1	13	BD	BD	BD	5.1	27	15	2,100	--
	2	270	1.3	2.8	BD	48	140	13	2,800	--
07/04/88	1	4.7	BD	BD	0.43[b]	2.3	6.2	5.4	1,100	--
	2[c]	--	--	--	--	--	--	--	--	--
07/13/88	1	71	8.2	BD	BD	38	68	61	--	--
	2	9,500	38	10	8.7[b]	380	340	98	--	--
10/16/88	1	42	2.2[b]	BD	BD	3.5	96	11	980	--
	2[c]	--	--	--	--	--	--	--	--	--
10/23/88[d]	1	--	--	--	--	--	--	--	--	--
	2	--	--	--	--	--	--	--	--	--

total organic carbon, and total-recoverable magnesium, zinc, calcium, and manganese were highest during the July 4, 1988, storm. The pattern of seasonal variation shown for loads of total-recoverable cadmium and strontium, with the highest loads occurring during the October 16, 1988, storm (fig. 11), is representative of the pattern for total-recoverable chromium and copper.

Table 3. — *Storm-water runoff and spring-flow volume and loads of selected constituents at the drainage-well and Mobley Spring sites during the period February to October 1988* — Continued

Date of storm	Site number	TOTAL ORGANIC NITROGEN as N	TOTAL AMMONIA NITROGEN as N	DISSOLVED NITRITE as N	DISSOLVED NITRATE as N	Total phosphorus as P	DISSOLVED ORTHO-PHOSPHORUS as P	METHYLENE BLUE ACTIVE SUBSTANCES	Fecal coliform, in colonies X 10(6)	Fecal streptococci, in colonies X 10(6)
10/16/88	1	110	31	3	40	78	52	57	--	--
	2[c]	--	--	--	--	--	--	--	--	--
10/23/88[d]	1	--	--	--	--	--	--	--	139	321
	2	--	--	--	--	--	--	--	1,270	9,800

[a]Storm-water-runoff volume estimated by integrating the storm-water-runoff hydrograph from the drainage-well site; spring-flow volume estimated by integrating the spring-flow hydrograph (including base flow) from Mobley Spring.

[b]Concentration in some samples from this storm were below analytical detection limit, and loads during the corresponding storm period were assumed zero; consequently, actual value may be larger than value shown.

[c]Mobley Spring did not rise enough to activate the automatic sampler.

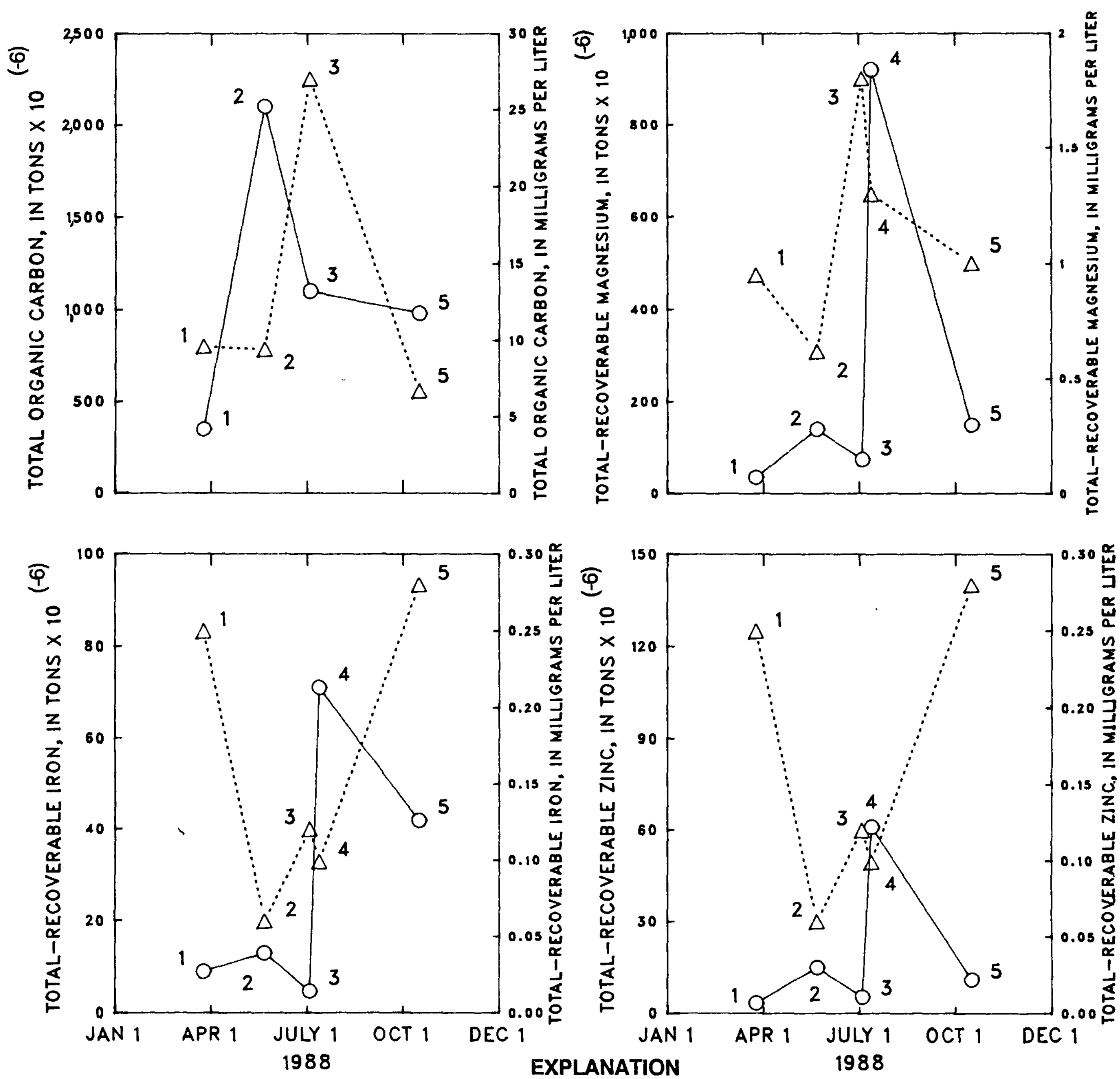
[d]Analysis of samples from this storm was limited to fecal coliform and fecal streptococcus bacteria.

Several climatological variables may mediate seasonal influence on loading rates. The time distribution of rainfall, both during the period preceding the storm as well as during the storm, may influence loading rates. The variation in storm loads and mean concentrations of selected constituents at the drainage-well site with variation in amount of antecedent rainfall and in rainfall intensity during the storm is shown in figure 12. Correlation of storm loads of total-recoverable metals and total organic carbon with amount of antecedent rainfall (represented by the amount of rainfall during the 7-day period preceding the storm) was low, with r^2 less than 0.70 for all constituents except total-recoverable sodium and copper. In contrast, a strong positive correlation of storm loads with rainfall intensity during the storm (represented by the maximum amount of rain falling within a 30-minute period) was observed, with r^2 greater than 0.70 for almost all constituents. Mean concentrations of constituents did not correlate well (r^2 less than 0.70) with either antecedent rainfall or rainfall intensity.

Storm of March 25, 1988

The 0.12 inch of rainfall for this storm fell over a 2-hour period, with a maximum intensity of 0.06 inch in a 30-minute period. Antecedent rainfall amounts in the area were small: 0.11 inch of rain had fallen in the preceding 12-day period. The volume of runoff at the drainage-well site, 1,172 ft^3, was approximately half of the storm-water volume at the Mobley Spring site, 2,637 ft^3, and about one-tenth the total volume of spring flow, 9,165 ft^3. Runoff quality at the drainage-well site was represented by two time-weighted composite samples, and at the Mobley Spring site by four composite samples.

Specific-conductance values were high at the beginning of runoff at the drainage-well site then decreased sharply as runoff increased, probably as a result of dilution of the first flush of dissolved, ionized constituents (Supplement B). Concentrations of total organic carbon followed the same pattern (but increased slightly at the end), indicating that timing of transport of organic



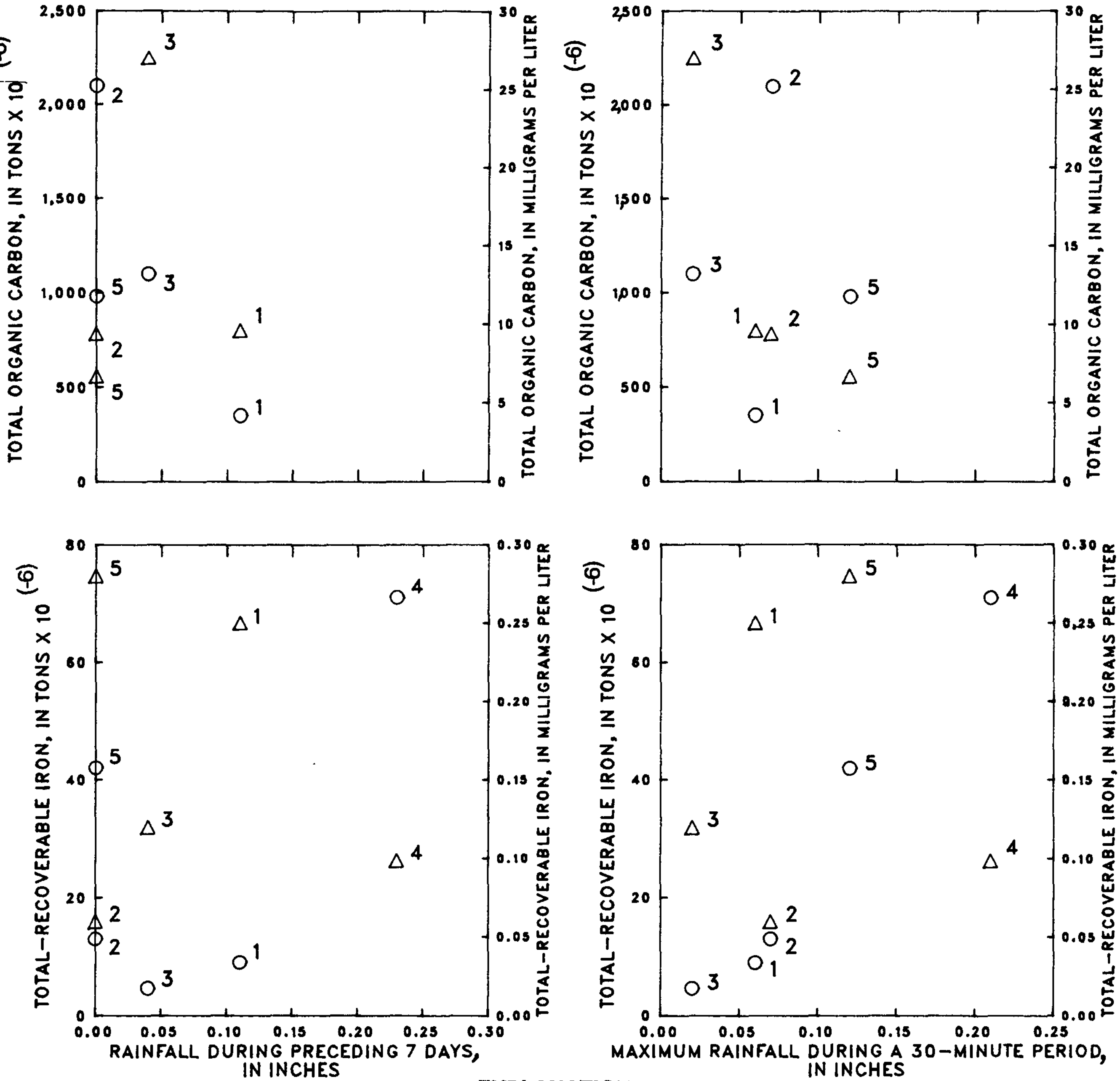
EXPLANATION

○—○ STORM LOAD AND NUMBER

△⋯△ STORM MEAN CONCENTRATION AND NUMBER

STORM NUMBER	STORM DATE
1	March 25, 1988
2	May 22-23, 1988
3	July 4, 1988
4	July 13, 1988
5	October 16, 1988

Figure 11.--Seasonal variation in storm loads and mean concentrations of selected constitutents in storm-water runoff at the drainage-well site.



EXPLANATION

○ 2 STORM LOAD AND NUMBER

△ 2 STORM MEAN CONCENTRATION AND NUMBER

STORM NUMBER	STORM DATE
1	March 25, 1988
2	May 22-23, 1988
3	July 4, 1988
4	July 13, 1988
5	October 16, 1988

Figure 12.--Variation in storm loads and mean concentrations of selected constitutents in storm-water runoff at the drainage-well site with antecedent rainfall and storm rainfall intensity.

material was similar to that of ionized constituents. The concentration of most of the major inorganic constituents (represented by magnesium in *Supplement E*) and all of the trace metals (represented by iron in *Supplement E), with the exception of zinc, is higher in the first composite sample than the second. Although it is difficult to correlate levels in two composite samples with the several discrete samples collected over the same period, for total organic carbon and specific conductance, the overall pattern of variation of levels of all these constituents and properties appear similar.*

Although samples were not available from the rising stages at the beginning of the storm hydrograph at Mobley Spring, it is presumed from the trend that specific conductance values fall throughout the rising limb of the hydrograph, as the more mineralized base flow is diluted with less mineralized storm recharge. Specific-conductance values then steadily increase as discharge decreases to the base-flow level. The change in concentration of total organic carbon with discharge at Mobley Spring is the reverse of this pattern: levels are highest during the peak of discharge and fall in concert with discharge. The pattern of variation of total-organic-carbon levels is almost identical at Mobley Spring and the drainage-well site, with the time lag increasing throughout the duration of the hydrograph, from 0.5 to 2 hours. Whereas variation in concentration of major inorganic constituents at Mobley Spring was correlated with specific-conductance values, the variation in concentration of the trace metals was strongly correlated with the concentration of total organic carbon. Concentrations of all analyzed inorganic constituents decreased throughout the hydrograph, with the exception of total-recoverable zinc, which increased at the end of the hydrograph (*Supplement E*).

Analytical determinations for U.S. Environmental Protection Agency priority pollutants (table 4) were made for one sample each for the drainage-well and Mobley Spring sites. The composite sample from the beginning of the hydrograph at each site was selected for analysis. Results are listed in table 5. Two of these compounds were detected in the sample from the drainage-well site, isophorone [40 micrograms per liter (μg/L)] and bis(2-ethyl hexyl) phthalate (9.0 μg/L); none of the priority pollutants were detected at the Mobley Spring site.

Comparison of distribution of loading of various constituents throughout the hydrograph (table 2) at Mobley Spring also illustrates that trace metals and total organic carbon are transported together. Over 40 percent of the loads of total organic carbon, total-recoverable zinc, lead, iron, and copper was flushed by the first one-fourth of the runoff volume. Total-recoverable lead and iron showed the most notable flushing pattern. By comparison, the loading rates of the major metals and barium remain relatively constant throughout runoff.

Loadings of 14 constituents for this storm are given in table 3. Although runoff volume was smaller for this storm than for all other sampled storms (with the exception of the storm of October 23), the estimated load of total-recoverable copper at both the drainage-well and Mobley Spring sites was highest for this storm (table 3). Estimated loads for almost all constituents are one to two orders of magnitude higher at the spring than at the drainage well, with the exception of total-recoverable copper, lead, zinc, oil and grease, and total organic carbon, for which loads at the spring are only as much as three times greater than loads at the drainage well.

Storm of July 13, 1988

Rainfall during this storm totaled 0.40 inch over a 3.5-hour period, with a maximum intensity of 0.21 inch in a 30-minute period. Less than two dry days preceded this event; a 0.16-inch rainstorm occurred on July 11. Runoff volume at the

Table 4.—*U.S. Environmental Protection Agency priority pollutants analyzed in storm-water samples from the drainage-well and Mobley Spring sites, March 25, 1988*

[All units in micrograms per liter. Analytical detection limit for all compounds is 5.0, except where indicated]

Compound	Analytical detection limit
ACENAPTHYLENE	
ACENAPHTHENE	
ANTHRACENE	
BENZO B FLUORANTHENE	10.0
BENZO K FLUORANTHENE	10.0
BENZO A PYRENE	10.0
BIS 2-CHLOROETHYL ETHER	
BIS (2-CHLOROETHOXY) METHANE	
BIS (2-CHLOROISOPROPYL) ETHER	
N-BUTYLBENZYL PHTHALATE	
CHRYSENE	10.0
DIETHYL PHTHALATE	
DIMETHYL PHTHALATE	
FLUORANTHENE	
FLUORENE	
HEXACHLOROCYCLOPENTADIENE	
HEXACHLOROETHANE	
INDENO (1,2,3-CD) PYRENE	10.0
ISOPHORONE	
N-NITROSODI-N-PROPYLAMINE	
N-NITROSODIPHENYLAMINE	
N-NITROSODIMETHYLAMINE	
NITROBENZENE	
PARACHLOROMETA CRESOL	30.0
PHENANTHRENE	
PYRENE	
BENZOGHI PERYLENE 1,12 -BENZOPERYLENE	10.0
BENZO(A)ANTHRACENE 1,2-BENZANTHRACENE	
1,2-DICHLOROBENZENE	
1,2,4-TRICHLOROBENZENE	
1,2,5,6-DIBENZANTHRACENE	10.0
1,3-DICHLOROBENZENE	
1,4-DICHLOROBENZENE	
2-CHLORONAPHTHALENE	
2-CHLOROPHENOL	
2-NITROPHENOL	
DINOCTYL PHTHALATE	10.0
2,4-DICHLOROPHENOL	
2,4,DIMETHYLPHENOL	
2,4-DINITROTOLUENE	
2,4-DINITROPHENOL	20.0
2,4,6-TRICHLOROPHENOL	20.0
2,6-DINITROTOLUENE	
4-BROMOPHENYLPHENYLETHER	
4-CHLOROPHENYLPHENYLETHER	
4-NITROPHENOL	30.0
4,6-DINITROORTHOCRESOL	30.0
PHENOL (C6H-50)	
NAPHTHALENE	
PENTACHLOROPHENOL	30.0
BIS (2-ETYLHEXYL) PHTHALATE	
DINBUTYLPHTHALATE	
HEXACHLOROBENZENE	
HEXACHLOROBUTADIENE	

drainage-well site, 23,015 ft^3, was almost three-fourths of the storm-water volume at Mobley Spring, 30,933 ft^3. Because preceding base flow was so low, storm-water volume approximately equaled total-flow volume at the spring. Runoff quality at the drainage-well and Mobley Spring sites was represented by three time-weighted composite samples from each site.

Specific-conductance values were high at the beginning of runoff at the drainage-well site, decreased sharply as runoff increased, then recovered to a level higher than the initial values (*Supplement B*). Concentrations of total organic carbon were not determined from these storm samples, because of anticipated interference from the fluorescein dye used in a concurrent storm dye-trace investigation. The concentrations of each of the major inorganic constituents, represented by magnesium in *Supplement B*, was positively correlated with specific conductance, whereas concentrations of most of the trace metals were not. Comparison of distribution of loading of the various constituents throughout the hydrograph (table 2) illustrates this as well. About 40 percent of the loads of many trace metals was flushed by the first one-third of runoff volume. Total-recoverable copper showed the most notable flushing pattern, with all of the detectable load flushed by the first 9 percent of volume. By comparison, only about 25 percent of the loads of major constituents and zinc were transported by the first half of runoff volume.

Although samples were not available from the rising stages at the beginning of the storm hydrograph at Mobley Spring, specific-conductance values fell during the sampled part of rising limb of the hydrograph, as the more mineralized base flow was diluted with less mineralized storm recharge. Specific-conductance values then steadily increased as discharge decreased to the base-flow level. Concentrations of the major metals, represented by magnesium (*Supplement C*), *was correlated positively with specific conductance values. Concentrations of*

Table 5.—*Concentrations of organic compounds in water samples from test sites in the study area*

[μg/L, micrograms per liter. Storm samples were analyzed for compounds listed in table 4. Dry-weather samples were analyzed for compounds listed in table 7. Compounds detected are those that exceeded the analytical detection limit: for compounds analyzed in storm samples, detection limits are shown in table 5; for compounds analyzed in dry-weather samples, detection limit is 0.2 μg/L]

Station or well number	Date	Hydrologic condition	Compounds detected	Concentrations (μg/L)
Hospital Sinkhole	3-25-88	Storm	Isophorone	40.0
			Bis(2-ethyl hexyl) phthalate	9.0
Mobley Spring	3-25-88	Storm	None	
Mobley Spring	6-09-88	Dry weather	Chloroform	.7
			Dichloroethane	.3
			Tetrachloroethylene	.2
Seven Springs	7-29-88	Dry weather	None	
Porters Bluff Spring	7-29-88	Dry weather	Chloroform	.4
Mt:M-13	9-06-88	Dry weather	Trichloroethane	.4
Mt:M-14	9-06-88	Dry weather	Benzene	.3

trace metals, represented by iron and zinc (*Supplement B*), decreased throughout the hydrograph. Between 40 and 50 percent of the loads of the trace metals were flushed by the first one-fourth of storm-water volume, whereas loading rates of the major metals remained relatively constant throughout stormflow (table 3).

Loadings of 14 constituents for this storm are given in table 3. Estimated loads for almost all constituents were one to two orders of magnitude higher at the Mobley Spring site than at the drainage-well site, with the exceptions of total-recoverable copper and sodium, for which the loads were greater at the drainage-well site, and total-recoverable zinc, for which load was only two times higher at the Mobley Spring site. Loads for many constituents were several orders of magnitude higher during this storm than for any other sampled storms: sodium loading at the drainage-well site was about 100 times higher than for all other sampled storms, and iron and lead loads at the Mobley Spring site were about 20 times higher. The greater volume of runoff and spring flow did not account for all of these differences. Furthermore, wet antecedent conditions contraindicate the accumulation of contaminants in the watershed as a plausible explanation for these high loads.

ESTIMATED CONSTITUENT LOADS IN STORM-WATER RUNOFF

Regression models have been developed by several investigators to estimate storm loads and annual loads for various constituents in storm-water runoff. The models developed by Tasker and Driver (1988) predict the mean runoff load for an individual storm event for 10 constituents, based on physical and land-use characteristics of the watershed and climate, for drainage areas ranging from 0.015 to 1 mi^2. These models were applied to the watershed for the drainage-well site to predict a mean-runoff load for total copper, lead, zinc, and various nutrient species (table 6). Prediction error for each model is also presented in table 6. These estimates are compared to the observed mean loads, calculated as the average load for all sampled storms, for each constituent (table 6).

The difference between predicted and observed loads for all constituents, with the exception of dissolved orthophosphorus, are outside the range of the average prediction error. Predicted loads for the trace metals are one to two orders of magnitude higher than observed loads, whereas predicted loads for total nitrogen, total phosphorus, and dissolved orthophosphorus are within an order of magnitude of observed loads. One reason for overprediction may be that the size of the watershed, 0.019 mi^2, is near the low end of the range of drainage-area sizes considered suitable for application of the equations. Another possible explanation is that the sampled runoff events do not constitute a representative sample of hydrologic conditions, due to below-normal-rainfall amounts during the sampling period. In particular, the observed loads for nutrients may be low because they are calculated from only one runoff event, October 16, 1988.

Total loading of constituents for the period February to October 1988, can be estimated by extrapolating loading rates calculated for the sampled volumes of runoff, as the quotient of storm load and runoff volume, to the total volume of runoff that occurred during this period. Several techniques can be used for the extrapolation, ranging in sophistication from regression models, developed from data for sampled storms, to a flow-weighting procedure. The latter technique was used in this investigation, because the number of sampled storms (nine) was not a large enough data set for the development of a regression model. Seasonal differences in loading rates were incorporated by calculating two average loading rates for each constituent, representing cool-season (October to March) and warm-season (April to September) storms (table 6). For those constituents for which sampling was done in only one season, the same loading rate was used for both seasons. Constituent loads for storms for which constituent concentrations were below the detection limit (indicated by the entry 'BD' in table 3) were assumed to be zero.

The product of the average-seasonal-loading rate and the total-runoff volume during that season is the seasonal load. Total-runoff volume was calculated by summing the volume from each runoff event that occurred during the period (*Supplemental Information*). The total cool-season and warm-season loads and the total load of 22 constituents at the drainage-well site during the study period are given in table 6. Total loads for trace metals ranged from 0.030 pound for cadmium to 12 pounds for strontium. Total loads of the primary nutrients ranged from 0.97 pound for nitrite, as N, to 34 pounds for organic nitrogen, as N.

Total loads for five constituents (calcium, magnesium, sodium, ammonia nitrogen, as N, and nitrate, as N) in rain falling on the watershed for the drainage well were estimated using precipitation-chemistry data collected at the rain gage operated by the Tennessee Valley Authority at Land-Between-the-Lakes, Kentucky, approximately 50 miles northwest of the study area. Concentration data for weekly rainfall samples collected during the period February to June 1988

Table 6. – *Observed and predicted mean storm loads and estimated total loads of selected constituents in storm-water runoff at the drainage-well site, and estimated total loads of selected constituents in rainfall during the period February to October 1988*

[Constituents shown in capital letters are the most common highway contaminants; Predicted mean storm loads computed from regression models of Tasker and Driver (1988); Observed mean storm loads computed as average of all sampled storms; NM, constituent not modeled; --, precipitation-chemistry data not available]

	Load in storm-water runoff									Load in rainfall
	Mean storm load, in pounds		Average variance of prediction		Average seasonal loading rates, in pounds per cubic feet X 10^6		Seasonal load, in pounds		Total load for period, in pounds	Total load for period, in pounds
Constituent	Predicted	Observed	+ percent	- percent	Cool season	Warm season	Cool season	Warm season		
Calcium, total recoverable	NM	6.3			730	920	230	400	630	11
Magnesium, total recoverable	NM	.52			62	63	19	28	47	1.5
Sodium, total recoverable	NM	17			18	130	5.5	56	62	5.9
ARSENIC, TOTAL	NM	.00028			.073[a]	.073[a]	.022	.032	.054	--
Barium, total recoverable	NM	.0049			1.4	.86	.43	.38	.81	--
Cadmium, total recoverable	NM	.00022			.095	.0020	.029	.00088	.030	--
COPPER, TOTAL RECOVERABLE	0.38	.0036	140	58	1.6	.019	.50	.0083	.51	--
IRON, TOTAL RECOVERABLE	NM	.056			17	5.7	5.2	2.5	7.7	--
LEAD, TOTAL RECOVERABLE	.49	.0044	133	57	1.1	.24	.34	.11	.45	--
Manganese, total recoverable	NM	.020			2.1	2.7	.65	1.2	1.8	--
Strontium, total recoverable	NM	.083			28	7.7	8.6	2.4	12	--
ZINC, TOTAL RECOVERABLE	.26	.037	128	53	5.2	5.9	1.6	2.6	4.4	--
ORGANIC CARBON, AS C, TOTAL	NM	2.3			500	1,100	160	500	600	--
OIL AND GREASE, TOTAL RECOVERABLE	NM	.15[b]			120[b]	120[b]	37	53	90	--
TOTAL NITROGEN, AS N	1.6	.37	131	57	77[b]	77[b]	24	33	57	--
ORGANIC NITROGEN, AS N, TOTAL	NM	.22			46[b]	46[b]	14	20	34	--
AMMONIA NITROGEN, AS N, TOTAL	2.3	.062	119	54	13[b]	13[b]	4.0	5.7	9.7	9.7
NITRITE, AS N, DISSOLVED	NM	.0060			1.3[b]	1.3[b]	.40	.57	.97	--
NITRATE, AS N, DISSOLVED	NM	.080			17[b]	17[b]	5.2	7.4	13	21
Total Phosphorus, as P	.47	.16	107	52	33[b]	33[b]	10	14	24	--
ORTHOPHOSPHORUS, AS P, DISSOLVED	.098	.10	144	59	22[b]	22[b]	6.8	9.6	17	--
METHYLENE BLUE ACTIVE SUBSTANCES	NM	.11			24[b]	24[b]	7.4	11	18	--

[a]Loading rate estimated from warm-season storm data because no samples were collected during the cool season.
[b]Loading rate was estimated from data from a single storm.

were provided by the National Atmospheric Deposition Program (1989). These data were applied to rainfall amounts recorded during these same weekly intervals at the Cumberland River at Clarksville station (03436500) to obtain loads. Loads for the entire study period (February to October 1988) were estimated by multiplying the volume-weighted mean concentrations for constituents for the period February to June by the total volume of rainfall for the study period. The total rainfall loads are compared to the total storm-water-runoff loads for the five constituents (table 6). The estimated loads contributed by rainfall were between one to two orders of magnitude lower than the estimated load in storm-water runoff for sodium, calcium, and magnesium. The estimated loads contributed by rainfall for the ammonia nitrogen, as N, and nitrate, as N, were equal to and greater than, respectively, the corresponding estimated load in storm-water runoff. This may be due to inaccuracies in the estimates of storm-water-runoff load, which were obtained by extrapolating data from only one sampled storm. It is also possible that the watershed is acting as a sink for the nitrate; however, this is unlikely.

EFFECTS OF STORM-WATER RUNOFF ON GROUND-WATER QUALITY

Storm-water quality and water quality of the water in the local aquifer, as characterized by dry-weather samples from three springs and two observation wells in the Clarksville area, are shown in figure 13. Concentrations of the total-recoverable trace metals cadmium, chromium, copper, lead, and nickel were higher in many storm-water samples from both the drainage-well and Mobley Spring sites than in samples from any other site. In addition, concentrations of total organic carbon, methylene blue active substances, and total-recoverable oil and grease were higher in many storm-water samples from the drainage-well site than in any ground-water samples. All of the constituents listed above, with the exception of lithium, are constituents commonly associated with roadway runoff, indicating that the watershed for the drainage well may be contributing relatively large amounts of these constituents to local ground water during storms.

The skewed concentration-frequency distribution of certain constituents in the storm-sample sets from the drainage-well and Mobley Spring sites are illustrated in figure 13. Of the 20 constituents (19 metals and total organic carbon) for which the number of analyzed samples from the sinkhole was larger than 10, the frequency distributions for 16 were skewed to the right (mean value greater than median value). For the metals sodium, barium, and iron, skewness was pronounced (mean value greater then two times the median value). In the case of iron, the skewness can be attributed to the "first-flush" effect: high concentrations of constituents near the beginning of the hydrograph. In the case of sodium and barium, the distribution is skewed by the extremely high concentrations (140 and 0.48 mg/L, respectively) in the sample from the February 14, 1988 storm.

Of the 20 constituents for which the number of analyzed samples from Mobley Spring was larger than 10, the frequency distributions for 14 were skewed to the right. For two metals, iron and cobalt, the skewness was pronounced and can be attributed to the "first-flush" effect.

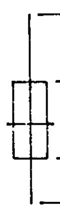
The highest concentrations of total-recoverable zinc (430 μg/L) and dissolved chloride (35 mg/L) occurred in the sample from well Mt:M-13. The chemistry of the sample from well Mt:M-14 was different from that of all other samples. Values of hardness and specific conductance and concentrations of total-recoverable strontium, magnesium, and dissolved fluoride were much higher in this sample.

Analytical determinations for volatile organic compounds (table 7) were made for each

EXPLANATION

[Use this explanation for figure 13 (pages 33 through 40).]

PERCENTILE--Percentage of analyses equal to or less than the indicated value



◇ SINGLE SAMPLE

(2) NUMBER OF SAMPLES

—— —— MAXIMUM CONTAMINANT LEVEL--Tennessee drinking-water standards

·············· ANALYTICAL DETECTION LIMIT

1 DRAINAGE WELL--Storm-water runoff samples

2 MOBLEY SPRING--Storm-water spring discharge samples

3 MOBLEY SPRING--Dry-weather sample(s)

4 SEVEN SPRINGS--Dry-weather sample

5 PORTERS BLUFF CAVE SPRING--Dry-weather sample

6 Mt:M-13--Dry-weather sample

7 Mt:M-14--Dry-weather sample

(See figures 3, 6, and 7 for locations of sites.)

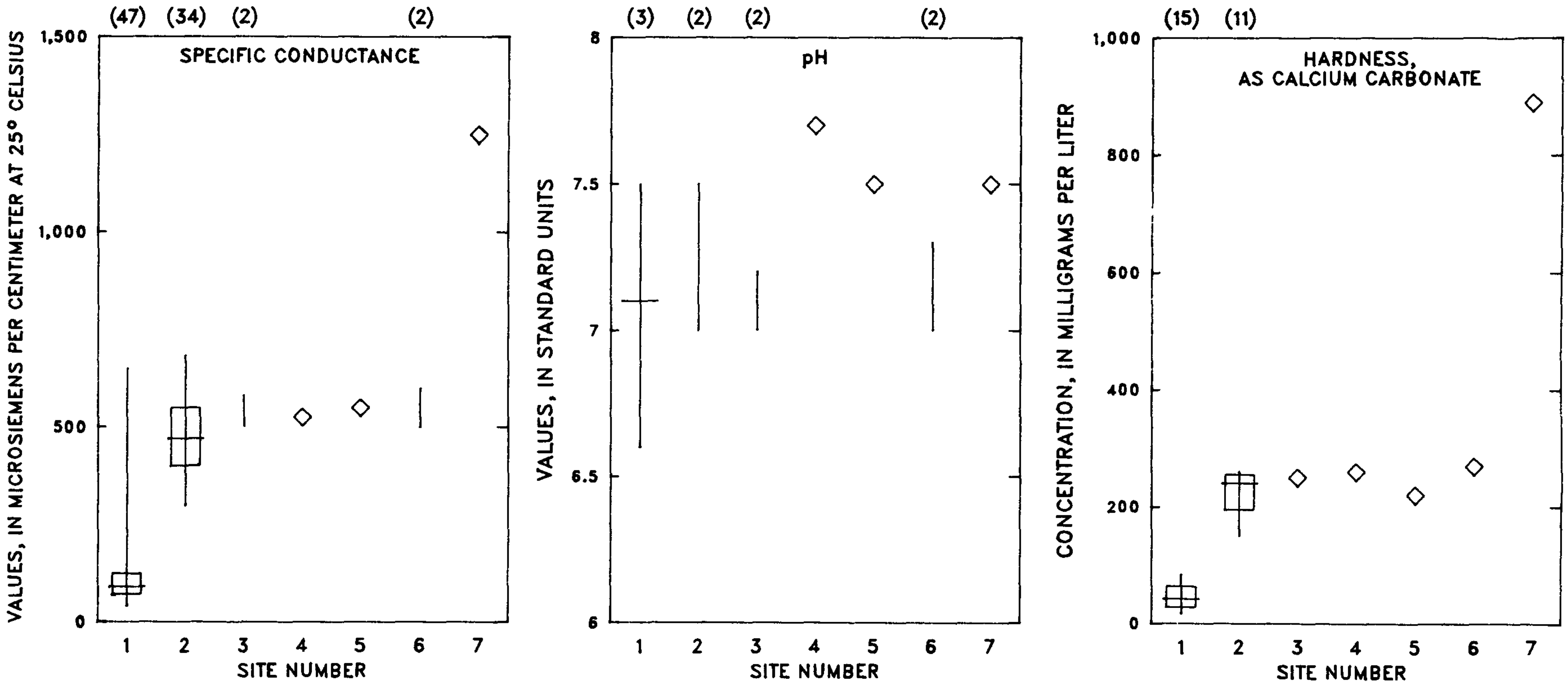


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods.

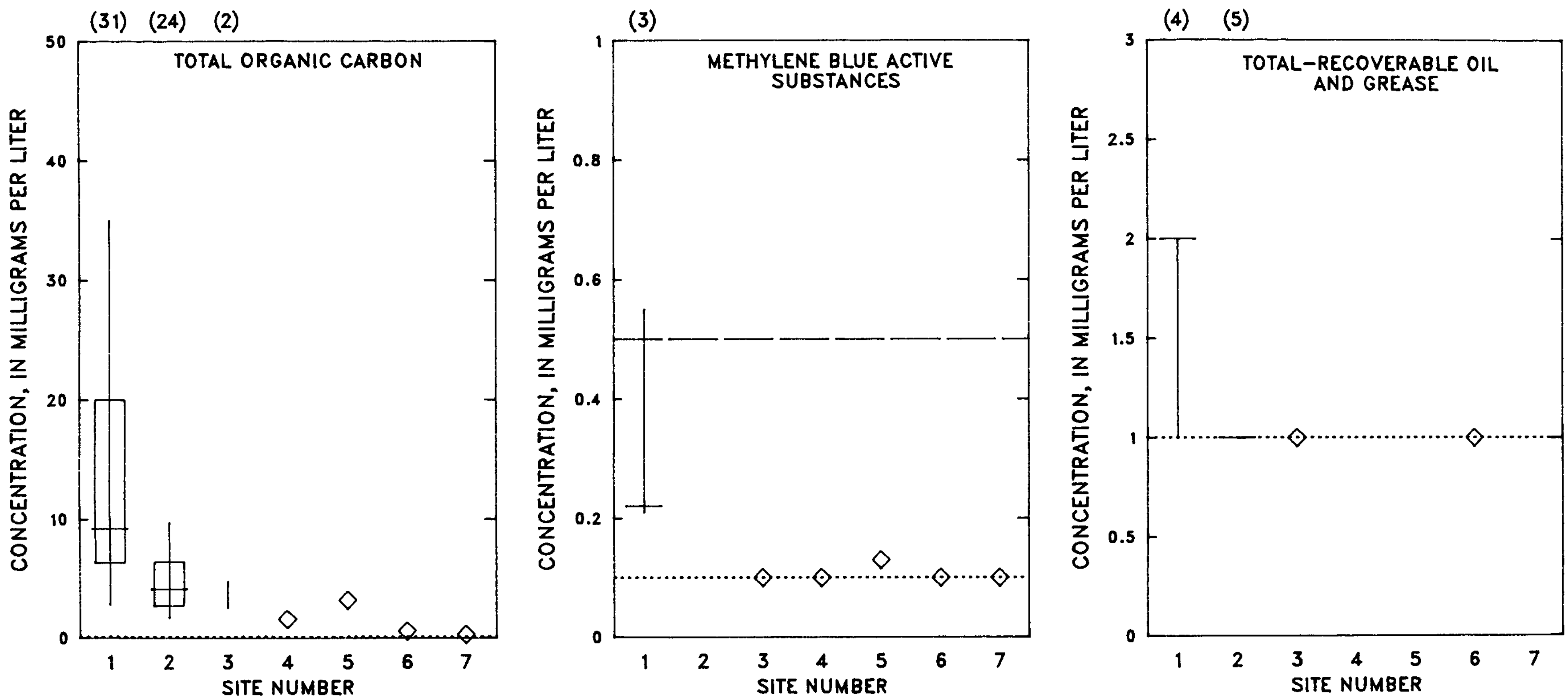


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

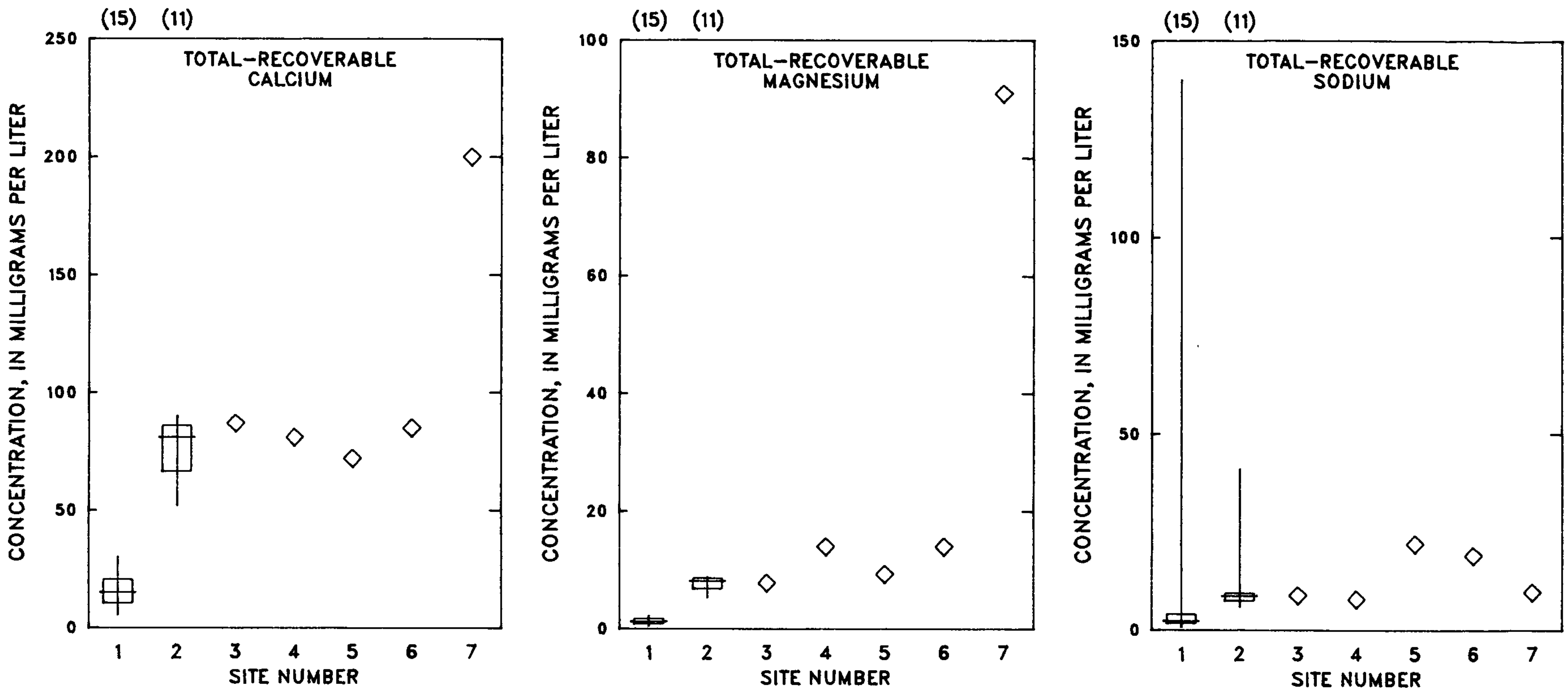


Figure 13.–Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods–Continued.

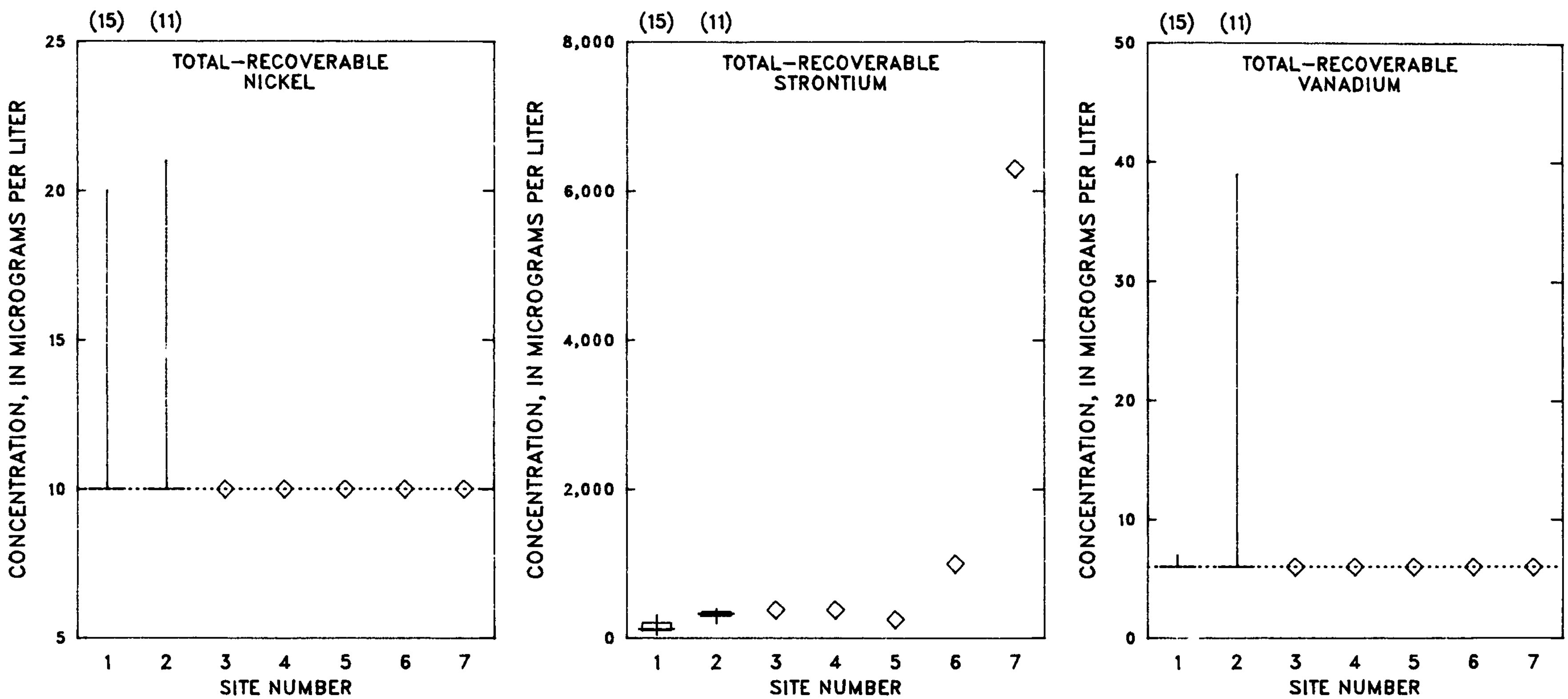


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

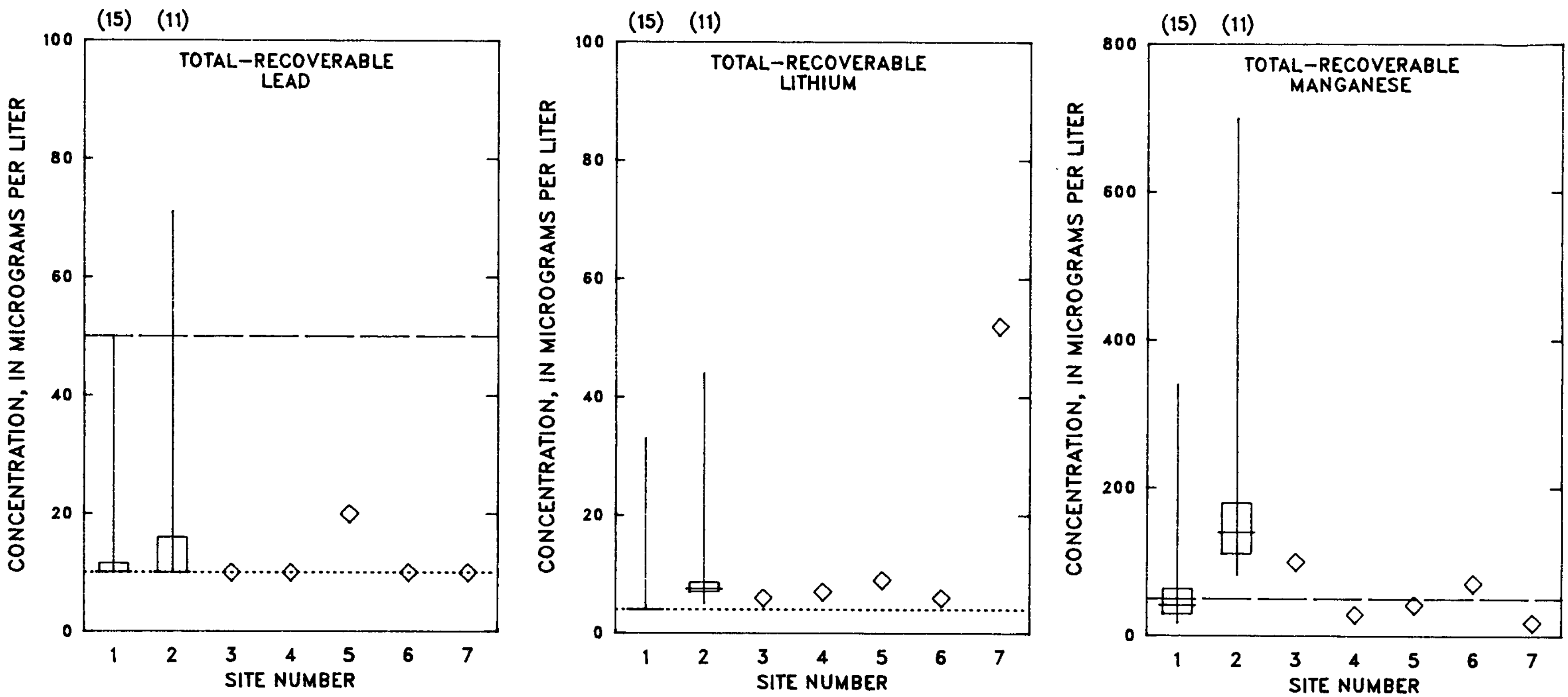


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

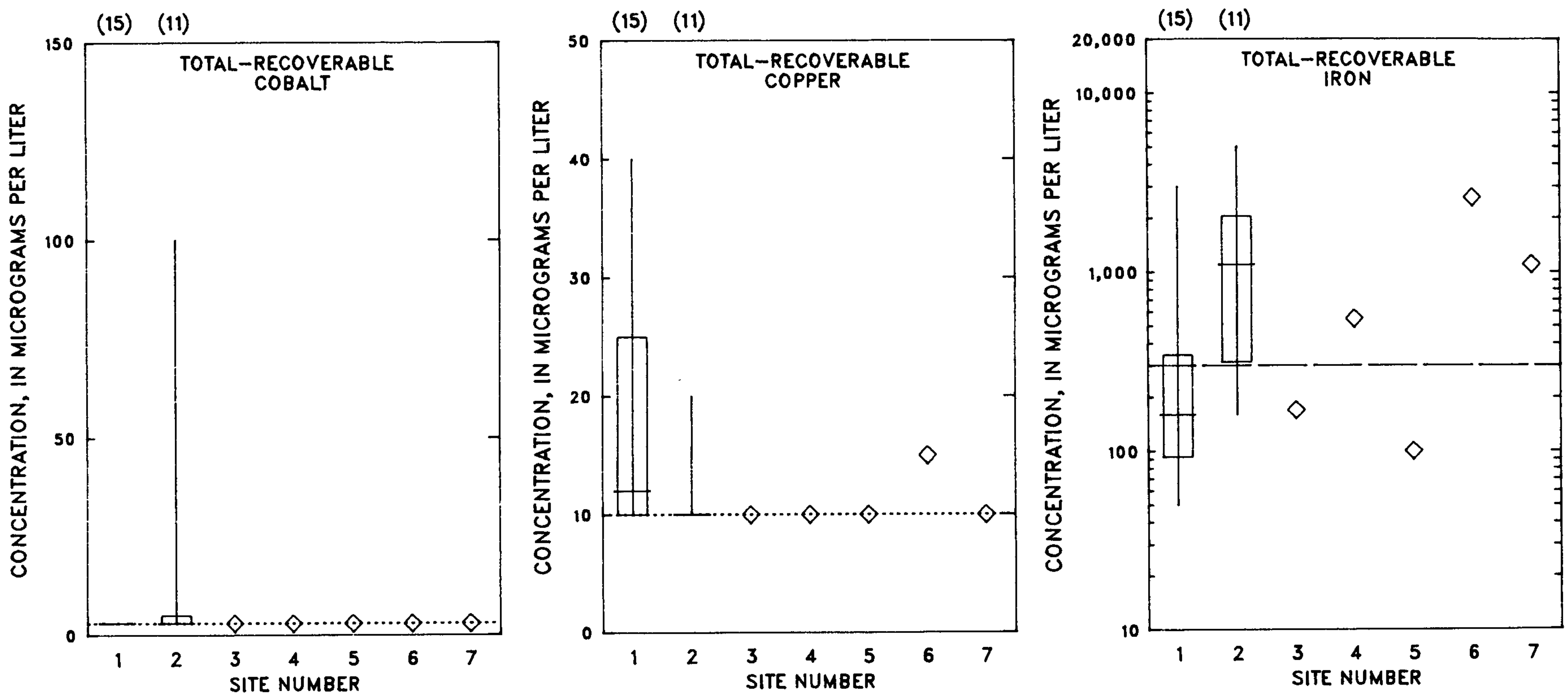


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

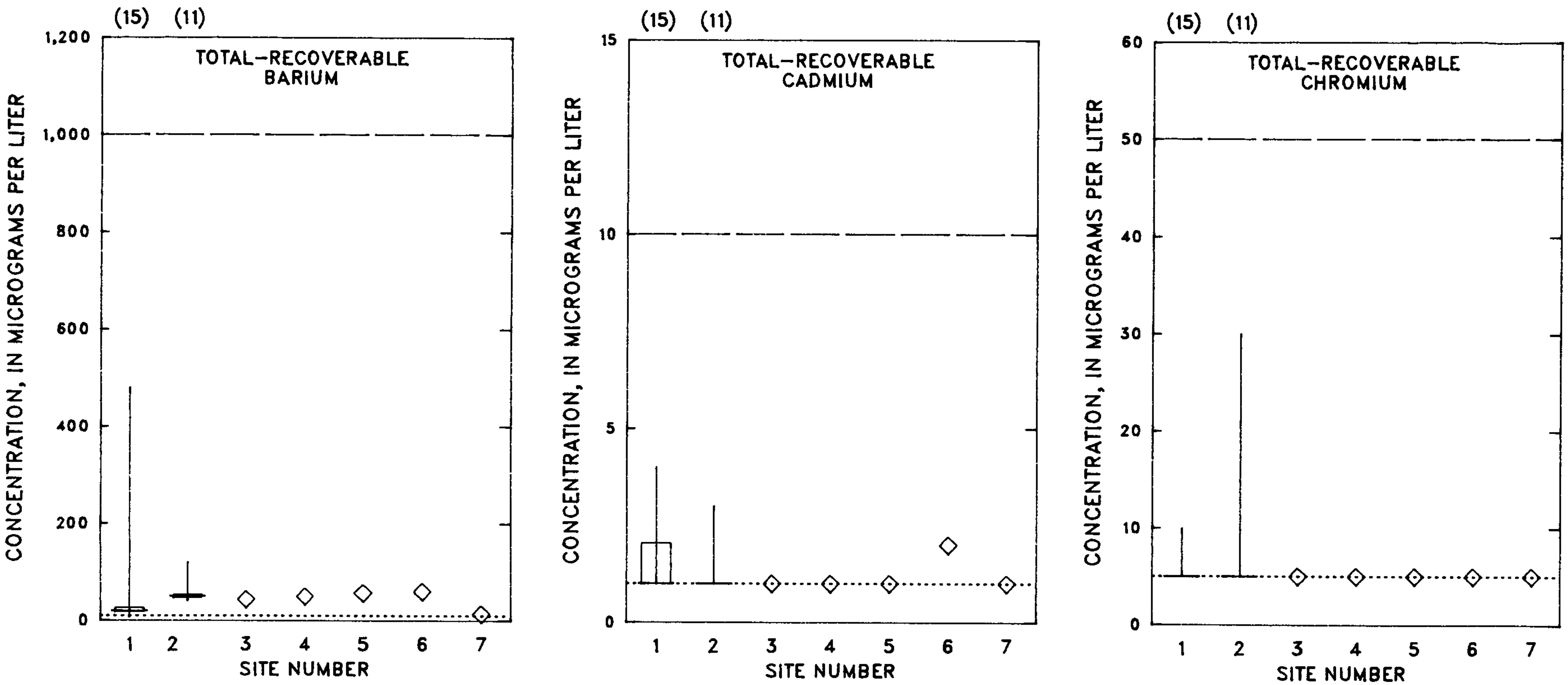


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

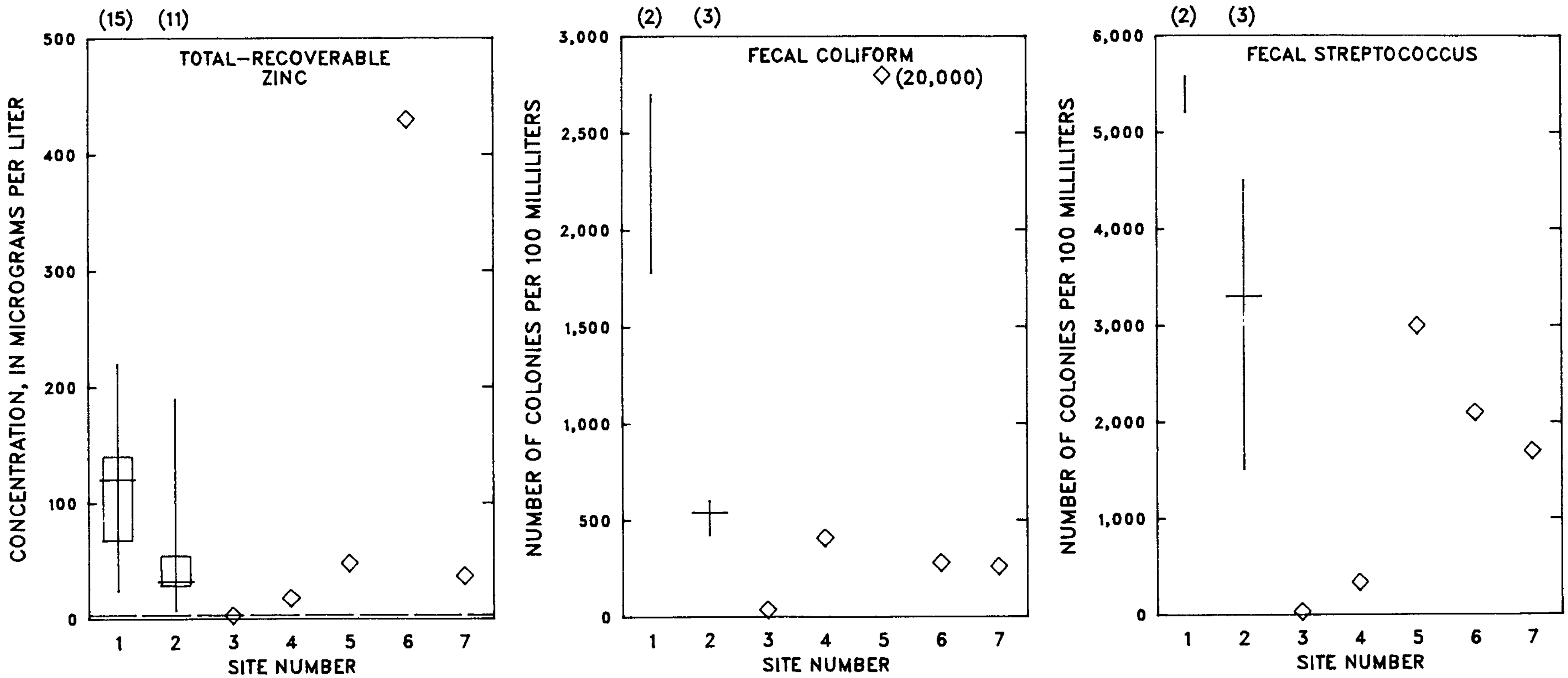


Figure 13.--Selected water-quality constituents and properties in storm-water runoff and spring discharge as compared to ground water in dry-weather periods--Continued.

of the dry-weather ground-water samples from each site. Results are listed in table 5. Three compounds were detected at Mobley Spring in low concentrations: chloroform (0.7 μg/L), dichloroethane (0.3 μg/L), and tetrachloroethylene (0.2 μg/L). Samples from Porters Bluff Cave Spring, Mt:M-13, and Mt:M-14 contained low concentrations of chloroform (0.4 μg/L), trichloroethane (0.4 μg/L), and benzene (0.3 μg/L).

Water quality varied markedly in the dry-weather samples collected from Mobley Spring, Porters Bluff Cave Spring, and Seven Springs. The constituents with the most pronounced variation in concentration among sites (greater than 50-percent difference) were total-recoverable sodium, iron, lead, zinc, manganese, dissolved chloride, fluoride, sulfate, nitrite (as N), total phosphorus (as P), ammonia nitrogen (as N), organic nitrogen (as N), fecal coliform, and fecal streptococcus bacteria. With the exception of iron and magnesium, for which concentrations were higher at Seven Springs, concentrations of all these constituents were highest at either Porters Bluff Cave or Mobley Springs, and lowest at Seven Springs.

The contrast in land use in the inferred ground-water basin for each spring site may contribute to differences in water quality between the sites. Land use in the area of both Porters Bluff and Mobley Springs is medium- to high-density residential, with commercial activity related to shopping centers, gasoline service stations, and, for Mobley Spring, the Memorial Hospital complex. Land use in the area of Seven Springs is low-density residential.

Concentrations of selected constituents in the storm-water and dry-weather samples at all sites are shown in figure 13 along with established drinking-water maximum-contaminant levels (MCL) (Tennessee Department of Health and Environment, 1988). Several wells and at least one spring in the Clarksville area have been reported to be in use for domestic water supply, even in areas serviced by the municipal water system (Phillip Kemmerly, Austin Peay State University, oral commun., 1989).

Densities of fecal coliform and fecal streptococcus bacteria and total-recoverable concentrations of iron, manganese, and methylene blue active substances in storm samples from the drainage-well site exceeded the MCL by as much as 2,500 and 5,500 colonies per 100 mL, and 2.7, 0.29, and 0.05 mg/L, respectively. Densities of

Table 7.—*Volatile organic compounds analyzed in dry-weather ground-water samples*

[Analytical detection limit for all compounds is 0.2 micrograms per liter]

Benzene	1,4-Dichlorobenzene	Methyl bromide
Bromoform	Dichlorobromomethane	Methyl chloride
Carbon tetrachloride	Dichlorodifluoromethane	Methylene chloride
Chlorobenzene	1,1-Dichloroethane	Styrene
Chlorodibromomethane	1,2-Dichloroethane	1,1,2,2-Tetrachloroethane
Chloroethane	1,1-Dichloroethylene	Tetrachloroethylene
1,1,2-Chloroethane	1,2-trans-Dichloroethylene	Toluene
2-Chloroethyl vinyl ether	1,2-Dichloropropane	1,1,1-Trichloroethane
Chloroform	1,3-Dichloropropane	Trichloroethylene
1,2-Dibromoethylene	cis-1,3-Dichloropropene	Trichlorofluoromethane
1,2-Dichlorobenzene	trans-1,3-Dichloropropene	Vinyl chloride

fecal coliform and fecal streptococcus bacteria and total-recoverable concentrations of iron, manganese, and lead in storm samples from Mobley Spring exceeded the MCL by as much as 500 and 4,500 colonies per 100 mL, and 18.7, 0.65, and 0.021 mg/L, respectively.

For iron, manganese, and bacteria, these undesirable levels are not necessarily attributable to storm-water recharge, because concentrations of these constituents also exceeded drinking-water standards in one or more of the dry-weather samples from springs and observation wells in the area. The concentration of total-recoverable iron in dry-weather samples from Seven Springs and the observation wells Mt:M-13 and Mt:M-14 exceeded the MCL by 0.25, 2.3, and 0.8 mg/L, respectively. The concentration of total-recoverable manganese in dry-weather samples from Mobley Spring and Mt:M-13 exceeded the MCL by 0.05 and 0.02 mg/L, respectively. Densities of fecal coliform and fecal streptococcus bacteria in all samples exceeded the MCL of less than 1 colony per 100 mL; in fact, in all samples except the dry-weather sample from Mobley Spring, densities were over 200 colonies per 100 mL for both species of bacteria.

OTHER FACTORS AFFECTING GROUND-WATER QUALITY

Early in the course of this investigation, it was discovered that the water-quality problems at Mobley Spring were chronic and apparently of diverse origin. Even during dry-weather flow, a strong odor of petroleum could be detected. In addition, a sewer line passing about 30 feet upslope from the spring was observed to leak intermittently throughout the period of data collection. It is evident that other sources of contamination exist within the ground-water basin for Mobley Spring, in addition to the potential source of storm-water runoff entering the drainage well. Consequently it is not possible to attribute degradation of water quality of the spring following recharge events solely to storm-water runoff entering the drainage well. Although concentrations of several constituents increase following storm recharge at Mobley Spring as compared to dry-weather conditions (fig. 13), the sources of these constituents are not known. Several constituents, such as iron and magnesium, may be derived from aquifer material that becomes mobilized by the increased ground-water velocities resulting from increased hydraulic gradients following recharge.

Comparison of storm loads of many constituents at the drainage-well site to the Mobley Spring site also indicates that the relative contribution of constituents in storm water from the drainage-well site is not significant. The exceptions to this are for constituents associated with roadway runoff: arsenic, copper, lead, organic carbon, and oil and grease. In addition, the marked similarity in the concentration-time data for total organic car-bon at the drainage-well site compared to the Mobley Spring site during the storm of March 25, 1988 (*Supplement B*), also indicates that the drainage well may be contributing relatively large amounts of total organic carbon to local ground water during storms.

SUMMARY AND CONCLUSIONS

Storm-related water-quality data were collected at a drainage-well site and at a spring site in Clarksville, Tennessee, to define the effects of storm-water runoff on the quality of ground water in the area. A dye-trace test verified the direct hydraulic connection between the drainage well and Mobley Spring. Samples of storm runoff and spring flow were collected at these sites for nine storms during the period February to October 1988. Water samples also were collected from two other springs and two observation wells in the area during dry-weather conditions to assess the general quality of ground water in an urban karst terrain.

Evaluation of the effect of storm-water runoff on the quality of local ground water is complicated by the presence of other sources of contaminants in the area. Concentrations and loads for most major constituents were much smaller in storm-water runoff at the drainage well than in the discharge of Mobley Spring, indicating that much of the chemical constituent load discharged from the spring comes from sources other than the drainage well. However, for some of the minor constituents associated with roadway runoff (arsenic, copper, lead, organic carbon, and oil and grease), the drainage well contributed relatively large amounts of these constituents to local ground water during storms. The close correlation between concentrations of total organic carbon and concentrations of most trace metals at the drainage-well and Mobley Spring sites indicates that these constituents are transported together. Many trace metals were flushed early during each runoff event.

Mean storm loads for copper, lead, zinc, and four nutrient species (total nitrogen, ammonia nitrogen, total phosphorus, and orthophosphorus) in storm-water runoff at the drainage-well site were lower than mean storm loads predicted from an existing regression model. The overprediction by the model may be a result of the small size of the drainage area relative to the range of drainage areas used in the development of the models, or to the below-normal amounts of rainfall during the period of sampling for this investigation. Loads for trace metals for the period February to October 1988, calculated by extrapolating from sampled storms, ranged from 0.030 pound for cadmium to 12 pounds for strontium. Loads of the primary nutrients ranged from 0.97 pound for nitrite as nitrogen to 34 pounds for organic nitrogen.

Concentrations of total-recoverable cadmium, chromium, copper, lead, and nickel were higher in many storm-water samples from both the drainage-well and Mobley Spring sites than in samples from any other site in the local aquifer. In addition, concentrations of total organic carbon, methylene blue active substances, and total-recoverable oil and grease were generally higher in storm-water samples from the drainage-well site than in any ground-water sample.

Densities of fecal coliform and fecal streptococcus bacteria and total-recoverable concentrations of iron, manganese, and methylene blue active substances in storm samples from the drainage-well site exceeded the maximum contaminant levels listed in Tennessee's drinking-water standards (1988) by as much as 2,500 and 5,500 colonies per 100 milliliters, and 2.7, 0.29, and 0.05 milligrams per liter, respectively. Densities of fecal coliform and fecal streptococcus bacteria and total-recoverable concentrations of iron, manganese, and lead in storm samples from Mobley Spring exceeded the maximum contaminant levels by as much as 500 and 4,500 colonies per 100 milliliters, and 18.7, 0.65, and 0.02 milligrams per liter, respectively. For iron, manganese and bacteria, these undesirable levels are not necessarily attributable to storm-water recharge, because concentrations of these constituents also exceeded drinking-water standards in one or more of the dry-weather samples from selected springs and observation wells in the area.

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SUPPLEMENTAL INFORMATION

Supplement A.—*Storm characteristics and antecedent conditions for sampled storms in Clarksville, Tennessee, for the period February to October 1988*

[--, no data]

Date of storm	Total rainfall (inches)	Duration of rainfall (hours)	Maximum 30-minute rainfall rate (inches per hour)	Preceding dry days (day with less than 0.05 inch of rain)	Rainfall during preceding 1 day (inches)	Rainfall during preceding 3 days (inches)	Rainfall during preceding 7 days (inches)	Peak water level at drainage-well site (feet)	Storm-water-runoff volume at drainage-well site[a] (cubic feet)	Storm-water volume a Mobley Spring[b] (cubic feet)
02-01-88	0.28	8.0	0.08	0	0.22	0.22	0.22	--	12,180	--
02-02-88	.96	12.0	.16	0	.28	.50	.50	--	41,760	--
02-04-88	.11	2.5	.04	1	.01	1.46	1.46	--	4,785	--
02-11-88	.10	4.0	.02	6	.00	.00	.11	--	4,350	--
02-13-88	.15	4.5	.04	1	.00	.10	.10	--	6,525	--
02-14-88	.67	7.5	.19	0	.15	.25	.25	--	37,845	--
02-19-88	.28	5.0	.06	4	.00	.01	1.03	--	12,180	52,248
02-23-88	.24	5.0	.05	3	.00	.00	.29	0.69	10,440	27,279
03-03-88	.82	8.0	.21	8	.00	.00	.00	2.23	35,670	--
03-08-88	.04	1.5	.02	3	.00	.00	.82	.32	1,740	621
03-09-88	.46	9.0	.08	4	.04	.04	.86	1.41	20,010	112,791
03-12-88	.18	4.0	.06	2	.00	.46	.50	.77	7,830	26,241
03-18-88	.11	5.0	.02	5	.00	.00	.18	.32	4,785	--
03-25-88	.12	2.0	.06	12	.00	.00	.11	.42	6,525	2,637
03-26-88	.10	1.0	.08	0	.15	.15	.15	.34	4,350	189
03-29-88	.17	2.0	.09	2	.00	.10	.25	.79	7,395	7,302
03-31-88	1.52	27.5	.12	1	.01	.18	.43	2.86	66,120	771,531
04-06-88	.11	2.5	.04	4	.00	.01	1.54	.75	4,785	13,740
04-15-88	.06	1.5	.04	13	.00	.00	.00	.33	2,610	567
04-18-88	.20	2.5	.10	0	.12	.18	.18	1.40	8,700	42,894
05-03-88	1.06	7.0	.29	14	.00	.00	.00	3.20	46,110	98,970
05-09-88	.23	3.0	.12	0	.05	.05	1.11	.98	10,005	8,718
05-09-88	.07	1.5	.03	0	.05	.05	1.11	1.32	3,045	14,586
05-22-88	.20	3.5	.07	12	.00	.00	.00	.78	8,700	9,855
05-23-88	.39	11.5	.04	0	.18	.18	.39	1.27	16,965	66,171
07-04-88	.03	1.0	.02	18	.00	.00	.04	.43	1,305	1,986
07-11-88	.16	3.5	.07	2	.00	.05	.13	.49	6,960	2,256
07-13-88	.40	3.5	.21	2	.02	.18	.23	1.83	17,400	31,059
07-18-88	.00	0.0	.00	1	.39	.39	.97	.34	--	414
07-19-88	1.62	7.5	.28	2	.00	.39	.81	5.74	70,470	167,436
07-30-88	.08	1.0	.07	9	.00	.04	.08	.40	3,480	1,008
08-03-88	.05	.5	.05	3	.00	.00	.08	.43	2,175	2,499
08-11-88	.00	.0	.00	7	.00	.00	.01	.37	--	6,945
08-19-88	2.20	4.0	.67	7	.00	.00	.00	4.18	95,700	104,955
08-23-88	.23	2.0	.17	2	.00	.16	2.36	.40	10,005	3,705
08-28-88	.32	1.5	.30	4	.00	.00	.23	1.46	13,920	8,535
09-03-88	.49	5.0	.13	5	.00	.00	.33	3.76	21,315	201,630
09-11-88	.17	3.5	.07	7	.00	.00	.00	.49	7,395	3,480
09-16-88	1.21	9.0	.23	4	.00	.00	.16	2.16	52,635	102,945
09-20-88	.22	1.5	.16	2	.00	.06	1.21	1.08	9,570	5,148
09-24-88	.58	7.0	.12	3	.00	.00	.28	2.30	25,230	78,411
10-16-88	.25	3.0	.12	14	.00	.00	.00	.64	10,875	4,665
10-23-88	.08	2.5	.03	2	.00	.13	.38	.26	3,480	2,484

[a]Volume estimated using the rational formula.
[b]Volume estimated by integrating the spring flow hydrograph, after subtracting base flow.

Supplement B. – *Water-quality and specific-conductance data for storm-water runoff at the drainage-well site for selected storms during the period February to October 1988*

[μS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; mL, milliliters; μg/L, micrograms per liter; E, value for a composite of discrete measured samples]

Date	24-Hour time	Specific conductance, field (%S/cm)	Carbon, organic total (mg/L as carbon)	Coliform, fecal, 0.7 um-mf (colonies per 100 mL)	Strep-tococci, fecal, kf agar (colonies per 100 mL)
02/02/88	1630	65	2.8	--	--
02/14/88	1515	650	--	--	--
02/19/88	0700	E122	4.8	--	--
03/25/88	0525	115	11	--	--
03/25/88	0535	96	9.4	--	--
03/25/88	0545	99	8.5	--	--
03/25/88	0555	100	9.6	--	--
03/25/88	0605	105	9.1	--	--
03/25/88	0635	112	9.3	--	--
03/25/88	0655	110	9.2	--	--
03/25/88	0700	155	--	--	--
03/25/88	0715	120	9.9	--	--
05/22/88	2350	100	32	--	--
05/23/88	0000	89	22	--	--
05/23/88	0010	94	18	--	--
05/23/88	0020	77	13	--	--
05/23/88	0030	57	8.0	--	--
05/23/88	0040	57	7.5	--	--
05/23/88	0055	54	6.7	--	--
05/23/88	0110	56	6.1	--	--
05/23/88	0125	53	8.1	--	--
05/23/88	0140	58	6.0	--	--
05/23/88	0200	80	7.6	--	--
07/04/88	1920	140	35	--	--
07/04/88	1940	125	23	--	--
07/04/88	2005	160	27	--	--
07/04/88	2030	142	25	--	--
07/04/88	2120	160	31	--	--
10/16/88	1025	140	22	--	--
10/16/88	1045	50	5.5	--	--
10/16/88	1110	46	4.1	--	--
10/16/88	1135	65	5.5	--	--
10/16/88	1210	80	6.5	--	--
10/23/88	1130	--	--	2,700	5,200
10/23/88	1145	--	--	1,800	5,600

Supplement B. — *Water-quality and specific-conductance data for storm-water runoff at the drainage-well site for selected storms during the period February to October 1988* — Continued

Date	24-Hour time	pH, lab (standard units)	Alkalinity, lab (mg/L as calcium carbonate)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO4)	Fluoride, dissolved (mg/L)	Oil and grease, total recov. gravimetric (mg/L)	Methylene blue active substances (mg/L)
02/02/88	1630	7.10	22	0.60	3.8	5.4	0.20	<1	--
02/14/88	1515	--	--	--	--	--	--	--	--
02/19-19/88	0700	7.50	--	--	--	--	--	2	--
03/25-25/88	0516	--	--	--	--	--	--	2	--
03/25-25/88	0517	6.60	28	--	4.0	11	--	--	--
03/25-25/88	0621	--	--	--	--	--	--	2	--
10/16-16/88	1026	--	--	--	--	--	--	--	0.55
10/16-16/88	1116	--	--	--	--	--	--	--	.21
10/16-16/88	1156	--	--	--	--	--	--	--	.22

Date	24-Hour time	Hardness, total (mg/L as calcium carbonate)	Calcium, total recoverable (mg/L)	Magnesium, total recoverable (mg/L)	Sodium, total recoverable (mg/L)	Arsenic, total (μg/L)	Barium, total recoverable (μg/L)	Beryllium, total recoverable (μg/L)	Cadmium, total recoverable (μg/L)	Chromium, total recoverable (μg/L)	Cobalt, total recoverable (μg/L)
02/02/88	1630	27	9.8	0.68	2.5	--	20	<0.5	3	<5	<3
02/14-14/88	1515	84	30	2.1	140	--	480	< .5	4	<5	<3
02/19-19/88	0700	65	23	1.7	11	--	39	< .5	2	10	<3
03/25-25/88	0516	42	15	0.97	4.1	--	27	< .5	1	<5	<3
03/25-25/88	0621	41	15	0.88	4.1	--	24	< .5	<1	<5	<3
05/22-23/88	2351	31	11	0.81	1.8	1	12	< .5	<1	<5	<3
07/04/88	1921	49	17	1.5	2.1	1	19	< .5	<1	<5	<3
07/04/88	2006	62	21	2.2	2.4	2	25	< .5	<1	<5	<3
07/04/88	2121	66	23	2.1	2.1	1	26	< .5	<1	<5	<3
07/13-13/88	0206	51	18	1.4	2.3	--	20	< .5	2	<5	<3
07/13-13/88	0226	16	5.4	0.51	0.77	--	7	< .5	<1	<5	<3
07/13-13/88	0341	57	20	1.7	93	--	30	< .5	<1	<5	<3
10/16-16/88	1026	29	9.6	1.2	1.8	--	19	< .5	4	5	<3
10/16-16/88	1116	22	7.6	0.78	1.0	--	16	< .5	2	<5	<3
10/16-16/88	1156	32	11	1.1	1.4	--	17	< .5	<1	<5	<3

Supplement B. — *Water-quality and specific-conductance data for storm-water runoff at the drainage-well site for selected storms during the period February to October 1988* — Continued

Date	24-Hour time	Copper, total recov-erable (µg/L)	Iron, total recov-erable (µg/L)	Lead, total recov-erable (µg/L)	Manga-nese, total recov-erable (µg/L)	Molyb-denum, total recov-erable (µg/L)	Nickel, total recov-erable (µg/L)	Silver, total recov-erable (µg/L)	Stron-tium, total recov-erable (µg/L)	Vana-dium, total recov-erable (µg/L)	Zinc, total recov-erable (µg/L)	Lithium total recov-erable (µg/L)
02/02/88	1630	<10	820	<10	48	<10	<10	--	110	<6	130	33
02/14-14/88	1515	40	840	10	340	<10	<10	<10	310	<6	220	<4
02/19-19/88	0700	40	3000	50	89	<10	<10	--	140	7	150	<4
03/25-25/88	0516	30	250	20	41	<10	<10	--	260	<6	92	<4
03/25-25/88	0621	20	180	<10	30	<10	<10	--	270	<6	120	<4
05/22-23/88	2351	<10	62	<10	23	<10	<10	--	120	<6	68	<4
07/04-04/88	1921	<10	160	<10	63	<10	20	--	110	<6	150	<4
07/04-04/88	2006	<10	78	<10	59	<10	<10	--	200	<6	130	<4
07/04-04/88	2121	<10	50	<10	41	<10	<10	--	210	<6	67	<4
07/13-13/88	0206	12	250	<10	65	<10	<10	--	140	<6	170	<4
07/13-13/88	0226	<10	96	11	33	<10	<10	--	41	<6	24	<4
07/13-13/88	0341	<10	89	12	64	<10	<10	--	110	<6	120	<4
10/16-16/88	1026	30	440	20	29	<10	<10	5.0	78	<6	98	<4
10/16-16/88	1116	20	120	<10	17	<10	<10	3.0	66	<6	39	<4
10/16-16/88	1156	20	130	10	18	<10	<10	3.0	95	<6	44	<4

Date	24-Hour time	Nitrogen, ammonia dissolved (mg/L as nitrogen)	Nitrogen, ammonia total (mg/L as nitrogen)	Nitrogen, ammonia + organic total (mg/L as nitrogen)	Nitrogen, nitrite dissolved (mg/L as nitrogen)	Nitrogen, NO2+NO3 dissolved (mg/L as nitrogen)	Phos-phorus, total (mg/L as phos-phorus)	Phos-phorus, dissolved (mg/L as phos-phorus)	Phos-phorus ortho, dissolved (mg/L as phos-phorus)
10/16-16/88	1026	--	0.280	1.3	--	--	0.570	0.500	--
10/16-16/88	1116	0.120	0.140	.60	0.020	0.290	.460	.460	0.350
10/16-16/88	1156	0.110	0.110	.70	.030	.390	.510	.420	.330

Supplement C. —*Water-quality and specific-conductance data for storm-water spring discharge at the Mobley Spring site for selected storms during February to October 1988*

[μS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; mL, milliliters; μg/L, micrograms per liter; E, value for a composite of discrete measured samples]

Date	24-hour time	Specific conductance, field (μS/cm)	Carbon, organic total (mg/L as carbon)	Coliform, fecal, 0.7 um-mf (colonies per 100 mL)	Streptococci, fecal, kf agar (colonies per 100 mL)
02/02/88	1700	358	2.1	--	--
02/14/88	1515	E684	--	--	--
02/29/88	1030	500	2.5	--	--
03/25/88	0520	460	7.9	--	--
03/25/88	0600	500	3.9	--	--
02/25/88	0620	550	2.9	--	--
03/25/88	0640	550	2.4	--	--
03/25/88	0700	560	3.7	--	--
03/25/88	0720	554	2.4	--	--
03/25/88	0750	549	2.7	--	--
03/25/88	0820	543	1.7	--	--
03/25/88	0900	563	2.5	--	--
03/25/88	0930	554	4.1	--	--
05/23/88	0045	470	9.7	--	--
05/23/88	0125	540	4.7	--	--
05/23/88	0205	520	6.4	--	--
05/23/88	0245	468	9.2	--	--
05/23/88	0325	298	8.4	--	--
05/23/88	0321	E324	2.7	--	--
05/23/88	0405	305	6.7	--	--
05/23/88	0505	420	5.0	--	--
05/23/88	0605	400	4.3	--	--
05/23/88	0705	470	4.1	--	--
05/23/88	0805	490	3.7	--	--
10/23/88	1345	--	--	420	3,300
10/23/88	1430	--	--	600	4,500
10/23/88	1710	--	--	540	1,500

Date	24-Hour time	pH, lab (standard units)	Alkalinity, lab (mg/L as calcium carbonate)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO4)	Fluoride, dissolved (mg/L)	Oil and grease, total recov. gravimetric (mg/L)
02/02/88	1700	7.00	127	1.3	14	15	0.20	--
02/29/88	1030	7.80	217	1.3	19	18	.20	<1
03/25-25/88	0541	--	--	--	--	--	--	<1
03/25-25/88	0631	--	--	--	--	--	--	<1
03/25-25/88	0542	7.50	219	--	18	18	--	--
03/25-25/88	0741	--	--	--	--	--	--	<1
03/25-25/88	0841	--	--	--	--	--	--	<1

Supplement C.—*Water-quality and specific-conductance data for storm-water spring discharge at the Mobley Spring site for selected storms during February to October 1988*—Continued

Date	24-Hour time	Hardness, total (mg/L as calcium carbonate)	Calcium, total recoverable (mg/L)	Magnesium, total recoverable (mg/L)	Sodium, total recoverable (mg/L)	Arsenic, total (μg/L)	Barium, total recoverable (μg/L)	Beryllium, total recoverable (μg/L)	Cadmium, total recoverable (μg/L)	Chromium, total recoverable (μg/L)	Cobalt, total recoverable (μg/L)
02/02/88	1700	150	52	5.3	7.8	--	49	<0.5	2	<5	<3
02/14-14/88	1515	240	81	8.5	41	--	56	< .5	<1	<5	<3
03/25-25/88	0541	240	81	7.9	8.7	--	50	< .5	<1	<5	<3
03/25-25/88	0631	260	90	8.8	9.0	--	51	< .5	<1	<5	<3
03/25-25/88	0741	260	88	8.6	9.4	--	50	< .5	<1	<5	<3
03/25-25/88	0841	260	88	8.6	10	--	52	< .5	<1	<5	<3
05/23-23/88	0121	250	85	8.7	9.3	<1	46	< .5	<1	<5	<3
05/23-23/88	0601	200	70	6.8	7.6	<1	41	< .5	<1	<5	<3
07/13-13/88	0446	210	71	8.1	7.5	--	120	< .5	3	30	100
07/13-13/88	0746	160	53	5.7	6.0	--	54	< .5	<1	9	20
07/13-13/88	1126	190	63	6.7	6.7	--	45	< .5	<1	<5	7

Date	24-Hour time	Copper, total recoverable (μg/L)	Iron, total recoverable (μg/L)	Lead, total recoverable (μg/L)	Manganese, total recoverable (μg/L)	Molybdenum, total recoverable (μg/L)	Nickel, total recoverable (μg/L)	Silver, total recoverable (μg/L)	Strontium, total recoverable (μg/L)	Vanadium, total recoverable (μg/L)	Zinc, total recoverable (μg/L)	Lithium, total recoverable (μg/L)
02/02/88	1700	<10	2700	<10	99	<10	<10	--	200	<6	57	44
02/14-14/88	1515	<10	220	<10	140	<10	<10	<1.0	360	<6	7	7
03/25-25/88	0541	20	1400	20	190	<10	<10	--	320	<6	58	7
03/25-25/88	0631	10	430	<10	170	<10	<10	--	350	<6	32	7
03/25-25/88	0741	10	360	<10	120	<10	<10	--	360	<6	27	7
03/25-25/88	0841	10	270	<10	110	<10	<10	--	350	<6	32	9
05/23-23/88	0121	<10	1100	12	150	<10	<10	--	390	<6	30	8
05/23-23/88	0601	<10	160	<10	82	<10	<10	--	310	<6	37	5
07/13-13/88	0446	<10	19000	71	700	<10	21	--	330	39	190	17
07/13-13/88	0746	<10	4800	20	220	<10	<10	--	250	9	52	5
07/13-13/88	1126	<10	1200	<10	110	<10	<10	--	290	<6	13	8

Supplement D. – *Water-quality and specific-conductance data for ground water during dry-weather conditions at selected sites in the study area*

[μS/cm, microsiemens per centimeter at 25° Celsius; mg/L, milligrams per liter; mL, milliliters; μg/L, micrograms per liter; E, value for a composite of discrete measured samples]

Date	24-Hour time	Temperature, water	Specific conductance (μS/cm)	Carbon, organic total (mg/L as carbon)	Oxygen, dissolved (mg/L)	Coliform, fecal, 0.7 um-mf (colonies per 100 mL)	Streptococci, fecal, kf agar (colonies per 100 mL)
03436139 - MOBLEY SPRING AT CLARKSVILLE, TENN.							
02/29/88	1030	--	500	2.5	--	--	--
06/09/88	1400	--	--	4.7	--	--	--
07/29/88	0830	16.5	580	--	7.1	37	33
03436137 - SEVEN SPRINGS AT CLARKSVILLE, TENN.							
07/29/88	1120	16.0	525	1.6	8.7	410	340
034361396 - PORTERS BLUFF CAVE SPRING AT CLARKSVILLE, TENN.							
07/29/88	1005	17.0	550	3.2	6.4	>20,000	3,000
363054087182801 - MT:M-013							
05/09/88	1500	16.0	600	.6	--	--	--
09/06/88	1200	16.0	500	--	--	280	2,100
363057087185501 - MT:M-014							
09/06/88	0930	16.0	1,250	--	--	200	1,700

Date	24-Hour time	pH (standard units)	pH, lab (standard units)	Alkalinity, carbonate it-fld (mg/L as calcium carbonate)	Alkalinity, lab (mg/L as calcium carbonate)	Potassium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L as SO4)	Fluoride, dissolved (mg/L)	Oil and grease, total recov. gravimetric (mg/L)	Methylene blue active substances (mg/L)
03436139 - MOBLEY SPRING AT CLARKSVILLE, TENN											
02/29/88	1030	--	7.80	--	217	1.3	19	18	0.20	<1	--
07/29/88	0830	7.20	--	262	--	--	--	--	--	--	--
03436137 - SEVEN SPRINGS AT CLARKSVILLE, TENN											
07/29/88	1120	7.70	7.90	268	234	--	11	17	.30	--	<0.10
034361396 - PORTERS BLUFF CAVE SPRING AT CLARKSVILLE, TENN											
07/29/88	1005	7.50	7.80	322	175	--	22	36	.50	--	.13
363054087182801 - MT:M-013											
05/09/88	1500	--	7.30	--	131	1.4	35	32	.20	<1	--
09/06/88	1200	6.98	--	254	--	--	--	--	--	--	--
363057087185501 - MT:M-014											
09/06/88	0930	7.50	--	188	--	--	--	--	--	--	--

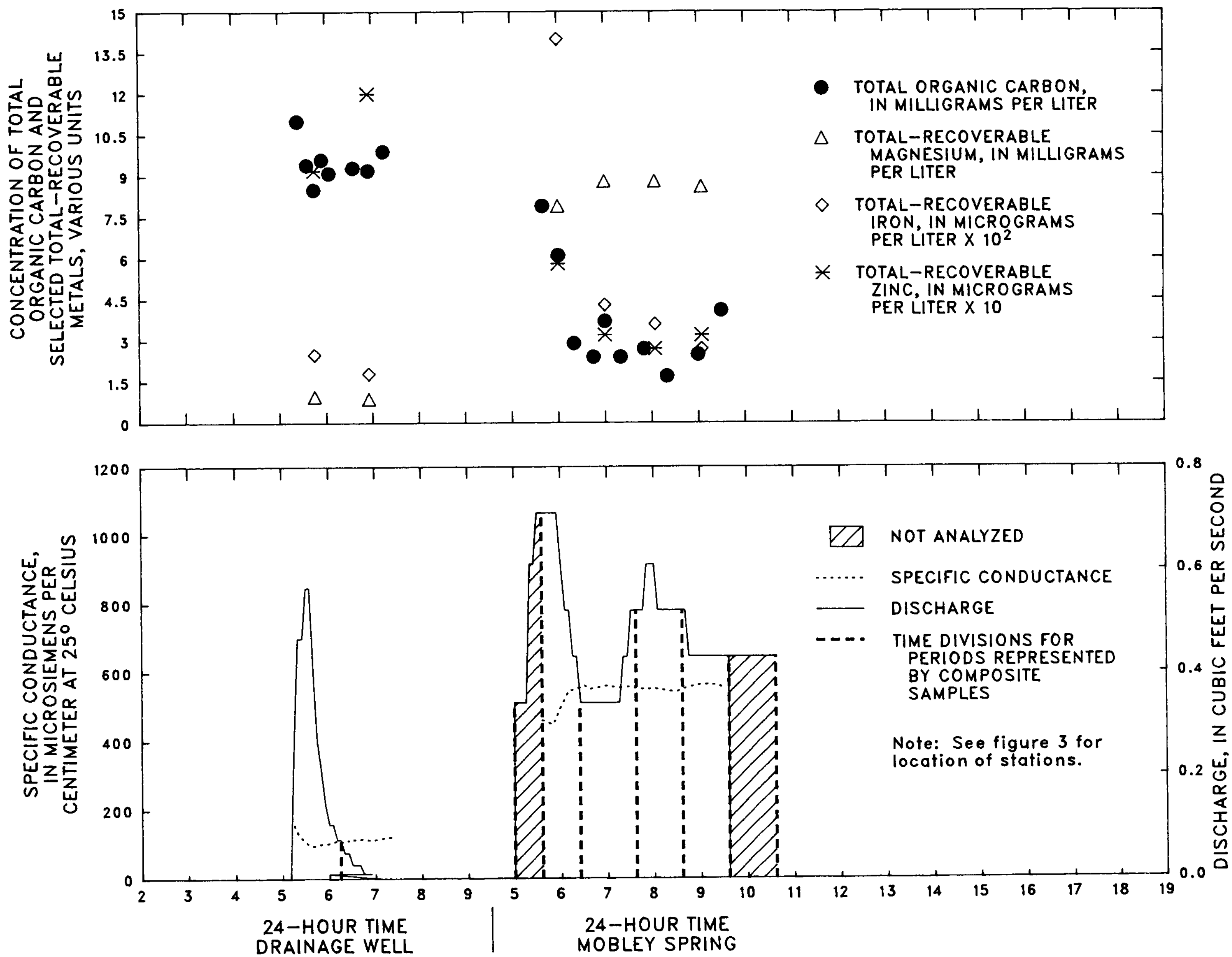
Supplement D. — *Water-quality and specific-conductance data for ground water during dry-weather conditions at selected sites in the study area* — Continued

Date	24-Hour time	Hardness, total (mg/L as calcium carbonate)	Calcium, total recoverable (mg/L)	Magnesium, total recoverable (mg/L)	Sodium, total recoverable (mg/L)	Barium, total recoverable (μg/L)	Beryllium, total recoverable (μg/L)	Cadmium, total recoverable (μg/L)	Chromium, total recoverable (μg/L)	Cobalt, total recoverable (μg/L)
03436139 - MOBLEY SPRING AT CLARKSVILLE, TENN										
06/09/88	1400	250	87	7.8	8.9	44	<0.5	<1	5	<3
03436137 - SEVEN SPRINGS AT CLARKSVILLE, TENN										
07/29/88	1120	260	81	14	7.9	50	< .5	<1	<5	<3
034361396 - PORTERS BLUFF CAVE SPRING AT CLARKSVILLE, TENN										
07/29/88	1005	220	72	9.3	22	57	< .5	<1	<5	<3
363054087182801 - MT:M-013										
05/09/88	1500	270	85	14	19	60	< .5	2	<5	<3
363057087185501 - MT:M-014										
09/06/88	0930	890	200	91	9.7	14	< .5	<1	<5	<3

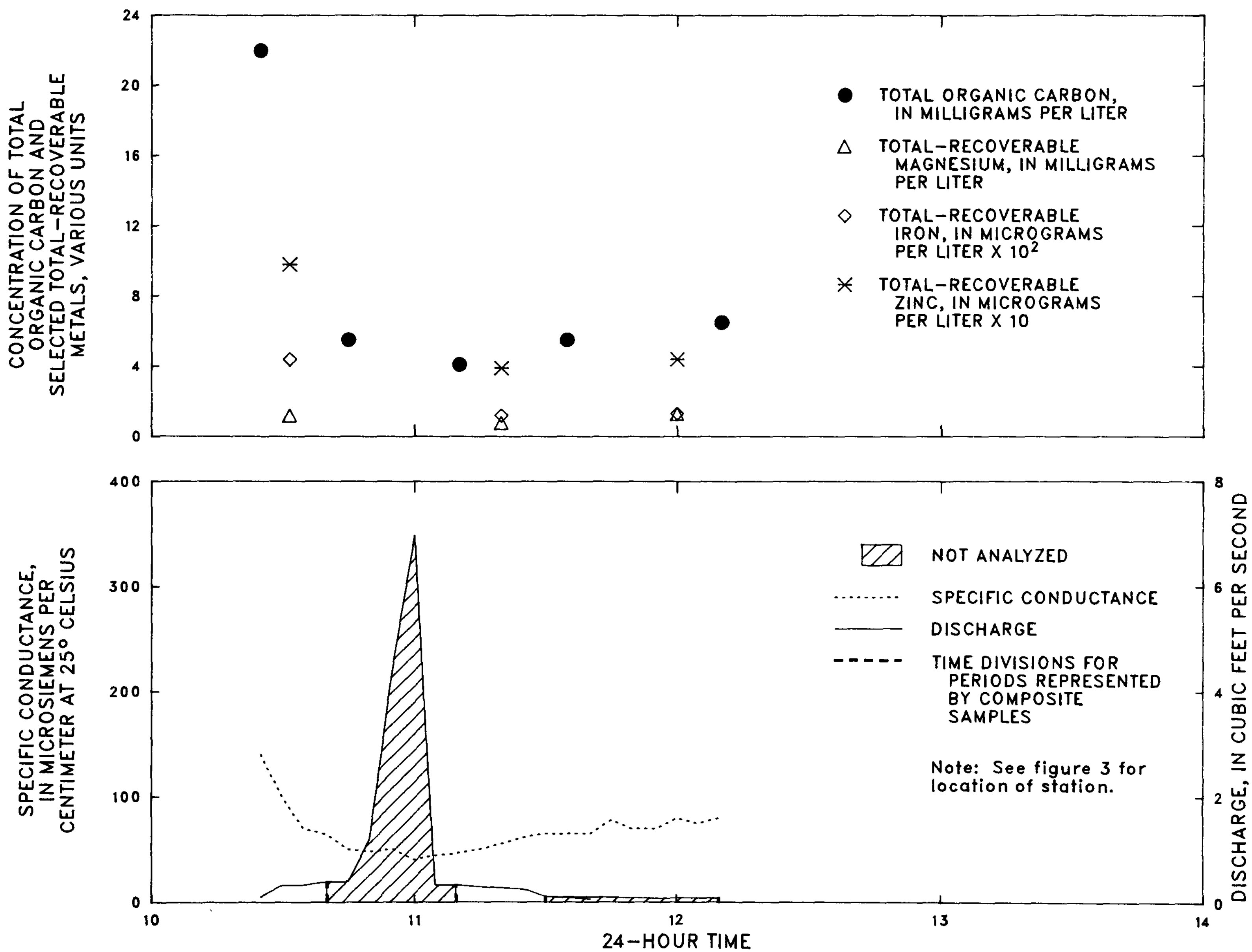
Date	24-Hour time	Copper, total recoverable (μg/L)	Iron, total recoverable (μg/L)	Lead, total recoverable (μg/L)	Manganese, total recoverable (μg/L)	Molybdenum, total recoverable (μg/L)	Nickel, total recoverable (μg/L)	Strontium, total recoverable (mg/L)	Vanadium, total recoverable (μg/L)	Zinc, total recoverable (μg/L)	Lithium, total recoverable (μg/L)
03436139 - MOBLEY SPRING AT CLARKSVILLE, TENN											
06/09/88	1400	<10	170	<10	100	<10	<10	380	<6	<3	6
03436137 - SEVEN SPRINGS AT CLARKSVILLE, TENN											
07/29/88	1120	<10	550	<10	29	<10	<10	380	<6	18	7
034361396 - PORTERS BLUFF CAVE SPRING AT CLARKSVILLE, TENN											
07/29/88	1005	<10	100	20	42	<10	<10	250	<6	48	9
363054087182801 - MT:M-013											
05/09/88	1500	15	2,600	<10	71	<10	<10	1,000	<6	430	6
363057087185501 - MT:M-014											
09/06/88	0930	<10	1,100	<10	18	<10	<10	6,300	<6	37	52

Supplement D.—*Water-quality and specific-conductance data for ground water during dry-weather conditions at selected sites in the study area*—Continued

Date	24-Hour time	Nitrogen, ammonia dissolved (mg/L as nitrogen)	Nitrogen, ammonia total (mg/L as nitrogen)	Nitrogen, ammonia + organic total (mg/L as nitrogen)	Nitrogen, nitrite dissolved (mg/L as nitrogen)	Nitrogen, NO2+NO3 dissolved (mg/L as nitrogen)	Phosphorus, total (mg/L as phosphorus)	Phosphorus, dissolved (mg/L as phosphorus)	Phosphorus ortho, dissolved (mg/L as phosphorus)
			03436139 - MOBLEY SPRING AT CLARKSVILLE, TENN						
07/29/88	0830	0.040	0.020	0.80	0.060	1.10	0.040	0.030	0.010
			03436137 - SEVEN SPRINGS AT CLARKSVILLE, TENN						
07/29/88	1120	.130	< .010	.20	< .010	2.30	.130	.120	.110
		034361396 - PORTERS BLUFF CAVE SPRING AT CLARKSVILLE, TENN							
07/29/88	1005	1.90	3.60	4.6	.050	1.50	.820	.780	.710
				363054087182801 - MT:M-013					
09/06/88	1200	.020	< .010	< .20	< .010	.690	.020	.020	.010
				363057087185501 - MT:M-014					
09/06/88	0930	.230	.250	.30	< .010	< .100	.160	< .010	.010



Supplement E.--Typical relation among selected water-quality constituents and properties in water samples collected at the drainage-well and Mobley Spring sites, March 25, 1988.



Supplement F.--Typical relation among selected water-quality constitutents and properties in water samples collected at the drainage-well site, October 16, 1988.

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