HYDROLOGY AND WATER QUALITY NEAR THE SOUTH WELL FIELD, SOUTHERN FRANKLIN COUNTY, OHIO, WITH EMPHASIS ON THE SIMULATION OF GROUND-WATER FLOW AND TRANSPORT OF SCIOTO RIVER

By Carolyn J.O. Childress, Rodney A. Sheets, and E. Scott Bair

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
inch per year (in/yr)	25.4	millimeters per year
foot per day (ft/d)	0.3048	meter per day
foot squared per second (ft^2/s)	0.09290	meter squared per second
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per foot [(ft^3/s)/ft]	0.09290	cubic meter per second per meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C) + 32$$

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

Water-quality units: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Volume is also expressed in milliliters (ml); one thousand milliliters is equivalent to one liter.

Specific electrical conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (µmho/cm), formerly used by the U.S. Geological Survey.

HYDROLOGY AND WATER QUALITY NEAR THE SOUTH WELL FIELD, SOUTHERN FRANKLIN COUNTY, OHIO, WITH EMPHASIS ON THE SIMULATION OF GROUND-WATER FLOW AND TRANSPORT OF SCIOTO RIVER

Carolyn J.O. Childress, Rodney A. Sheets, and E. Scott Bair

ABSTRACT

This report presents results of a study, in cooperation with the City of Columbus, Ohio, to investigate transport of Scioto River, ground-water flow and quality, and surface-water/ground-water interaction near the City of Columbus South Well Field during low-flow periods. Water quantity and quality of Scioto River in the study area are significantly affected by effluent from the Jackson Pike Wastewater Treatment Facility. During low-flow periods, this effluent can comprise as much as 90 percent of the total flow in Scioto River.

Data-collection activities included water-quality sample collection and analysis; water-level measurement in wells completed in the carbonate bedrock and glacial drift aquifers near the well field; and water-quality-sample collection, discharge measurement, traveltime measurement, and dye-dispersion measurement of Scioto River from the Jackson Pike Wastewater Treatment Facility to the Southerly Wastewater Treatment Facility. This reach encompasses the area from which the South Well Field is designed to induce infiltration of water across the riverbed.

During low flow, waters in Scioto River above the Jackson Pike Wastewater Treatment Facility and in its tributaries within the study area are dominated by the cations calcium and magnesium and by the anions bicarbonate and sulfate. This composition, which is similar to that of ground waters in the area, indicates that ground water is a principal component of streamflow. The river below the wastewater-treatment facility is dominated by effluent, as evidenced by increased concentrations of dissolved solids, chloride, sodium, nitrate, phosphorus, and several trace elements.

Ground waters from the carbonate bedrock and glacial drift aquifers are hard, calcium bicarbonate-type waters. Concentrations of iron and manganese routinely exceed State drinking-water standards. Concentrations of trace metals generally are below the detection limit, and the combined concentration of all nitrogen species generally is less than 1 milligram per liter. Ground waters from the carbonate bedrock aquifer can be distinguished from ground waters from the glacial drift aquifer by their greater dissolved-solids, sulfate, and calcium concentrations.

The surface-water-transport system was simulated by use of a one-dimensional Lagrangian transport model. Traveltimes for various flow conditions were simulated. For a discharge of 93 cubic feet per second from the Jackson Pike Wastewater Treatment Facility, simulated traveltime from Frank Road to the South Well Field during a 7-day, 2-year low-flow period is approximately 35 hours; for an effluent discharge of zero, traveltime would increase to 94 hours.

No lateral nonpoint sources of discharge to Scioto River were identified. A lateral sink of 0.00078 cubic feet per second per foot was identified in the stream reach from collector well 101 to collector well 103. This represents a loss of approximately 6.5 million gallons per day (10 cubic feet per second) over a 2.1-mile segment at a time (August 1988) when pumpage from three collector wells was approximately 18.4 million gallons per day.

A finite-difference ground-water-flow model was used to simulate leakage from Scioto River, lateral flow within the glacial drift aquifer, and upflow from the carbonate bedrock aquifer into the glacial drift aquifer. The model was calibrated to steady state by use of water levels measured in March 1986 and before 1967. Simulations show that, for pumping rates of 7.5 and 18.4 million gallons per day, 7 to 9 percent of the pumpage from three collector wells originates from bedrock, 51 to 75 percent originates from glacial drift, and 16 to 42 percent originates from Scioto River. Sensitivity analyses of model input parameters showed that, at increased pumping rates, the proportion of collector-well pumpage derived from the river is increased. An increase in vertical riverbed hydraulic conductivity at values greater than 0.5 foot per day does not result in a significant change in contribution from the river.

A mixing analysis of collector-well pumpage generally corroborates the percentage contributions from the glacial drift aquifer and Scioto River derived from the ground-water-flow model. A two-step mixing analysis shows that approximately 50 to 60 percent of pumpage was derived from the glacial drift aquifer and 5 to 25 percent was derived from Scioto River. At the time that water-quality samples were collected in August 1987, the pumping rate from the collector wells was approximately 15.8 million gallons per day. The contribution from the carbonate bedrock aquifer, 23 to 32 percent, is greater than that calculated by the ground-water-flow model. This difference could be due to a combination of factors, including variable data on chemical quality of the carbonate bedrock aquifer and uncertainties associated with estimates of vertical hydraulic conductivity of the glacial drift and carbonate bedrock aquifers.

INTRODUCTION

At present (1990), about 15 percent of the total water supply for the City of Columbus, Ohio, is provided by ground water withdrawn from the South Well Field in southern Franklin County. Four radial collector wells, completed in the glacial drift aquifer along Scioto River (three wells) and Big Walnut Creek (one well), are designed to induce stream infiltration. Much of the flow of Scioto River at the South Well Field originates from the Jackson Pike Wastewater Treatment Facility (WTF), one of two municipal wastewater-treatment plants operated by the City of Columbus. The Jackson Pike WTF discharges effluent into Scioto River about 6 mi upstream from the South Well Field (fig. 1). During periods of dry weather, effluent from the Jackson Pike WTF has comprised as much as 90 percent of the flow in the river.

When the City of Columbus recently implemented a new system, the rate at which effluent discharges from the Jackson Pike WTF was reduced by as much as 150 Mgal/d since 1970 to a relatively constant rate of about 60 Mgal/d, or about 93 ft^3/s. This reduction in treated effluent will result in reduced streamflow during future low-flow periods compared to past low-flow periods. Traveltime of the river will be affected, and, depending on upstream water quality compared to treated effluent quality, this reduction could have a positive effect (reduction of effluent loading) or a negative effect (reduction of dilution) on Scioto River quality in southern Franklin County. In addition, potential changes to low flows of Scioto River have led to questions about the proportion of water pumped at the South Well Field that originates from ground-water and surface-water sources. To address these anticipated issues, the U.S. Geological Survey (USGS), in cooperation with the City of Columbus, undertook a study to evaluate the hydrologic consequences of changes in effluent discharge to Scioto River and to clarify the interaction of Scioto River and carbonate bedrock and glacial drift aquifers at the South Well Field.

Purpose and Scope

This report describes the hydrology and water quality of the South Well Field area by presenting the results of (1) surface-water-transport simulations of a conservative constituent during low flow of Scioto River from Frank Road to the South Well Field and (2) ground-water-flow simulations of the glacial drift and carbonate bedrock aquifers at the South Well Field. These simulations are examined along with surface-water and ground-water quality to describe the relation between the quantity and quality of flow in the Scioto River; the nature of the ground-water-flow system; and the quantity, quality, and sources of water pumped from the South Well Field. Data collection in the study area in August and September 1987 and 1988 included

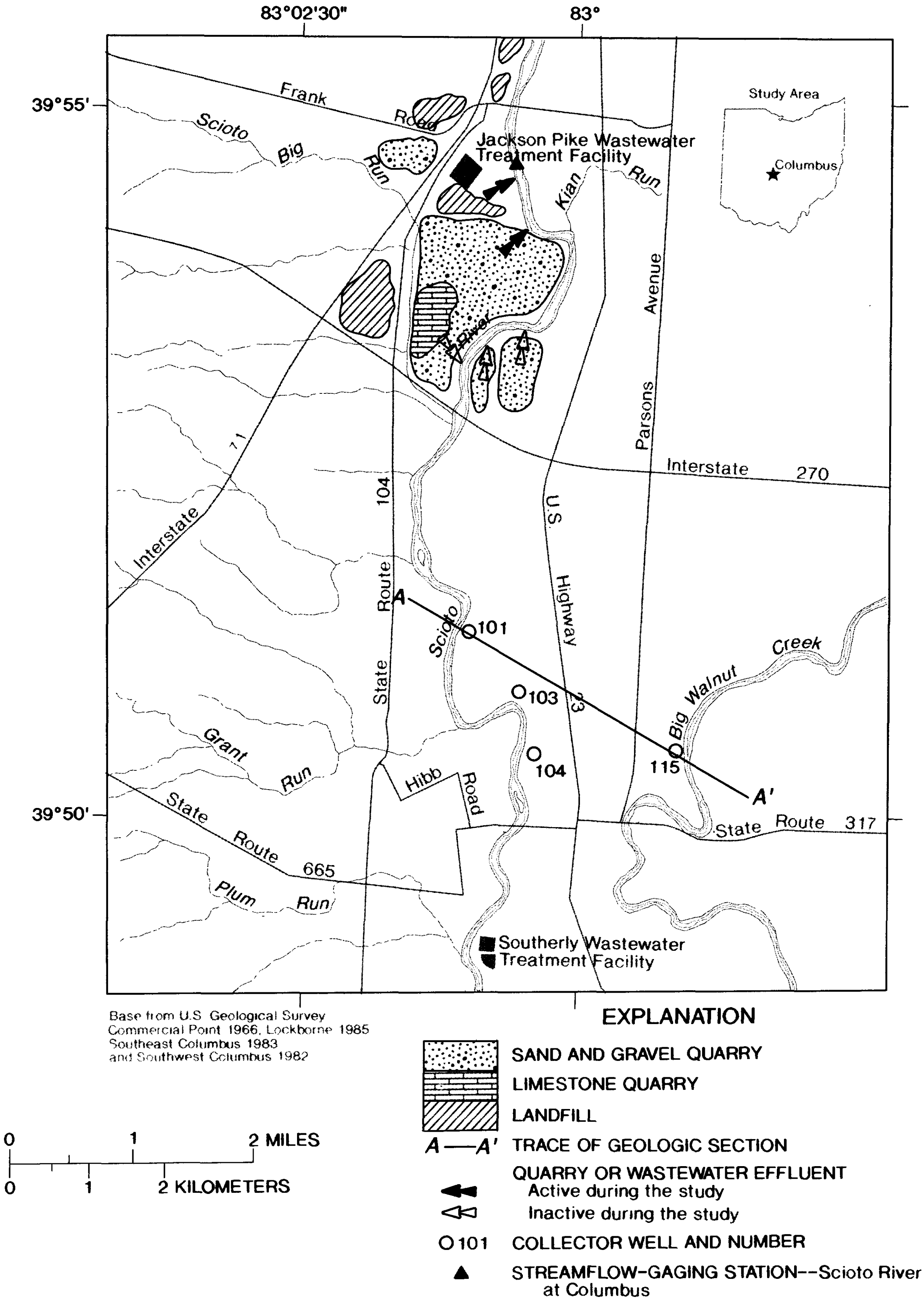

Figure 1.--Location of the study area, streamflow-gaging station, collector wells, quarries, landfills, and geologic section *A–A'*.

sampling for surface-water and ground-water quality and measurement of surface-water discharge, Scioto River travel-times, ground-water levels, and vertical riverbed hydraulic conductivity.

Description of Study Area

The study area (fig. 1) is in southern Franklin County, Ohio, south of Columbus. The area is approximately 48 mi^2 of relatively flat to gently sloping terrain in the Scioto River valley and adjacent upland areas. The surficial geologic materials consist of glacial and alluvial deposits. Scioto River flows from north to south through the central part of the study area. Big Walnut Creek flows from northeast to southwest through the southeastern part of the study area where it joins Scioto River.

Commercial and residential land uses predominate in the northeastern part of the study area, whereas agriculture is the primary land use in the area south of Interstate 270 (I-270) near the South Well Field. Active sand and gravel quarries, an active limestone quarry, five landfills located in abandoned sand and gravel quarries, and industry are the predominant land uses in the north-central and northwestern parts of the study area.

Three collector wells in the South Well Field are adjacent to Scioto River in the southern part of the study area; a fourth collector well is adjacent to Big Walnut Creek (fig. 1).

Previous Studies

Since 1980, the USGS has constructed a series of ground-water-flow models of the general area of the South Well Field. The first (Weiss and Razem, 1980) was a two-dimensional, steady-state model of flow in the glacial drift aquifer. For this model, vertical hydraulic conductivity of the riverbed was estimated from aquifer tests near streams (Stilson and Associates, 1976 and 1977) and was assumed to be homogeneous for all stream reaches. At maximum pumpage from the four collector wells, it was predicted that 70 percent of the yield from the South Well Field would be derived from induced stream infiltration.

The model by Weiss and Razem (1980) was subsequently modified to simulate two-dimensional transient flow (Razem, 1983) and was refined somewhat on the basis of new data. At pumping rates of 24.5 and 39 Mgal/d, it was predicted that induced stream infiltration would comprise 28 and 33 percent, respectively, of the total yield of the well field. Sedam and others (1989) constructed a three-dimensional steady-state ground-water-flow model to simulate the advective transport of hypothetical contaminant spills or landfill-leachate migration in relation to the hydraulic gradients in the cones of depression developed around the South Well Field and two nearby aggregate quarries. Quarry dewatering was identified as the major ground-water discharge in the area north of the South Well Field. Of the water pumped by the collector wells, 13 percent was estimated to originate from induced stream infiltration (Sedam and others, 1989).

Garner (1983) examined the chemical mixing of water from the glacial drift aquifer with water from the carbonate bedrock aquifer. Mixing between waters from the glacial drift aquifer and river water was described by de Roche and Razem (1984).

Acknowledgments

The authors thank Brad Rice and American Aggregates Corporation for allowing access through their property to Scioto River during the two traveltime studies. The authors also thank the many commercial and private landowners who permitted access to their wells. Ray Moreno, a student at The Ohio State University, measured vertical hydraulic conductivity of the streambed; his assistance is gratefully acknowledged.

METHODS OF STUDY

The network for collection of ground-water-level data consisted of 52 wells near the collector wells (fig. 2). Water-quality samples were collected from 14 of these wells (fig. 2); 9 wells were completed in the glacial drift aquifer, and 5 wells were completed in the carbonate bedrock aquifer. Water-level measurements were obtained in September 1987 and in August 1988. Water-quality samples were collected once from each well in either September 1987 or August 1988, except for two wells completed in carbonate bedrock aquifer, which were sampled in both years.

The surface-water data-collection network consisted of 19 sample-collection and (or) discharge-measurement sites on Scioto River and its tributaries and at major point sources of effluent from Frank Road to the Southerly WTF south of State Route 665 (fig. 3). Chemical-quality samples were collected at these sites in August 1987 and August 1988 during traveltime studies. Definition of the dye cloud was enhanced and travel-times were kept to less than 24 hours by dividing the study reach of Scioto River into three segments in 1987 and two segments in 1988.

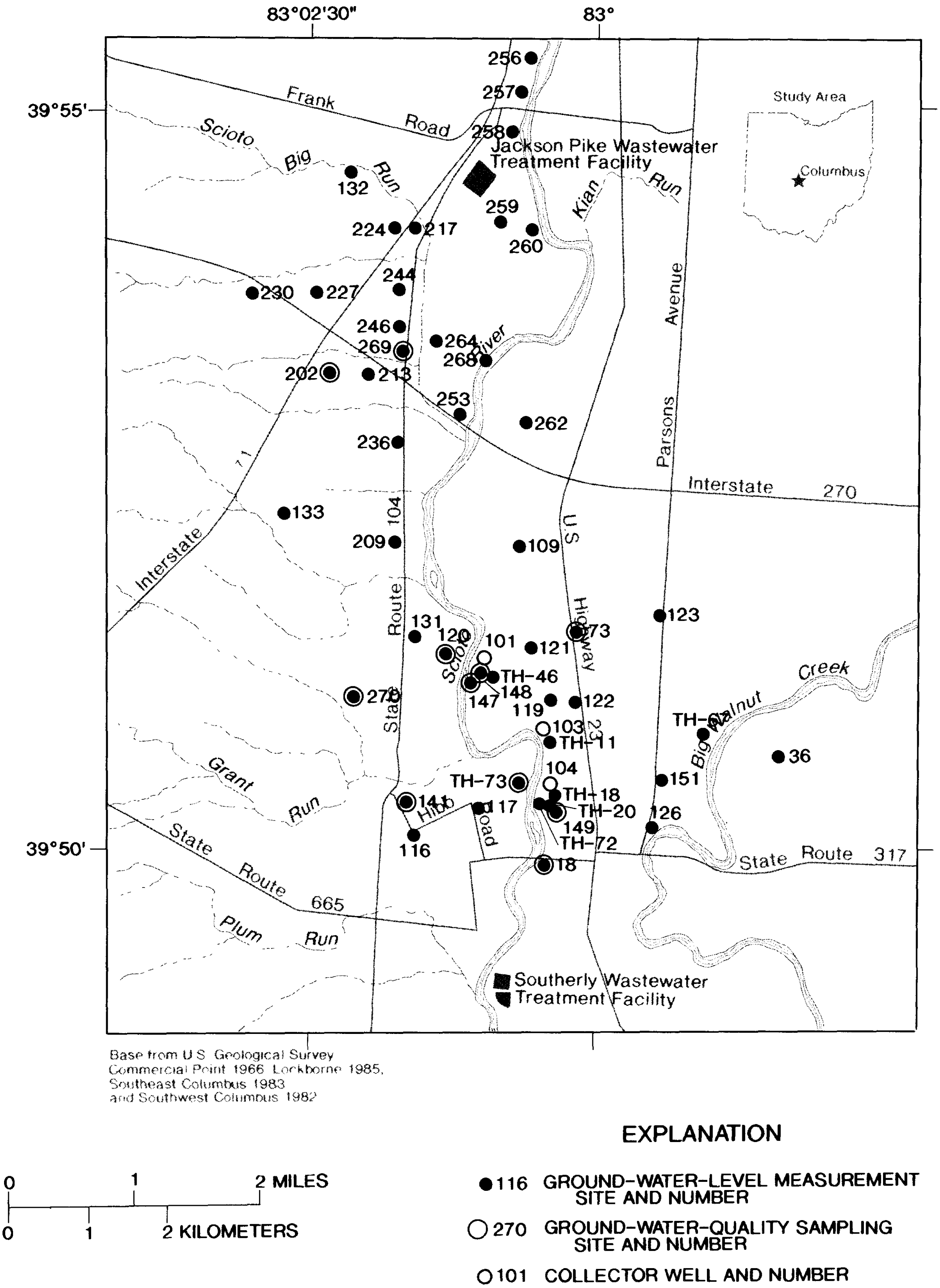

Figure 2.--Location of ground-water-level measurement sites and ground-water-quality sampling sites.

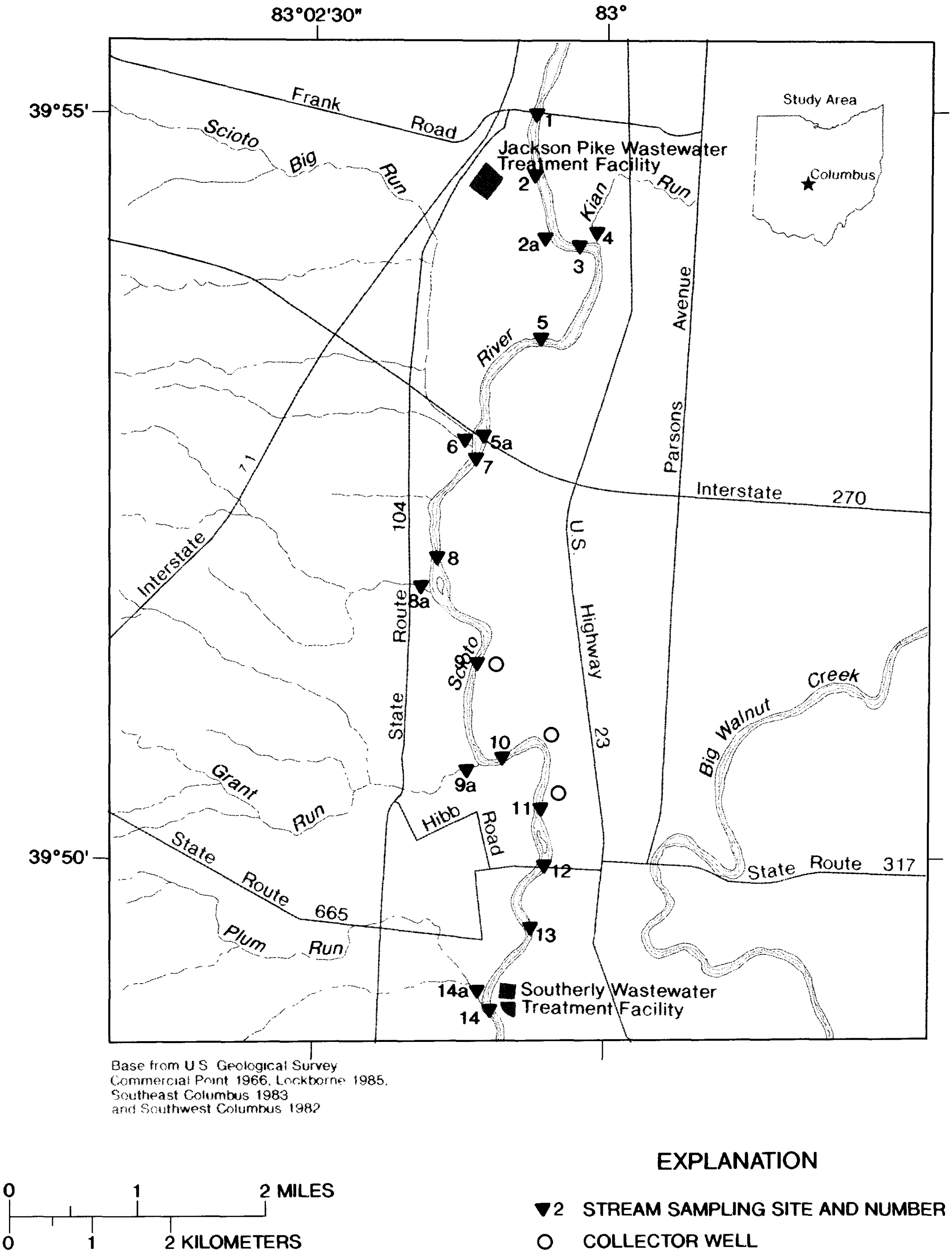

Figure 3.--Location of surface-water sampling sites.

Collection of Water Samples for Analysis

Surface-water samples that were representative of the entire cross section were collected to accurately characterize stream quality. The method used required collection of a flow-weighted volume of water from each of several equally spaced locations in the cross section. These subsamples were composited in a polyethylene churn splitter, from which individual sample bottles were filled. Samples of effluent from the Jackson Pike WTF and from the quarry lake (fig. 1) were collected directly into a polyethylene collection bottle held at the effluent pipe opening; samples were then poured into the churn splitter.

A volume of water at least three times the total volume of the well casing was purged from each sampled well by means of a submersible pump to obtain a ground-water sample that was representative of water in the aquifer. Specific conductance, pH, and water temperature were monitored continuously. Samples were collected when stabilized readings of these properties indicated that standing water had been purged from the well casing and that formation water was entering the well.

Surface-water and ground-water samples for analysis of dissolved constituents were filtered immediately at the site through a 0.45-micrometer pore-size membrane filter by use of a peristaltic pump. Samples were preserved either chemically or by chilling at 4 °C. Samples were analyzed at the USGS National Water Quality Laboratory according to methods described by Fishman and Friedman (1989). Specific conductance, water temperature, pH, and dissolved-oxygen concentration were measured electrometrically in the field. Ground water was pumped directly into a flow-through chamber so that dissolved-oxygen concentration could be measured without aeration. Alkalinity concentration also was analyzed in the field by electrometric titration to a pH of 4.5 (Fishman and Friedman, 1989).

Collection and Computation of Data for Simulation of Surface-Water Transport

Streamflow at river and tributary sites was measured with a current meter in accordance with standard procedures (Rantz and others, 1982, p. 79). Rate of effluent discharge from the Jackson Pike WTF was measured with a flow-metering device maintained at the WTF. Rate of effluent discharge from the quarry was estimated by use of a mathematical equation for calculating flow from a full, horizontal pipe (Anderson, 1977).

Samples for the analysis of rhodamine WT-dye concentration were collected by filling a 25-mL glass bottle at the center of flow just below the water surface. Samples were analyzed in the field with a Turner Model 11 Fluorometer[1] according to procedures described by Hubbard and others (1989) and Kilpatrick and Wilson (1989).

Known quantities of dye were injected simultaneously at the upstream terminus of each subreach in a slug-type injection (Kilpatrick and Wilson, 1989). The dye was spread evenly across the stream to enhance lateral mixing. Dye sampling was begun at each downstream site on the basis of estimates of the arrival time of the leading edge and peak of the dye cloud. Sufficient numbers of samples were collected at all sites so that the time of occurrence and concentration of the peak of the dye cloud could be determined. Additional samples were collected at selected sites so that the time of occurrence and concentration of the leading and trailing edges of the dye cloud also could be determined. The arrival of the leading edge was defined as the time when background fluorescence was first exceeded. The trailing edge was defined as the time when the concentration of dye decreased to 10 percent of the peak concentration or to 0.2 μg/L, whichever was less. In general, samples were collected well before the arrival of dye so that background fluorescence could be measured. If data were missing for determination of the time of the leading or trailing edges, data were extrapolated. For each site, a dye curve was produced by plotting dye concentration from the leading edge to the trailing edge of the dye cloud against time from dye injection.

The total mass of dye passing each sampling site was calculated from the area under the dye curve. At each site, the percentage of dye recovered was calculated on the basis of the total mass of dye injected into the study segment (tables 3 and 4). The measured dye concentrations were adjusted by the percentage of dye recovered at that site to account for dye lost to the system (for example, to degradation or adsorption to sediments).

When the peak of the dye cloud arrived at each site, water-quality samples were collected, and pH, specific conductance, temperature, dissolved-oxygen concentration, and streamflow were measured. Thus, a parcel of water was traced downstream from the dye-injection point, and the water quality and discharge of that parcel were characterized at selected points in the stream reach.

Measurement of Vertical Hydraulic Conductivity of the Riverbed

Spatial variations in vertical hydraulic conductivity in the bed of Scioto River within the study area were measured by means of minipiezometers and seepage meters fabricated from

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

Table 3.--Traveltime data for the Scioto River between Frank Road and the Southerly Wastewater Treatment Facility, August 1987

[Dashes indicate no data available.]

		Distance, in miles		Leading edge, in hours		Peak, in hours		Trailing edge, in hours			
Stream site number	Model grid number	From dye injection	From mouth	Travel-time	Cumulative travel-time	Travel-time	Cumulative travel-time	Travel-time	Cumulative travel-time	Percentage recovered	Discharge (cubic feet per second)
						STREAM SEGMENT 1					
1	1	0	127.2	--	--	--	--	--	--	--	72.8
	2	.7	126.5	--	--	--	--	--	--	--	--
3	3	1.2	126.0	8	8	9.75	9.75	23.75	23.75	65	201
5	4	2.4	124.8	11.75	11.75	15.25	15.25	26.75	26.75	63	207
5A	5	3.4	123.8	16.2	16.2	20.6	20.6	29.25	29.25	59	206
						STREAM SEGMENT 2					
7	--	0	123.7	--	--	--	--	--	--	--	208
8	6	1.1	122.6	2.25	18.45	2.4	23.0	[a]37.5	33.0	50	207
9	7	2.1	121.6	4.3	20.5	5.5	26.1	9.8	39.05	74	198
10	8	3.2	120.5	7.0	23.2	8.5	29.1	13.5	42.75	63	178
11	9	3.9	119.8	9	25.2	10.8	31.4	[a]15.0	44.25	54	187
						STREAM SEGMENT 3					
11	--	0	119.8	--	--	--	--	--	--	--	203
12	10	.4	119.3	.6	25.8	.6	32.0	1.3	45.55	--	208
13	--	1.1	118.7	--	--	--	--	--	--	--	203
14	11	1.8	118.0	3.25	28.45	3.7	35.1	5.2	49.45	--	197

[a]Extrapolated

Table 4.--Traveltime data for the Scioto River between Frank Road and State Route 665, August 1988

[Dashes indicate no data available.]

Stream site number	Model grid number	Distance, in miles: From dye injection	Distance, in miles: From mouth	Leading edge, in hours: Travel-time	Leading edge, in hours: Cumulative travel-time	Peak, in hours: Travel-time	Peak, in hours: Cumulative travel-time	Trailing edge, in hours: Travel-time	Trailing edge, in hours: Cumulative travel-time	Percentage recovered	Discharge, (cubic feet per second)
STREAM SEGMENT 1											
1	1	0	127.2	0							[a]74
	2	.7	126.5	--	--	--	--	--	--	--	--
3	3	1.2	126.0	7.25	7.25	8.5	8.5	15.5	15.5	54	[b]153
5	4	2.4	124.8	10.2	10.2	14.5	14.5	26.5	26.5	94	[c]155
STREAM SEGMENT 2											
3	3	0	126.0	0	--	--	--	--	--	168	164
5	4	1.2	124.8	3.7	--	4.8	--	13	--	80	168
5A	5	2.2	123.8	7.5	14.0	11.0	20.7	19.0	32.5	80	157
8	6	3.6	122.6	--	--	--	--	--	--	--	--
9	7	4.6	121.6	14.25	20.75	19.5	29.2	30.5	44.0	76	147
10	8	5.5	120.5	16.8	23.3	23.5	33.2	36.5	50.0	87	171
11	9	6.2	119.8	17.8	24.3	26.0	35.7	37.5	51.0	68	134
12	10	6.7	119.3	21.0	27.5	27.5	37.2	40	53.5	67	--

[a]Estimated by difference
[b]Based on gage height
[c]Estimated

55-gallon drums. The design of the seepage meters was modified from a design described by Lee (1977) and Lee and Cherry (1978). Discharge (+Q) or recharge (-Q) across a known area (A) of the riverbed was measured, as was the difference in head (dh/dl) between the water level in a piezometer driven into the riverbed and the river surface. The vertical hydraulic conductivity of the riverbed (K_{rb}) is derived from Darcy's Law such that $K_{rb} = Q/[A*(dh/dl)]$.

Before measuring K_{rb} in the field, the segment of the river south of the I-270 bridge and north of the bridge on State Route 665 was mapped during low flow to identify pools, riffles, and runs. For the purposes of classification, a pool is defined as a measured depression of the riverbed or as that part of a stream where little current is discernible. A riffle is defined as a shallow part of a stream, generally less than 1 ft deep, where the water surface is broken by turbulence due to the increased slope of the riverbed. A run is defined as a stream reach where the cross section is fairly uniform and current is discernible (Moreno, 1988).

Seepage measurements were made at eight cross sections in Scioto River (fig. 4), between I-270 and State Route 665 (SR 665), in June through November 1988 (Moreno, 1988). Two cross sections were in riffles, whereas six cross sections were in runs. It was not possible to measure K_{rb} values in pools because the water was too deep. At seven of the sites, three seepage meter and piezometer pairs were placed in a line across the river, perpendicular to the banks. At an eighth site, four pairs were used. The seepage meters generally were allowed to remain undisturbed on the river bottom for 24 hours before discharge measurements were made.

HYDROLOGY AND WATER QUALITY NEAR THE SOUTH WELL FIELD

Surface-water-transport simulations (Schoellhamer and Jobson, 1986b) were used to predict the concentration of a surrogate conservative constituent (rhodamine WT dye) in Scioto River near the South Well Field. These simulations were based on three scenarios of discharge from the Jackson Pike WTF and in Scioto River.

Steady-state ground-water-flow simulations for the area surrounding the three Scioto River collector wells were used to predict the proportion of pumpage contributed from three sources--the glacial drift aquifer, the carbonate bedrock aquifer, and induced flow from Scioto River--under various pumping regimes. The ground-water-flow model is a modified version of a previous model (Sedam and others, 1989); refinements were made principally to clarify the interaction between Scioto River and the ground-water system on the basis of direct

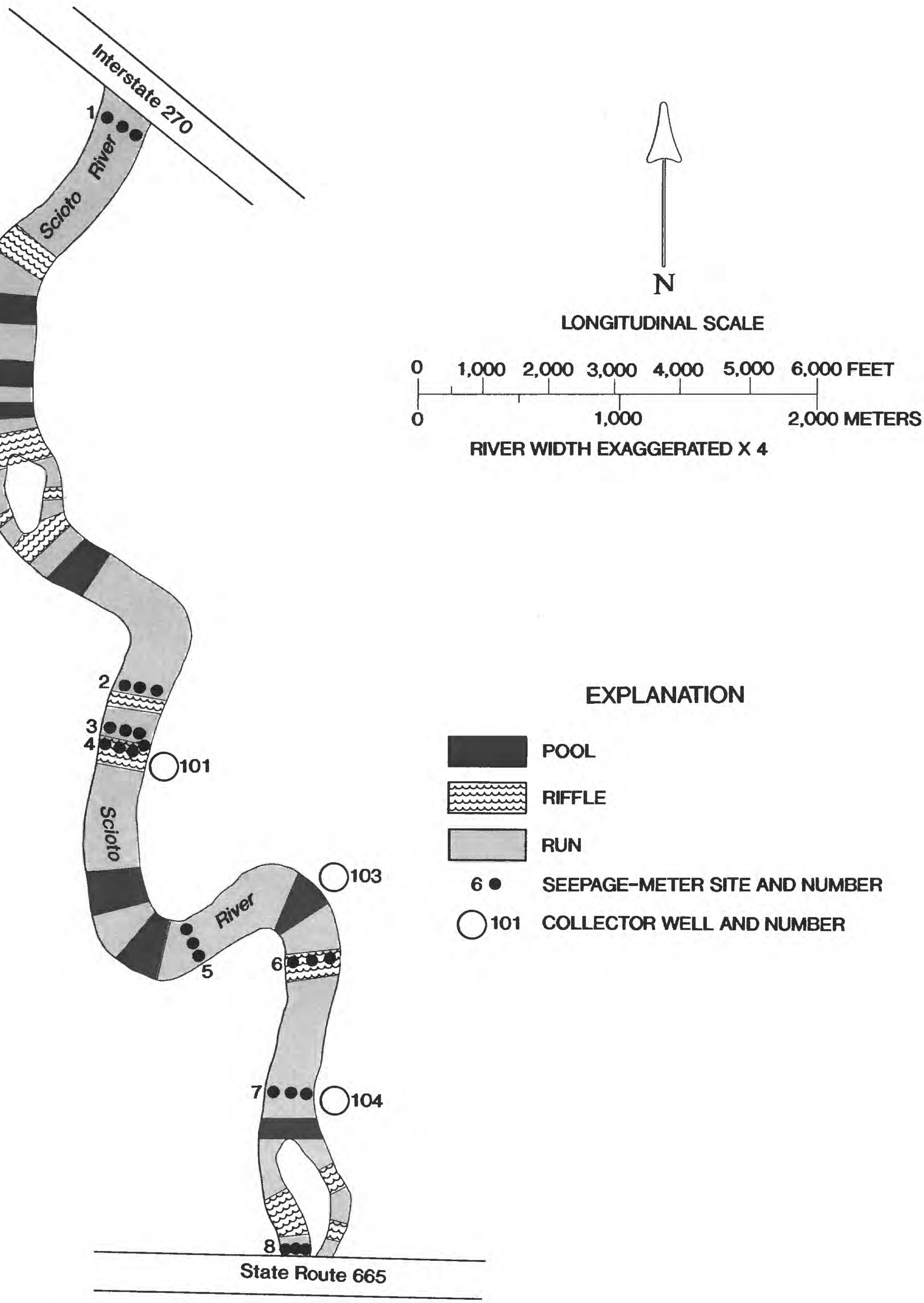


Figure 4.--Pools, riffles, runs, and seepage-meter sites on Scioto River between Interstate 270 and State Route 665. (Modified from Mareno, 1988, fig. 4.)

measurement of K_{rb}. The model was calibrated to post- and pre-1967 ground-water-level measurements and to streamflow gain-loss measurements on Scioto River. Estimates of the proportion of pumpage from the source waters that were generated by the model were compared with estimates generated by evaluation of chemical mixing of the source waters.

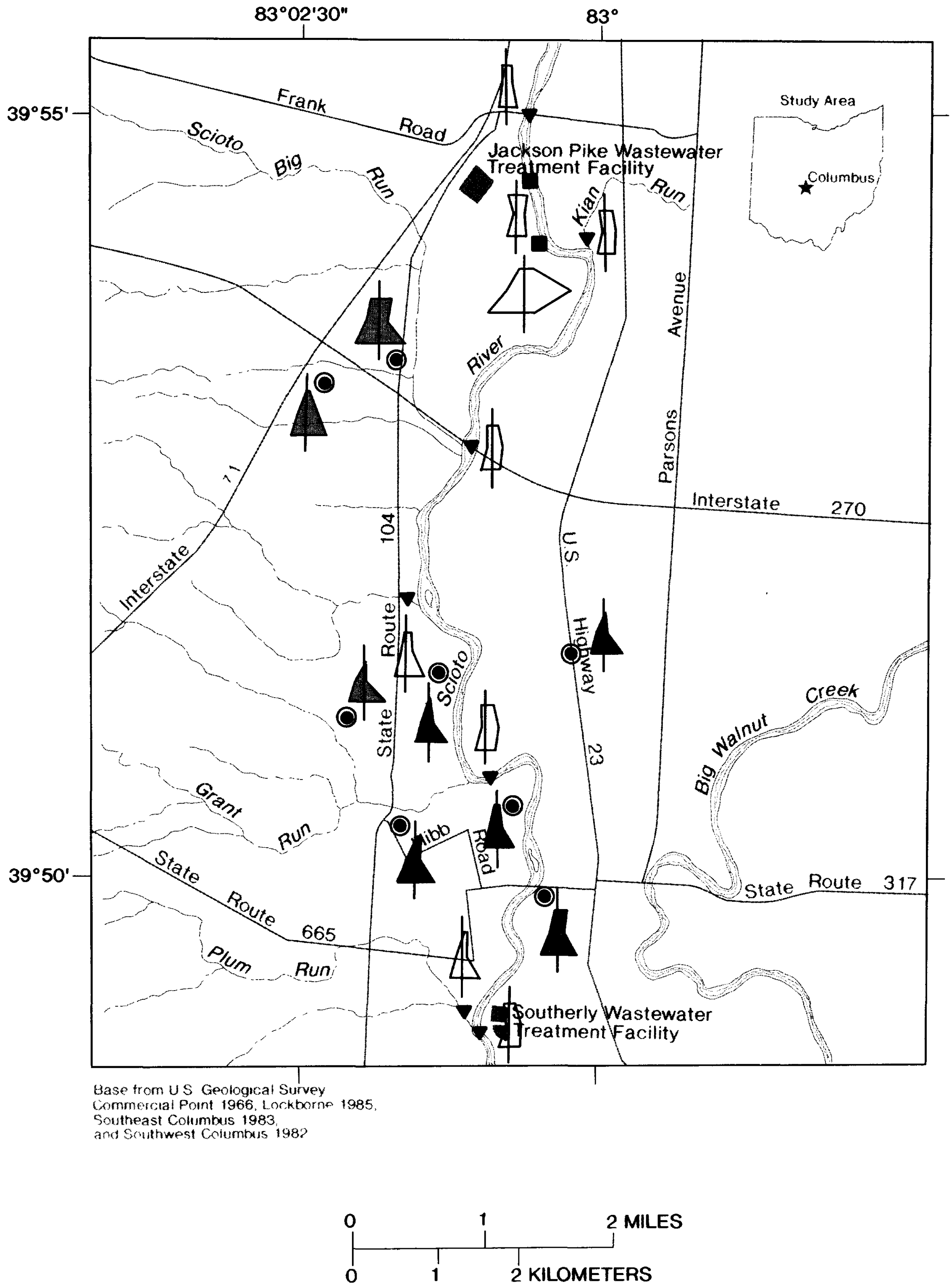
Scioto River

Scioto River drains 2,266 mi^2 in central Ohio at its confluence with Big Walnut Creek. The Scioto River streamflow-gaging station at Columbus, Ohio (03227500; fig. 1), is approximately 127 mi above the mouth and records drainage from the upper 1,629 mi^2 of the drainage area. Flow at the Columbus gage is affected by three reservoirs: Griggs Reservoir on the main stem in Columbus, O'Shaughnessy Reservoir on the main stem just north of Columbus, and Delaware Reservoir on the Olentangy River north of Columbus.

Quality

The relative percentage of concentrations of anions and cations, in milliequivalents per liter, from selected samples collected in August 1987 and 1988 is shown in figure 5. The dominant cations in Scioto River samples collected upstream from the Jackson Pike WTF outfall and in samples from its tributaries are calcium and magnesium. The dominant anions are bicarbonate and sulfate. The chemical similarity of these surface-water samples to ground-water samples collected in the study area (fig. 6) indicates that, in this study area, ground-water discharge is a sizable component of streamflow during low-flow periods. In contrast, the dominant cations in effluent from the Jackson Pike WTF are calcium and sodium, and the dominant anions are bicarbonate and chloride. Dominant cations in effluent from the quarry (fig. 5) are calcium and sodium, and sulfate is the dominant anion. Effluent from the quarry had little effect on mainstem water quality because discharge from the quarry was small (approximately 28 ft^3/s; table 1, at back of report) compared to discharge in the main stem (approximately 200 ft^3/s; table 1). Scioto River downstream from the Jackson Pike WTF outfall is a mixture of water of the calcium magnesium bicarbonate sulfate type upstream from the Jackson Pike WTF and the calcium sodium bicarbonate chloride type from the Jackson Pike WTF effluent.

Changes in the concentrations of several chemical constituents indicate that effluent from the Jackson Pike WTF has a marked effect on the downstream chemical quality in Scioto River throughout the study area. Median dissolved-solids, chloride, and sodium concentrations in 19 samples collected in


83°02'30"
83°
39°55'
39°50'
Frank Road
Scioto Big Run
Jackson Pike Wastewater Treatment Facility
Kian Run
Study Area
Columbus
River
Parsons Avenue
Interstate 270
Interstate 71
State Route 104
U.S. Highway 23
Scioto
Big Walnut Creek
Grant Run
ibb Road
State Route 317
State Route 665
Plum Run
Southerly Wastewater Treatment Facility
Base from U.S. Geological Survey
Commercial Point 1966, Lockbourne 1985,
Southeast Columbus 1983,
and Southwest Columbus 1982
0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

DIAGRAM SHOWING CONCENTRATIONS OF CATIONS AND ANIONS

SURFACE WATER

CARBONATE BEDROCK AQUIFER

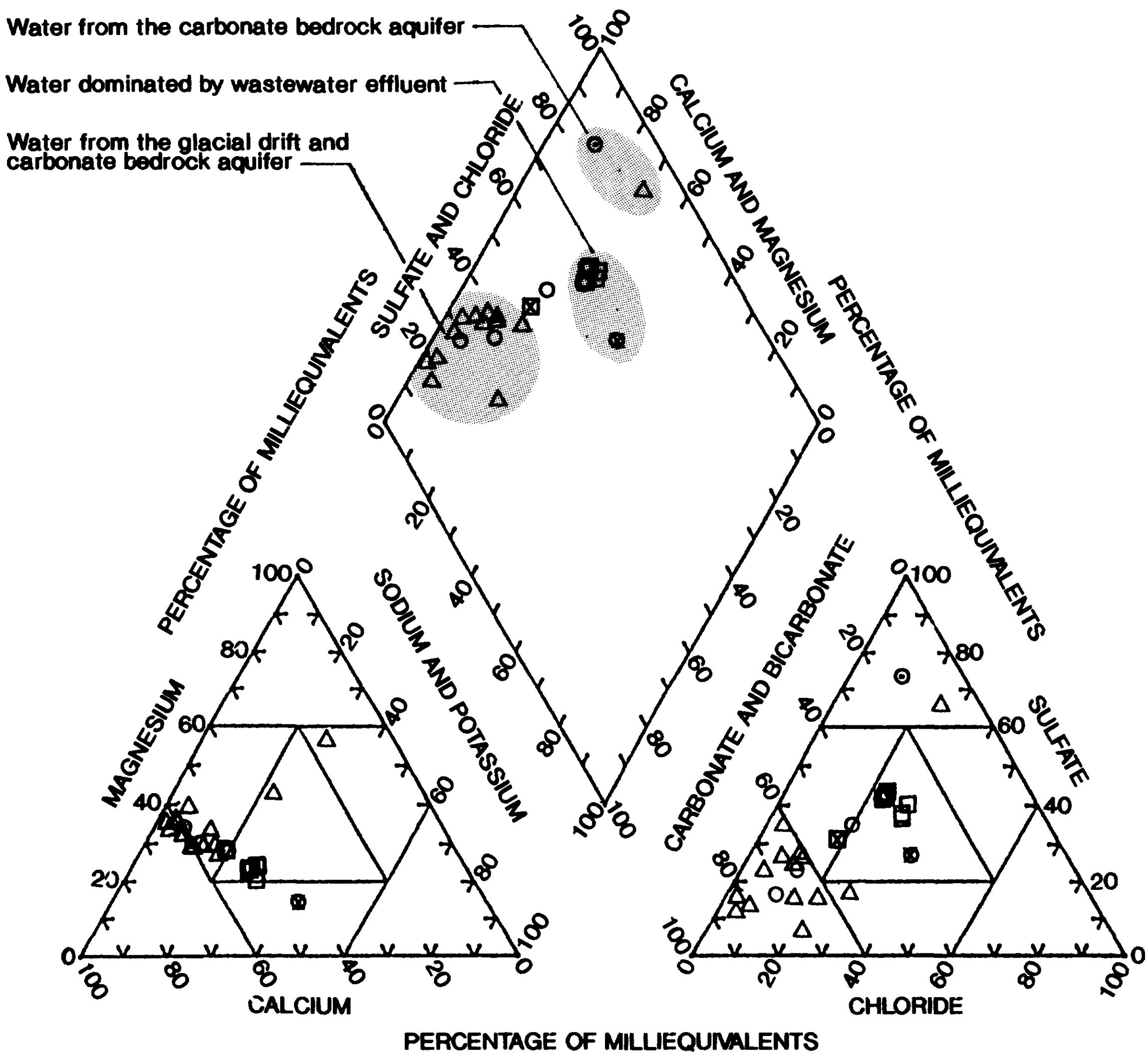
GLACIAL DRIFT AQUIFER

▼ SURFACE-WATER SITE LOCATION

■ EFFLUENT SITE LOCATION

◉ GROUND-WATER SITE LOCATION

Figure 5.--Concentrations of major cations and anions for selected surface-water and ground-water sites in the study area, August and September 1987 and 1988.



EXPLANATION

- △ GROUND-WATER SAMPLES
- O TRIBUTARIES
- ⊠ SCIOTO RIVER ABOVE JACKSON PIKE WASTEWATER TREATMENT FACILITY
- □ SCIOTO RIVER BELOW JACKSON PIKE WASTEWATER TREATMENT FACILITY
- ⊙ QUARRY EFFLUENT
- ⊗ JACKSON PIKE WASTEWATER TREATMENT FACILITY EFFLUENT

Figure 6.--Relative concentrations of major anions and cations in waters from the glacial drift and carbonate bedrock aquifers, Scioto River and its triburaries, Jackson Pike Wastewater Treatment Facility, and a limestone quarry, August and September 1987.

1987 and 1988, downstream from the Jackson Pike WTF, were 528, 64, and 49 mg/L, respectively, approximately double the concentration measured at Scioto River at Frank Road (fig. 7). Median nitrite plus nitrate (as N) and dissolved-phosphorus concentrations were 3.4 and 1.95 mg/L, respectively--an increase of as much as an order of magnitude compared with values measured at the Frank Road site (fig. 7). Concentrations of boron, zinc, molybdenum, lithium, bromide, fluoride, and potassium were much greater in and downstream from the Jackson Pike WTF outfall than upstream from the outfall or in tributaries (table 1). These elements are commonly found in municipal sewage and industrial wastes at concentrations greater than those usually found in streams (American Public Health Association and others, 1985). None of these elements was found at a concentration that exceeded Ohio water-quality criteria (Ohio Environmental Protection Agency, 1990a).

Dissolved-solids concentration of effluent from the quarry is very high (1,530 mg/L) relative to concentrations in samples from Scioto River, its tributaries, and local wells (table 1). Calcium and sulfate account for most of the dissolved solids in quarry effluent. The quarry lake is used to provide process water for quarry operations such as sorting gravel, wetting roads, and rinsing equipment. Concentrations of the other elements (with the exception of cadmium) and nutrient species analyzed are similar to concentrations found in water from wells completed in the carbonate bedrock aquifer (table 2, at back of report).

Flow

Median annual flow of Scioto River at the streamflow-gaging station at Columbus is 446 ft^3/s for the 68 years that streamflow data had been collected at that site. Flow measured at the Columbus station includes effluent from the Jackson Pike WTF. Typically, the WTF discharges about 60 Mgal/d (93 ft^3/s) of effluent. The 7-day low flow with a recurrence interval of 10 years (based on the 1951 through 1978 water years) is 95 ft^3/s (Johnson and Metzker, 1981). Thus, when Scioto River flow is low, treated effluent can comprise much of the flow in Scioto River downstream from the Jackson Pike WTF.

Effluent from quarry-dewatering operations enters the river at three locations between Frank Road and I-270 (fig. 1). Only one of these sources was actively discharging water during the period of study; it contributed no more than 12 percent of Scioto River flow. Streamflow in Scioto Big Run (fig. 1) was less than 10 ft^3/s during the study. Streamflow in all other tributaries was negligible during the study. There are no other significant sources of discharge to Scioto River between the Jackson Pike WTF and the Southerly WTF.

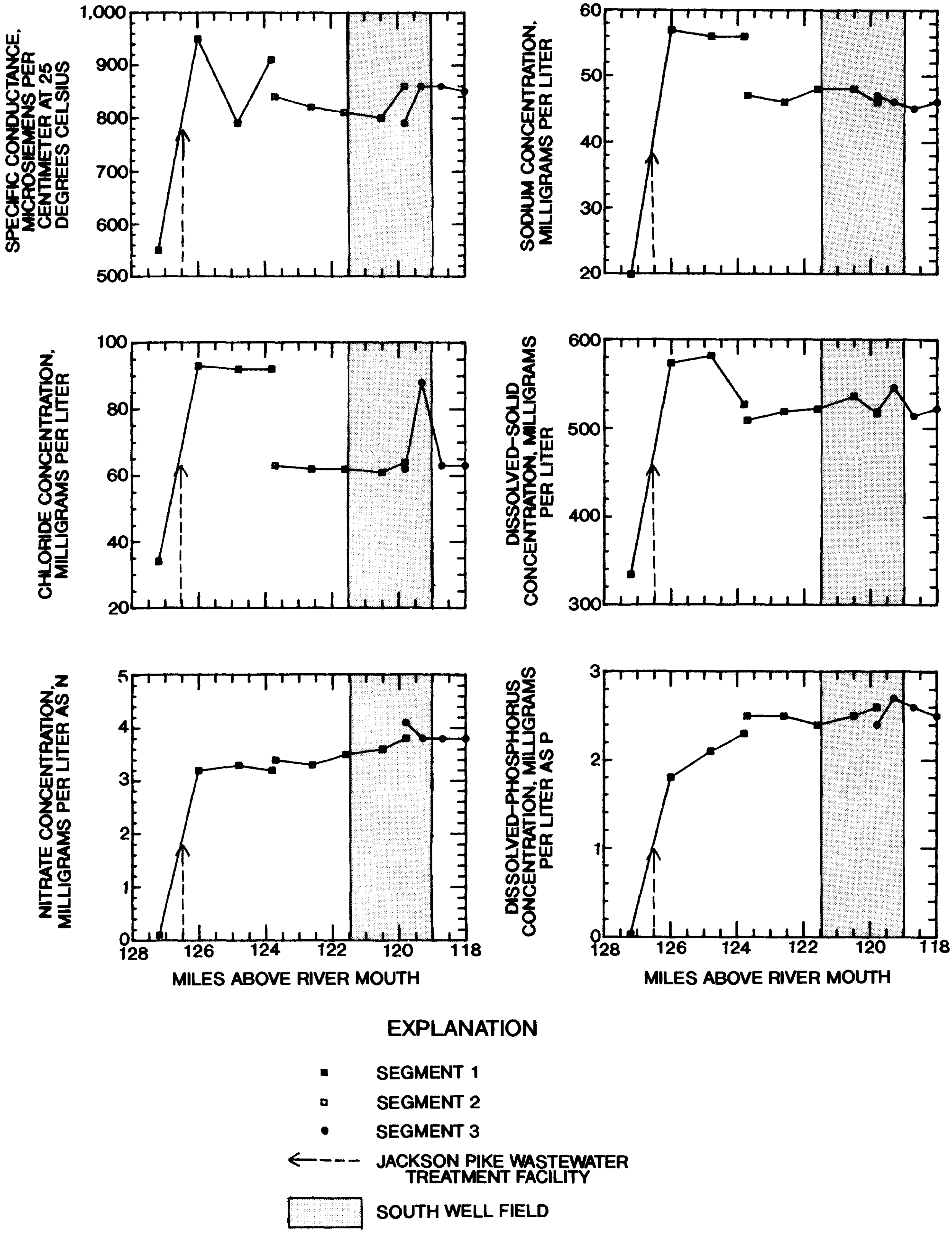


Figure 7.--Specific conductance and concentrations of selected constituents in Scioto River from Frank Road to the Southerly Wastewater Treatment Facility, August 18, 1987.

Simulation of Surface-Water Transport

Surface-water transport of Scioto River through the study area was simulated by use of a one-dimensional Lagrangian transport model (Schoellhamer and Jobson, 1986a). Longitudinal transport of dissolved constituents is controlled by the processes of advection and dispersion; however, within the Lagrangian reference frame, computational nodes (water parcels) are moved with river flow, and the advection term of the advection-dispersion equation is eliminated (Schoellhamer and Jobson, 1986a).

Description of model

Within the study reach, Scioto River was discretized into 11 sections of unequal length (fig. 8). Grid points were located at sampling sites and where major point sources entered the main stem. Three point sources provided significant flow (greater than 5 percent of Scioto River discharge) to the river: Scioto Big Run, the Jackson Pike WTF outfall, and the quarry (fig. 1). Only the quarry lake was discharging to the river at the time of sampling. On the basis of discharge measurements made in 1987 and 1988 (tables 3 and 4), no significant nonpoint sources of discharge were identified. The only nonpoint sink identified was that near the collector wells.

The model is based on assumptions of one-directional flow and fixed-channel geometry. The study reach is discretized by means of fixed grid points at which discharge, average cross-sectional area, average top width, and a dispersion coefficient must be provided. Tributaries and lateral nonpoint inflows or sinks also must be provided. The concentration of each constituent--in this study, rhodamine WT dye--is used as input for the upstream boundary and each tributary, point source, and lateral inflow. At every time step, a new parcel (computational element) is introduced, and each previous parcel is moved downstream at a distance determined by flow velocity and the length of the time step. Dispersion is calculated on the basis of exchange of flow between parcels. Changes in parcel concentration caused by dispersion are calculated by means of a mixing equation.

Input parameters

The transport model was calibrated to dye dispersion and traveltime data collected in 1987 and was verified with data collected in 1988. Input parameters required for model calibration are dispersion coefficients (Schoellhamer and Jobson, 1986a, p. 10), average cross-sectional area of the stream channel at each grid point, discharge at the boundaries at each time step, and main-stem and point-source boundary conditions for dye concentration at each time step.

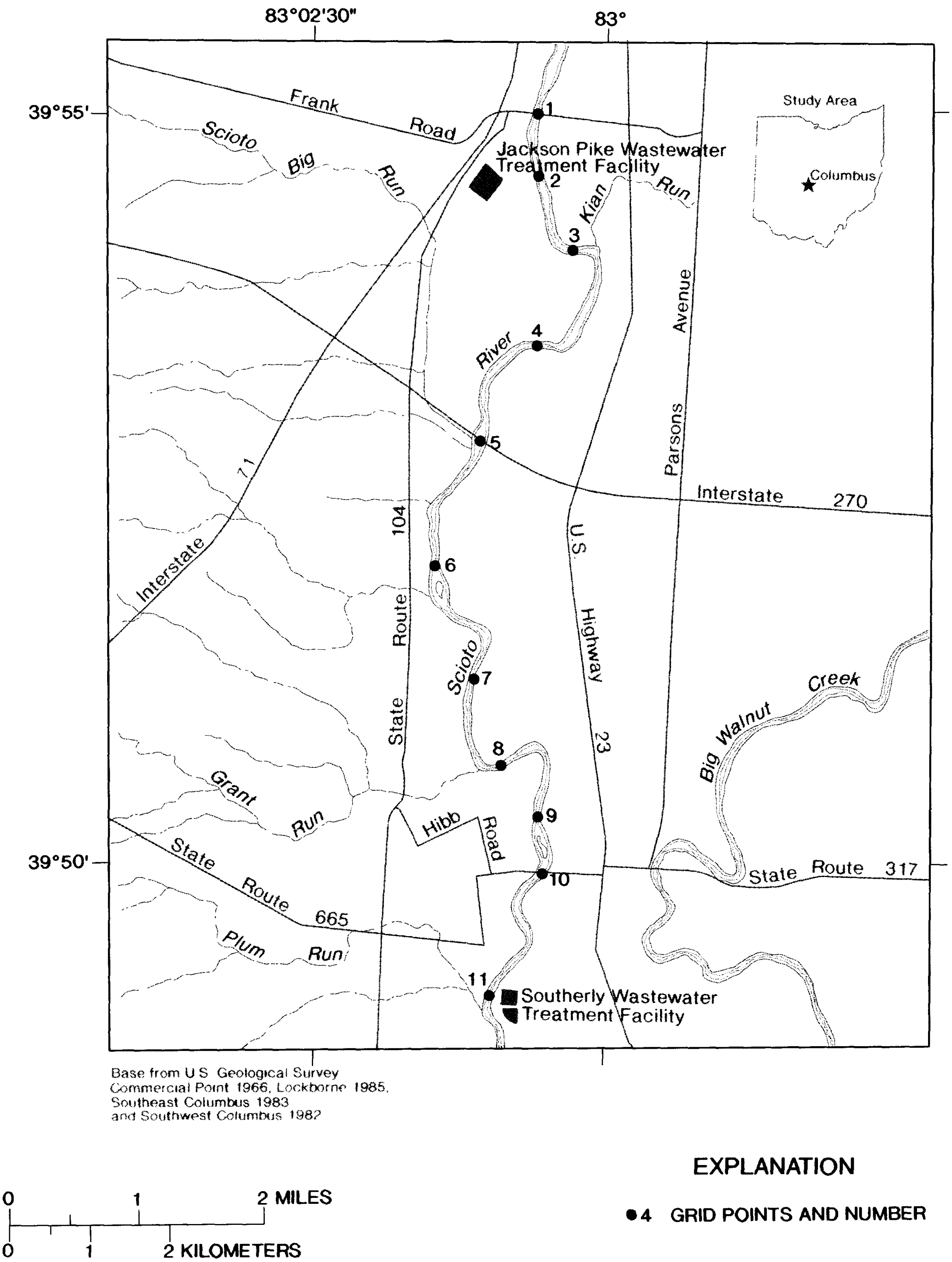


Figure 8.--Model grid points for the 1987 and 1988 traveltime studies.

As a slug of dye moves downstream, it spreads out longitudinally. This longitudinal dispersion occurs primarily because of horizontal and vertical gradients of velocity and secondarily because of the effects of features in the river channel such as meanders and embayments (Thomann and Mueller, 1987). Initial estimates of dispersion coefficients were made from complete dye-concentration curves by means of the method of moments (Yotsukura and others, 1970). Longitudinal dispersion coefficient (D) is defined as

$$D_x = \frac{\bar{U}^3 d\sigma_t^2}{2\ dx},$$

where U is mean cross-sectional velocity, $\frac{dx}{d\bar{t}}$,

where $\bar{t}$ is mean time of passage from injection to a point at distance x downstream, $\bar{t} = \frac{{}_0\int^{\infty} t^2 C dt}{{}_0\int^{\infty} C dt}$,

where C is dye concentration, and σ_t^2 is variance of the concentration versus time curve at x,

$$\sigma_t^2 = \frac{{}_0\int^{\infty} t^2 C dt}{C dt - [\bar{t}]^2}$$

The Lagrangian transport model calculates dispersion based on exchange of flow between adjacent parcels. Because water near the riverbed moves more slowly than water at the surface, each parcel receives inflow from and discharges water to its two adjacent parcels (Schoellhamer and Jobson, 1986b, p. 71); however, parcel volumes do not change. The input parameter for longitudinal dispersion (DQQ) is the ratio of the exchange flow to river discharge such that

$$DQQ = \frac{D_x}{U^2 \Delta t},$$

where Δt is the simulation time step (DQQ is dimensionless).

Dispersion coefficients were initially set to 0.20 to 0.60. Cross-sectional areas were derived from data available from the Ohio Environmental Protection Agency (written commun., 1982). Cross-sectional areas ranged from 50 ft^2 below I-270 to 1,200 ft^2 in the pool downstream from Frank Road. Discharges at the upstream boundary and at each point source were derived from the traveltime data (table 1). Discharge at the upstream boundary was assumed to be constant throughout the simulation.

Dye concentration on the upstream boundary was measured after injection of rhodamine WT dye. Concentration of dye in point sources was assumed to be zero for all time steps. Dye had to be injected at site 1 (fig. 3) rather than upstream because the long pool upstream from site 1 would have stretched out the dye curve. As a result, some difficulty was encountered in using site 1 as the upstream boundary for the simulation; instream, mixed dye concentration could not be measured at site 1 so that boundary dye concentration could be ascertained. As a result, calibration of this reach was begun at site 3 (fig. 3) instead of the Frank Road site (site 1).

Calibration

The model was calibrated to 1987 discharge and dye-concentration data. Each segment was modeled independently because a separate dye injection was made for each segment. Each of these segments was calibrated by first adjusting the initial estimates of cross-sectional area so that the simulated arrival of the peak closely approximated the measured arrival of the peak. Next, the dispersion of the dye cloud was simulated by adjusting the dispersion coefficient. The model "fit" was evaluated by minimizing the root mean square error (RMSE). The RMSE is the square root of the sum of the squared differences between the simulated concentration for a given time and grid point and the measured concentration at that time and grid point.

The first segment, from Frank Road to I-270 (fig. 8, table 3), was calibrated on a half-hour time step beginning at 0600 hours on August 18, 1987 (fig. 9a). Discharge was measured at the upstream boundary, metered at the Jackson Pike WTF, and estimated for the quarry. The second segment, from I-270 to collector well 103, was calibrated on a half-hour time step beginning at 0630 on August 18, 1987 (fig. 9b). Discharge was measured at the upstream boundary. Discharge measurements on the mainstem were used to estimate a loss of 0.00078 (ft^3/s)/ft for the river segment near collector wells 101 to 103. This represents a loss from the river of approximately 10 ft^3/s, or 6.5 Mgal/d, over that 2.1-mile segment that could be due to collector-well pumpage. Pumpage from the three collector wells in August 1987 was approximately 18.4 Mgal/d. The third segment, from collector well 103 to the Southerly WTF, was calibrated on a half-hour time step beginning at 0630 hours on August 18, 1987 (fig. 9c). Discharge at the upstream boundary was measured. There were no major tributaries or inflows. Once the segments were calibrated, all three segments were combined and the model was rerun. The cross-section areas where the segments meet were adjusted to calibrate traveltimes for the whole reach.

Verification

Traveltime and dispersion data were collected in 1988 from two segments of Scioto River (table 4): Frank Road to site 5 and site 3 to Shadeville (fig. 3). The calibrated model of the first segment was verified with half-hour time steps beginning at 0630 hours (fig. 10a). Discharge at Frank Road was calculated from the difference between discharge at site 3 and Jackson Pike WTF plus quarry discharge. Simulated peak traveltime was about 4 hours shorter than actual peak traveltime, and simulated peak concentrations were 3.0 and 0.9 µg/L higher than actual peak concentration at the first and second sites, respectively. The calibrated model of the second segment was verified with half-hour time steps beginning at 0630 hours (fig. 10b). Simulated traveltime was shorter than actual traveltime by no more than 2.5 hours near the collector wells. Simulated peak concentrations were no more than 1.9 µg/L greater than actual concentrations (fig. 10b).

Predicted traveltimes for three wastewater-discharge scenarios

Because streamflow measured at the Columbus streamflow-gaging station includes effluent from the Jackson Pike WTF, the wastewater component of total streamflow needed to be excluded from historical records of daily discharge to determine low-flow frequency statistics for the Scioto River component of streamflow. The daily mean effluent discharge recorded by the City of Columbus (City of Columbus Jackson Pike Wastewater Treatment Facility, written commun., 1987) was subtracted from daily mean discharge at the Columbus station for the period 1972-85. The calculated daily mean streamflow was then used to produce a theoretical 7-day low-flow frequency table (table 5) by means of the Log-Pearson Type III method (Riggs, 1972).

Three low-flow traveltime scenarios were simulated by means of the calibrated transport model:

1. Typical wastewater discharge from the Jackson Pike WTF during low-flow periods in the Scioto River for the period 1972-85. The 7-day, 2-year low flow[2]

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[2]Lowest flow, averaged over 7 consecutive days and recurring at a long-term average frequency of once every 2 years.

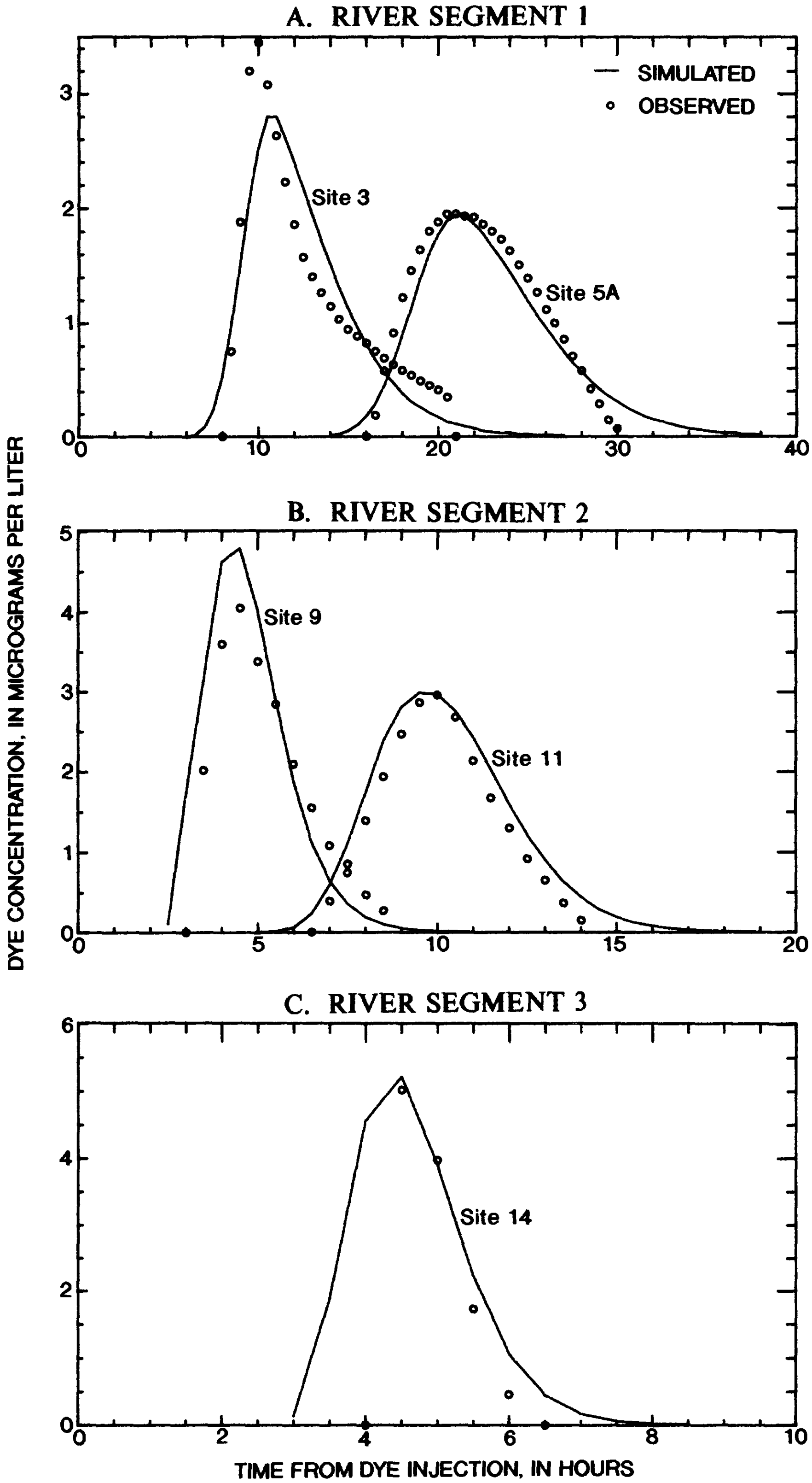
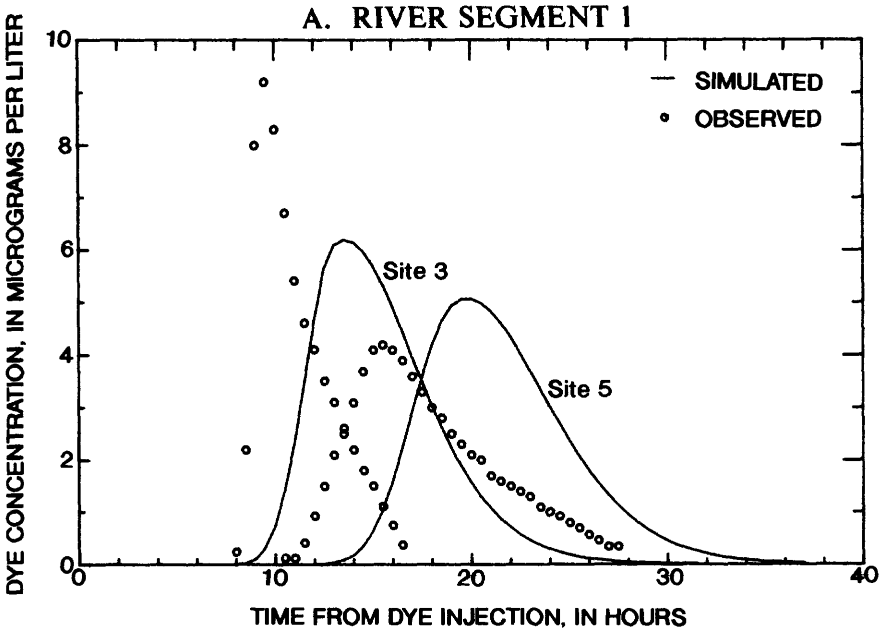


Figure 9.--Observed and simulated dye concentrations and traveltimes from calibration of surface-water-transport model.



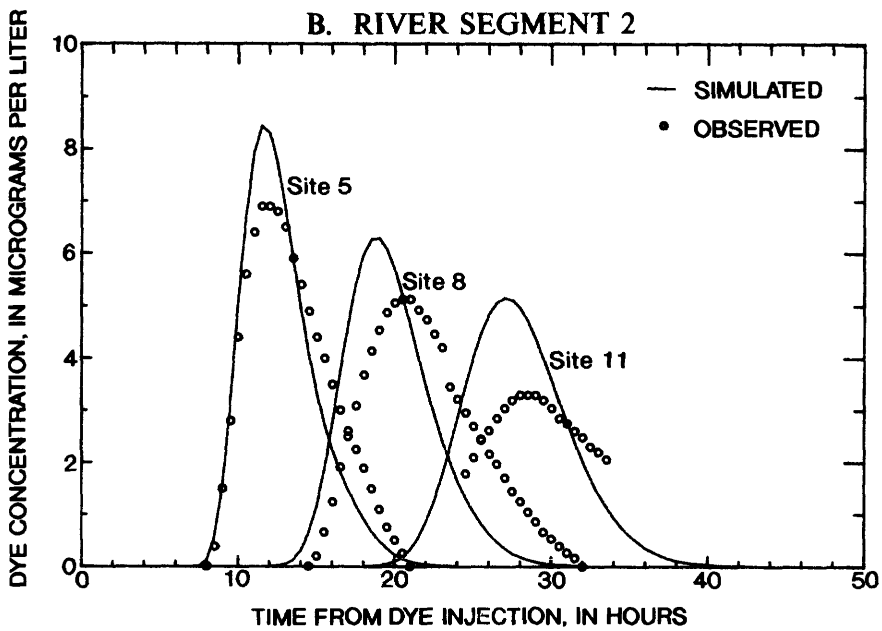


Figure 10.--Observed and simulated dye concentrations and traveltimes from verification of surface-water-transport model.

Table 5.--Summary of 7-day low-flow discharge for Scioto River at Columbus, Ohio (U.S. Geological Survey streamflow-gaging station 03227500) and for Scioto River at Columbus minus effluent from the Jackson Pike Wastewater Treatment Facility

[Based on record from 1972 through 1985]

Recurrence interval, years	7-day low-flow discharge, in cubic feet per second: Scioto River at Columbus	Scioto River at Columbus minus effluent
100	114	0
50	117	0
20	123	0
10	129	11.2
5	138	20.3
2	161	41.4
1.25	195	72.2
1.11	220	93.7
1.04	253	121
1.02	279	141
1.01	306	162

for Scioto River at Columbus streamflow-gaging station was 161 ft^3/s. This includes discharge from Jackson Pike WTF.

2. No effluent from Jackson Pike WTF. Had there been no flow from the Jackson Pike WTF during 1972-85, the calculated 7-day, 2-year low flow for Scioto River at Columbus would have been 41.4 ft^3/s.

3. Steady, but reduced, effluent flow from the WTF. The Jackson Pike WTF is now designed to discharge wastewater at a relatively steady rate of 93 ft^3/s. Under these conditions, the computed 7-day, 2-year low flow for Scioto River at Columbus is expected to be 134 ft^3/s.

The predicted traveltimes from Frank Road to the collector wells (specifically, collector well 101) for these three flow scenarios is shown below. The decrease in effluent discharge under current operating procedures compared with past operating procedures increases traveltime from Frank Road to the well field by approximately 6 hours. Under conditions of zero discharge from Jackson Pike WTF, traveltime would be increased by approximately 65 hours.

Scenario	Discharge, in cubic feet per second		Traveltime to collector well 101, in hours	
	Scioto River at Frank Road	Jackson Pike WTF effluent	Leading edge	Peak
1	41	120	21	29
2	41	0	76	94
3	41	93	25	35

Ground Water

Two aquifers are present within the study area. The uppermost aquifer is composed of glacial drift, predominantly ground-moraine and end-moraine deposits, outwash, and alluvial deposits. Thin deposits of till interspersed within the drift, outwash, and alluvium are generally underlain by a basal, clay-rich till. The glacial drift aquifer is underlain by a carbonate bedrock aquifer. A generalized geologic section (fig. 11) indicates vertical and lateral heterogeneity of the glacial drift and relief on the bedrock surface.

Quality

On the basis of concentrations of major anions and cations from data collected in other studies in the area (de Roche, 1985; de Roche and Razem, 1984; and Sedam and others, 1989), waters in the glacial drift aquifer and the carbonate bedrock aquifer generally can be classified as hard, calcium bicarbonate-type waters (Hem, 1985, p. 159-166). Magnesium is the second most prevalent cation, and sulfate the second most prevalent anion.

Ground-water samples were collected during a previous study from eight wells finished in glacial drift, upgradient from the landfills west of Scioto River and north of I-270 (de Roche, 1985). These samples are characterized by a median pH of 7.1, a median specific conductance of 770 µS/cm and a median dissolved-solids concentration of 538 mg/L. Concentrations of iron and manganese in these samples routinely exceeded the U.S. Environmental Protection Agency's Secondary Maximum Contaminant Levels for drinking water, 300 and 50 µg/L, respectively (Ohio Environmental Protection Agency, 1990b). Concentrations of trace metals (arsenic, copper, lead, nickel, and zinc) generally are less than 5 µg/L (table 2). The combined concentration of all nitrogen species generally is less than 1 mg/L. Samples collected from April 1975 through May 1980 (de Roche and Razem, 1984) and from June 1984 through April 1986 (Sedam and others, 1989) from wells in a larger area of southern Franklin County were similar in their chemical characteristics.

Because few wells are completed in bedrock, it is difficult to compare the water-quality characteristics of the glacial drift and the carbonate bedrock aquifers. On the basis of water-quality data collected in previous studies (de Roche, 1985; de Roche and Razem, 1984; and Sedam and others, 1989), however, concentrations of dissolved solids, sulfate, and calcium in samples from the carbonate bedrock aquifer commonly are greater than in samples from the glacial drift aquifer. The relative percentage of concentrations of major anions and cations in selected samples collected from wells completed in each aquifer is shown in figure 12. Most of the samples from the glacial drift aquifer were collected from a large part of southern Franklin County.

The collector wells that are adjacent to Scioto River consist of a central caisson from which several laterals made of slotted well screen extend several hundred feet into the glacial drift aquifer. On the basis of historic water-quality data, the water produced by the collector wells is classified as a hard, calcium bicarbonate-type water (fig. 12).

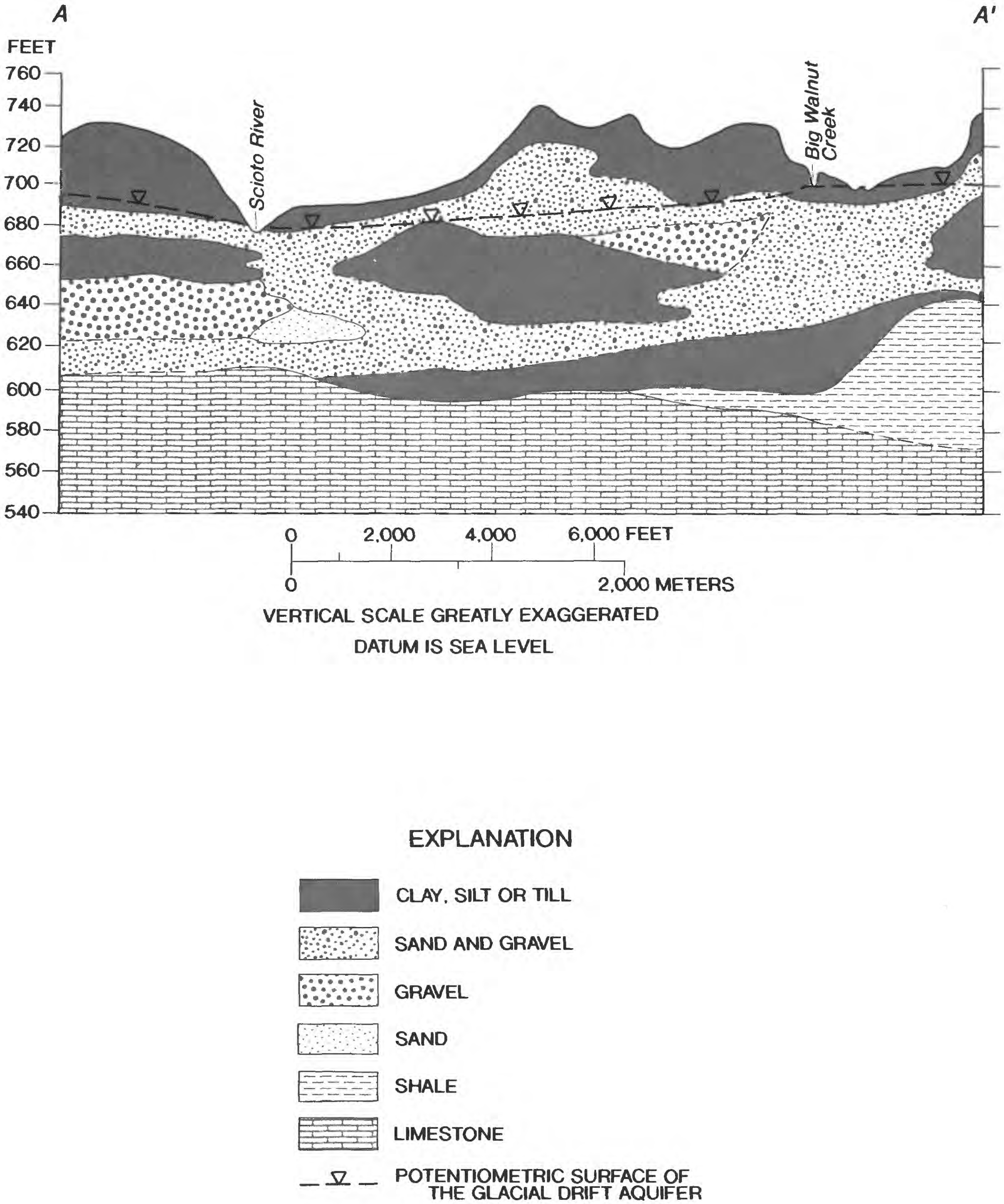
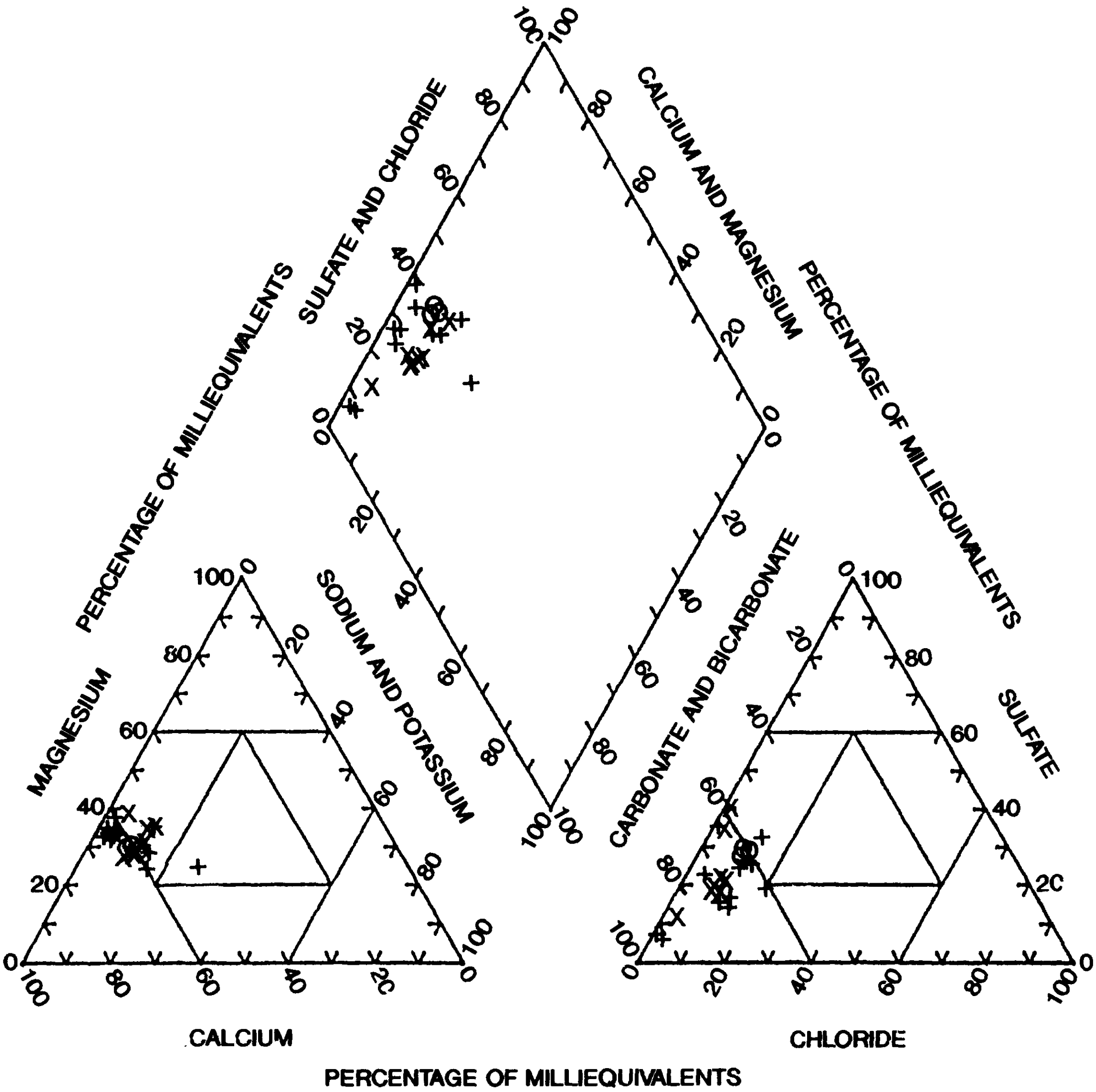


Figure 11.--Generalized geologic section *A–A'*. (From Sedam and others, 1989, fig. 7.)



EXPLANATION

+ GLACIAL DRIFT AQUIFER
X CARBONATE BEDROCK AQUIFER
O COLLECTOR WELLS

Figure 12.--Relative concentrations of major anions and cations in waters from the glacial drift and carbonate bedrock aquifers.

Flow

Potentiometric surfaces in the glacial drift and carbonate bedrock aquifers during March 1986 are shown in figures 13 and 14. Significant depressions in the potentiometric surfaces in the northern part of the study area were a result of quarry dewatering. The small depression in the south-central part of the study area (fig. 13) resulted from pumping at the collector wells in the South Well Field. In areas away from these cones of depression, the regional direction of ground-water flow in both aquifers is towards Scioto River.

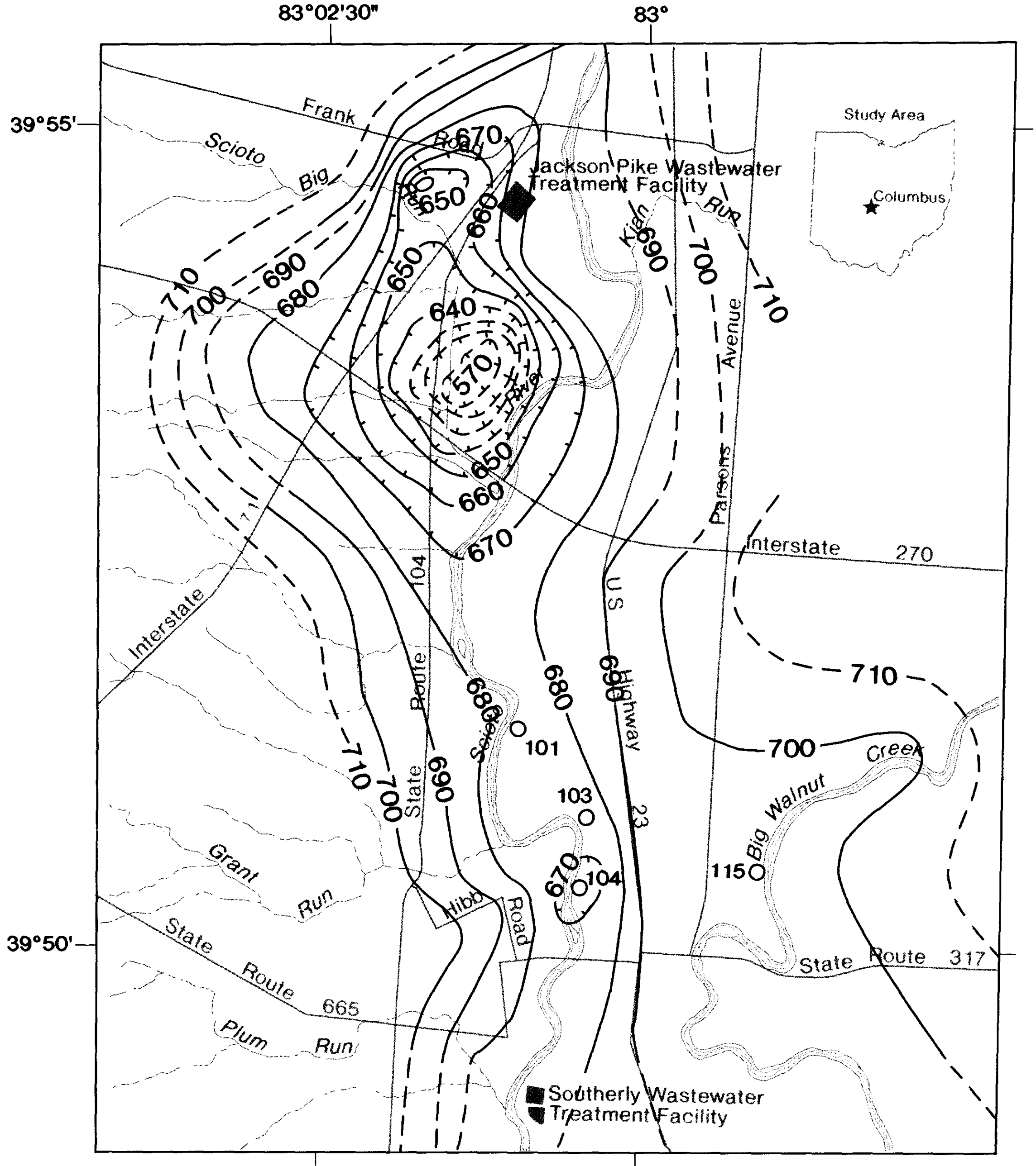
Simulation of Flow

The ground-water system was simulated by use of a three-dimensional finite-difference flow model (McDonald and Harbaugh, 1988). The program simulates ground-water flow in three dimensions by means of a block-centered, finite-difference approach. Model layers can be designated as confined, unconfined, or a combination of confined and unconfined. Flow associated with stresses, such as wells, recharge, evapotranspiration, drains, and streams, can be simulated.

The flow system is spatially discretized with a mesh of blocks, called cells, the locations of which are described in terms of rows, columns, and layers; the layers generally correspond to geohydrologic units. Within each cell is a nodal point at which the hydraulic head for that cell is calculated by use of a finite-difference form of the ground-water-flow equation.

Description of model

Three components of ground-water flow near the South Well Field area can be modeled: leakage to or from Scioto River, lateral flow within the glacial drift aquifer, and upflow from the carbonate bedrock aquifer into the glacial drift aquifer. A coupled regional-subregional modeling technique, described by Buxton and Reilly (1986), was used to simulate ground-water flow near the South Well Field to determine the relative magnitude of these three flow components to the collector wells. This technique allows for detailed vertical discretization so stresses from wells could be assigned to a different layer than stresses from streams. This technique also enables hydrologic representation of the South Well Field area (7.7 mi^2) with a previously constructed and calibrated ground-water-flow model (fig. 15). This previously constructed three-dimensional, steady-state model (Sedam and others, 1989; Eberts and Bair, 1990) is referred to as the "regional model" and represents an area of 48 mi^2 in southern Franklin County.



Base from U.S. Geological Survey
Commercial Point 1966, Lockbourne 1985,
Southeast Columbus 1983
and Southwest Columbus 1982

0 1 2 MILES

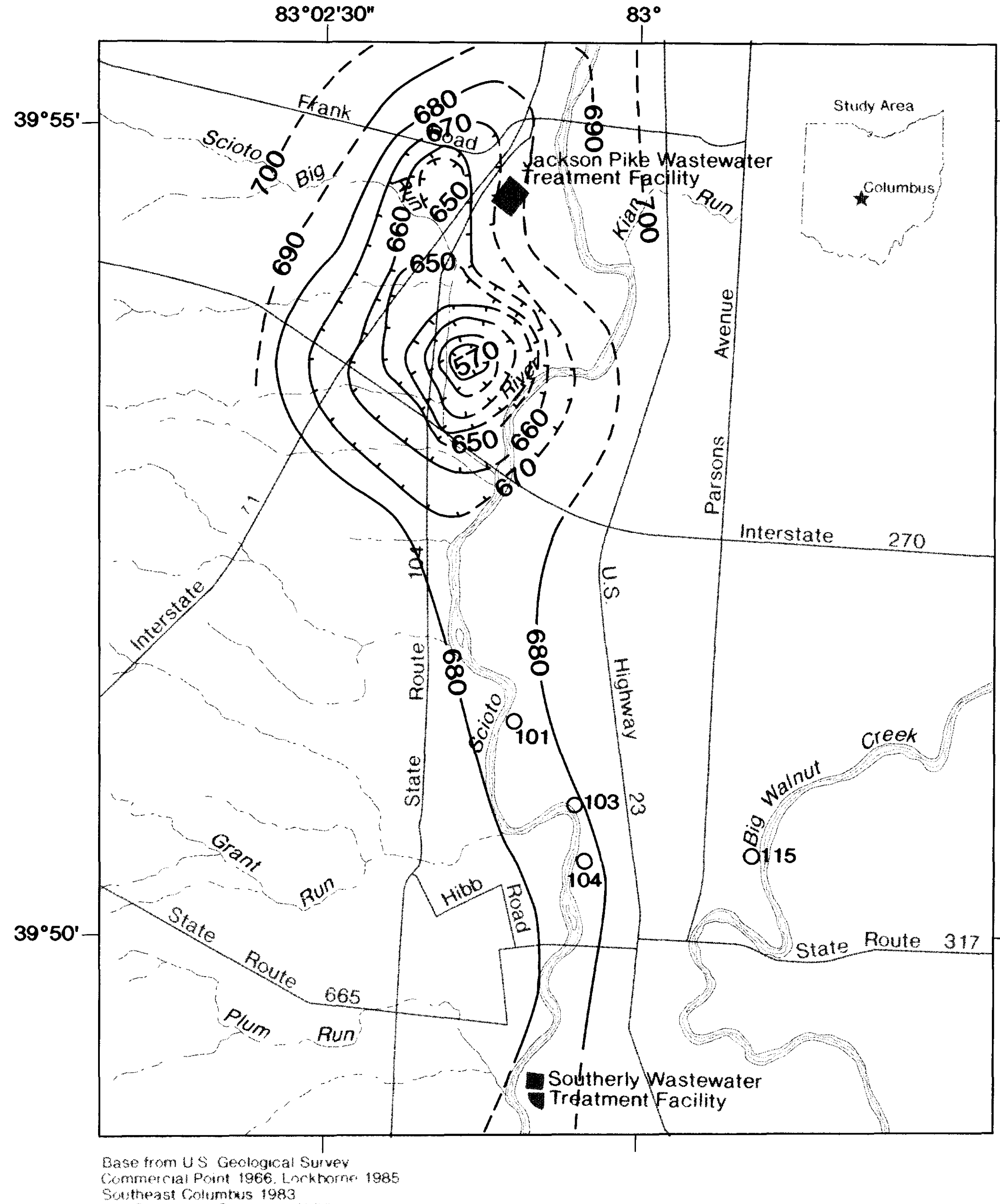
0 1 2 KILOMETERS

EXPLANATION

—680— — WATER-LEVEL CONTOUR--Showing equal altitude of water-level in glacial aquifer; dashed where approximate. Contour interval 10 feet except near large water-level depression. Datum is sea level. Hachures indicate depression contours

O101 COLLECTOR WELL AND NUMBER

Figure 13.--Water-level contours in the glacial drift aquifer, March 1986. (From Sedam and others, 1989, fig. 14.)



EXPLANATION

—680— —	POTENTIOMETRIC SURFACE CONTOUR--Showing equal altitude of potentiometric surface contour in carbonate bedrock aquifer; dashed where approximate. Contour interval 10 feet except near large water-level depression. Datum is sea level. Hachures indicate depression contours
O101	COLLECTOR WELL AND NUMBER

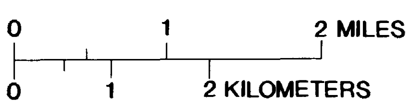


Figure 14.--Potentiometric surface in the carbonate bedrock aquifer, March 1986. (From Sedam and others, 1989, fig. 15.)

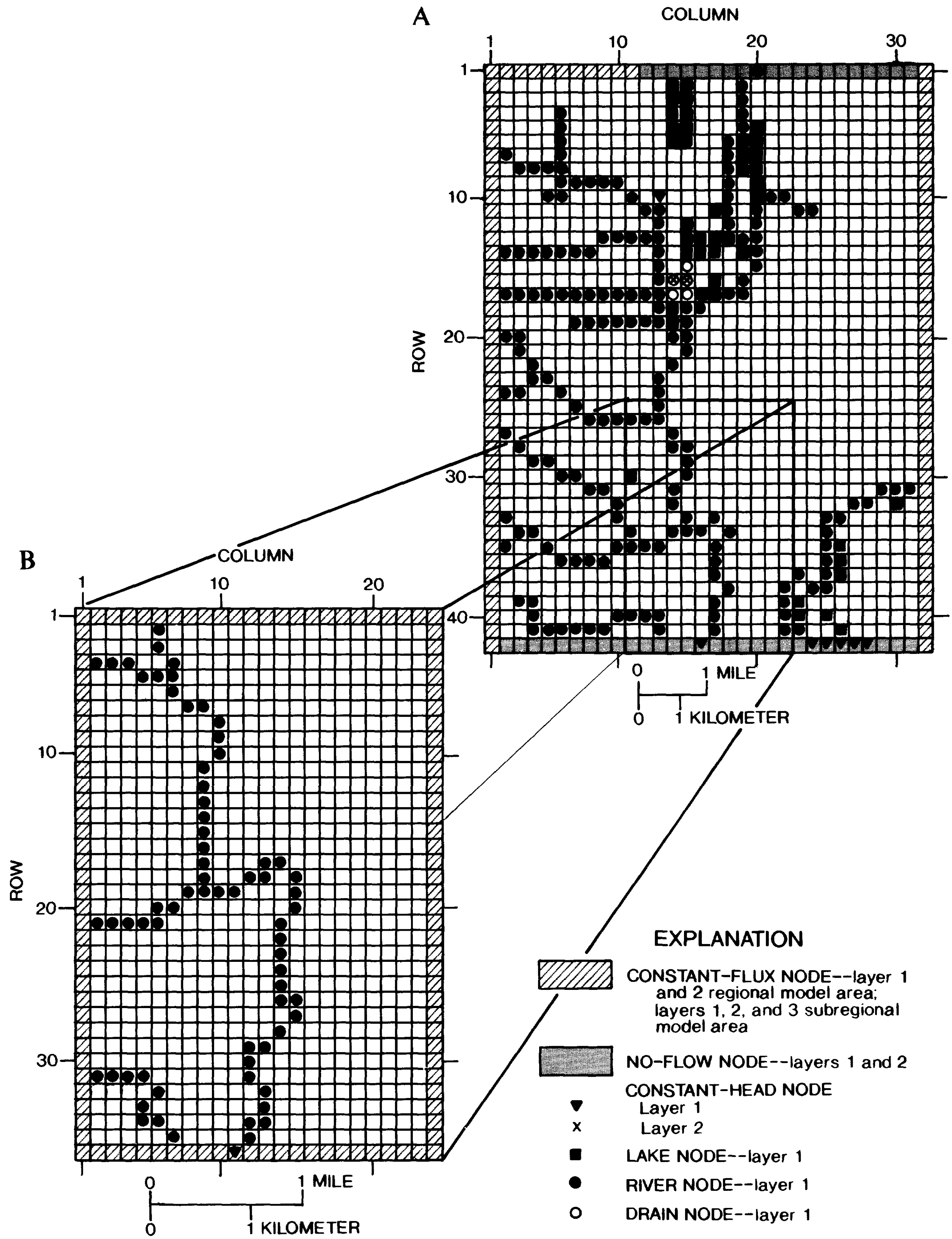


Figure 15.--Finite-difference grid and model boundaries for the (A) regional and (B) subregional model areas. (Regional model grid from Sedam and others, 1989, fig. 23.)

Subregional model boundary conditions are defined by the distribution of flow in the regional model. The finer grid resolution of the subregional model in the area of the collector wells along Scioto River allows a more detailed examination of flow components to the collector wells than was possible with the regional model.

Regional model.--The regional model grid consisted of 42 rows and 32 columns, and each block represented 1,000 ft in both horizontal directions (fig. 15). The model treated the flow system as two layers, one layer representing the glacial drift aquifer and the other representing the carbonate bedrock aquifer.

The boundary conditions defined for the regional model were approximations of the natural flow-system boundaries. Sedam and others (1989, p. 54-57) described these boundary conditions in detail. A brief summary follows.

Layer 1 (glacial drift aquifer) was simulated as an unconfined layer and was bounded on top by the water table and on the bottom by the top of bedrock. The bedrock surface was the top of layer 2 (bedrock or confined aquifer). The lower boundary of layer 2 was set at an altitude of 250 ft above sea level, which was presumed to be the base of a regional flow cell (Sedam and others, 1989, p. 54).

Constant-flux boundary conditions, calculated by use of Darcy's Law, were assigned to each node along the west, east, and western end of the northern boundaries of the model (fig. 15). Aquifer-test data, drillers' logs, and water levels were used to estimate hydraulic conductivities, and hydraulic gradients were used to compute flux values. Ground-water flow parallel to the southern boundary and the eastern end of the northern boundary constitutes no-flow boundaries for these areas in the model.

Elevations and depths for Scioto River, Big Walnut Creek, their tributaries, and numerous lakes in the modeled area were derived from USGS topographic maps and constitute the internal boundaries of the model grid.

Subregional model.--A small section of the regional model that included the three collector wells along Scioto River, the reach of Scioto River influenced by these wells, and the area of the glacial drift aquifer with greater than 1 ft drawdown under maximum pumping of these wells, was further discretized. The resulting subregional three-dimensional steady-state model contains approximately 7.7 mi^2 in the south-central part of the regional model (fig. 15). The horizontal grid pattern consists of a 36- by 24-block rectangle in which each block represents an area of 500 ft by 500 ft (fig. 15). As a result, each grid block in the regional model is represented by four grid blocks in the subregional model.

The vertical representation of the flow system in the subregional model is similar to that used in the regional model, except that the glacial drift aquifer is represented by two model layers--an upper layer that contains the river nodes and the upper saturated part of the glacial drift aquifer, and a lower layer which contains the lower saturated part of the glacial drift aquifer in which the collector wells are completed (fig. 16). Vertical flow across the bottom of layer 1 (top of layer 2) is initially unrestricted. Layer 3 in the subregional model area represents the carbonate bedrock aquifer and is the same as layer 2 of the regional model.

The southern boundary of the subregional model area is the same as that of the regional model. The other boundaries of the subregional model area were designated as constant-flux boundaries. The fluxes assigned to individual nodes in the subregional model for various pumping stresses were computed from the regional model output of cell-by-cell flow data under the same pumping stresses.

Stream, lake, and well locations were reassigned in the context of the smaller block size of the subregional model grid (fig. 15). Elevations and depths of streams and lakes were designated as in the regional model. New water-level data were collected in 1987 and 1988 to provide additional information within the subregional-model area.

Input parameters

Steady-state simulation of ground-water flow in the area of the South Well Field required calculation or estimation of several input parameters. These parameters included horizontal hydraulic conductivity of the glacial drift aquifer, transmissivity of the carbonate bedrock aquifer, vertical hydraulic conductivity of both aquifers and the riverbed hydraulic conductivity and recharge.

Regional model.--The following is a summary of the input parameter values used by Sedam and others (1989) and Eberts and Bair (1990) for the regional model.

Aquifer-test data and drillers' logs were used to determine the distribution of horizontal hydraulic conductivities of the glacial drift aquifer. The distribution of the horizontal hydraulic conductivities that provided the best match between simulated and observed water levels is shown in figure 17.

The initial hydraulic conductivities for the carbonate bedrock aquifer were the same as those used by Garner (1983); these values were subsequently adjusted during calibration.

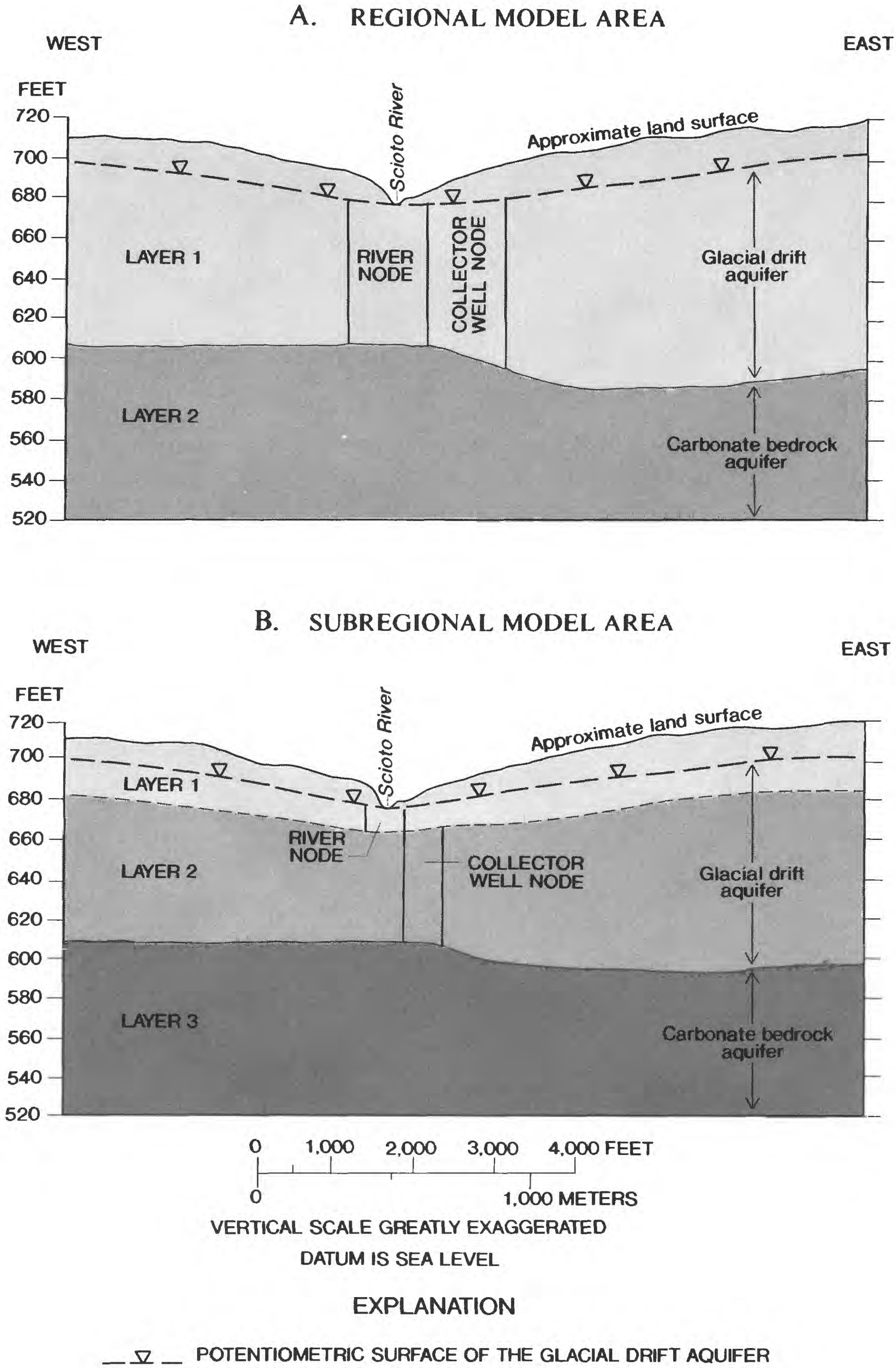


Figure 16.--Generalized hydrogeologic section of the glacial drift and carbonate bedrock aquifers within the study area for the (A.) regional and (B.) subregional model areas.

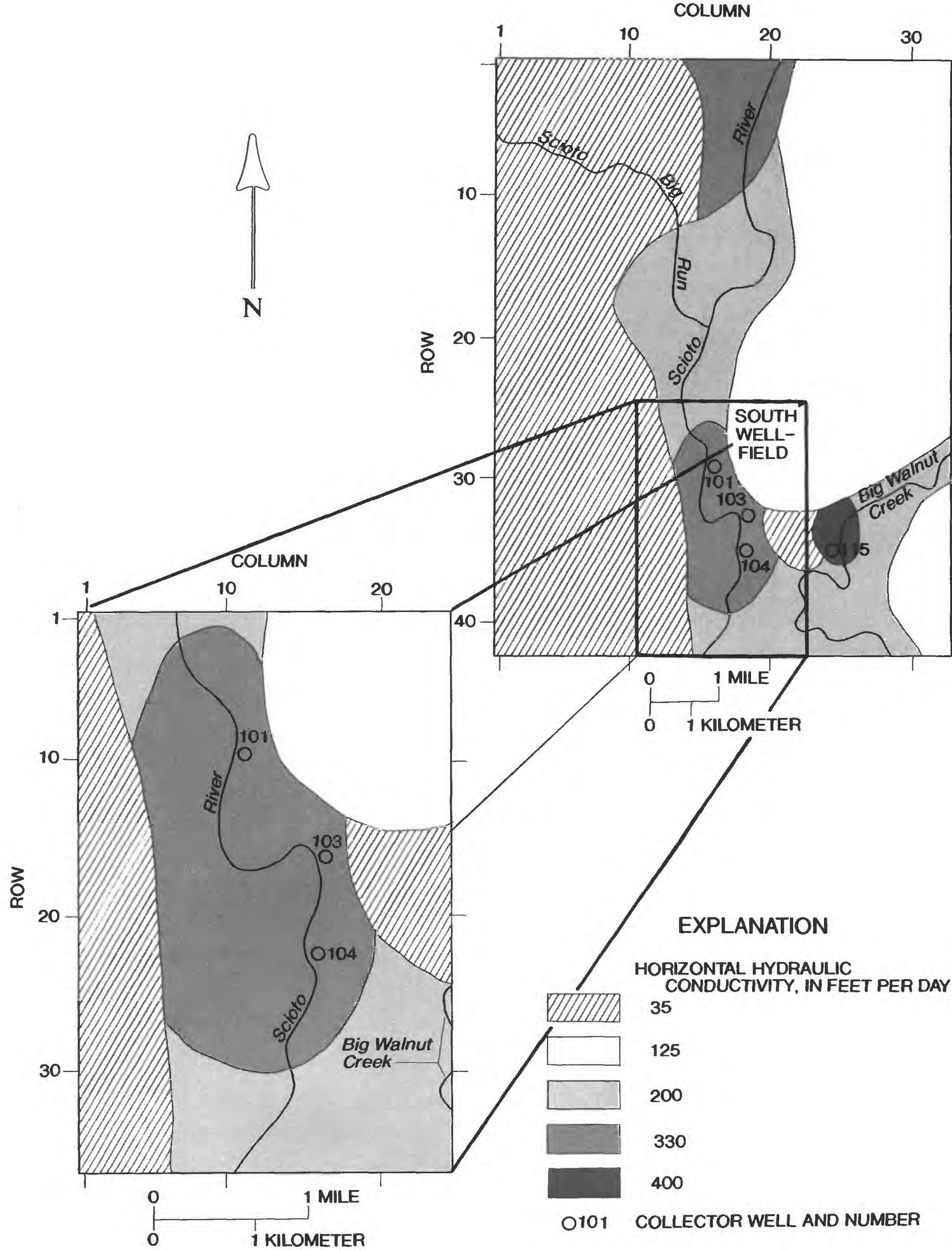


Figure 17.--Areal distribution of horizontal hydraulic conductivity used to simulate the glacial drift aquifer in the regional and subregional model areas.

The horizontal hydraulic conductivities (K) used for calculation of transmissivity (T) for the bedrock aquifer are shown in figure 18. Horizontal hydraulic conductivities of 10 ft/d were assigned to the eastern part of the study area where shale overlies the carbonate bedrock.

A vertical hydraulic conductivity of 5.0×10^{-3} ft/d was used for clay (or till) and shale deposits; otherwise, initial values were one order of magnitude lower than the corresponding horizontal hydraulic conductivities.

Leakage from river nodes was simulated in the regional model by riverbed conductance, calculated as

$$C = K_{rb}(A/b),$$

where
- C is conductance,
- K_{rb} is vertical hydraulic conductivity of the riverbed,
- A is area through which leakage occurs, and
- b is thickness of the riverbed.

Calibration of the regional model defined three areas of differing riverbed conductance (Sedam and others, 1988). Conductances of 1.0×10^5 ft^2/d were used to simulate leakage from Scioto River nodes above Jackson Pike WTF, in the northern part of the regional model. Downstream from the WTF, conductances were set to 3.3×10^4 ft^2/d, corresponding to a K_{rb} of 0.22 ft/d. Big Walnut Creek also was simulated with a conductance of 3.3×10^4 ft^2/d. All tributary streams were assigned a conductance of 5.0×10^3 ft^2/d.

Values for recharge from precipitation ranged from 4 to 9 in/yr. The areal distribution of recharge is shown in figure 19.

Pumping centers in the regional model included dewatering operations at the sand and gravel quarry near Frank Road and the limestone quarry (figs. 1 and 15), which were simulated by use of drains and (or) constant-head nodes. The March 1986 pumping rate at the four collector wells, 8.2 Mgal/d, was distributed among pumped wells in the model.

Subregional model.--Input-parameter values generally correspond to a subset of the parameter values used in the regional model. The areal distribution of horizontal hydraulic conductivities assigned to the upper two layers in the subregional model (which represent the glacial drift aquifer) is the same as the distribution used in the regional model (fig. 17).

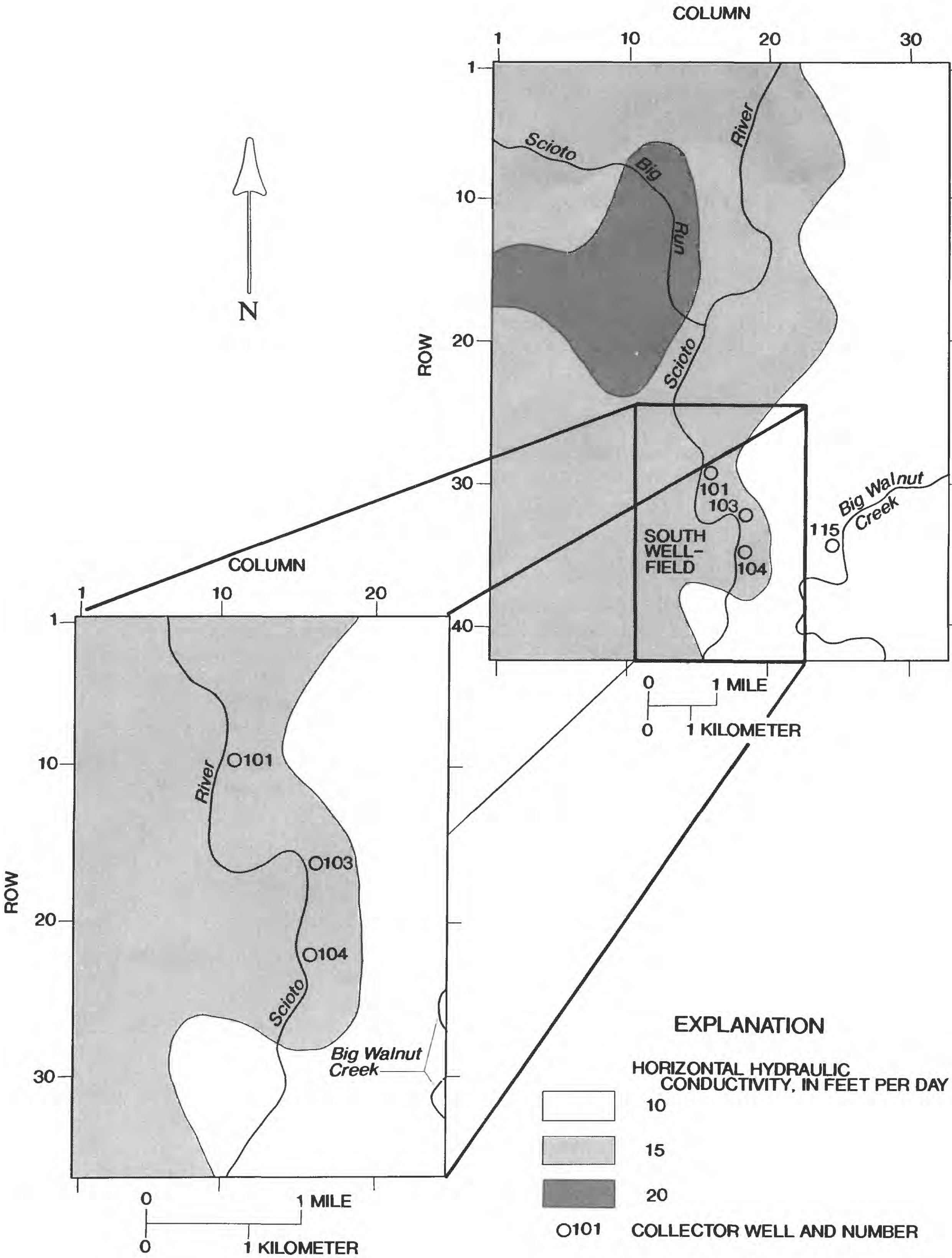


Figure 18.--Areal distribution of horizontal hydraulic conductivity used to calculate the transmissivity of the carbonate bedrock aquifer in the regional and subregional model areas.

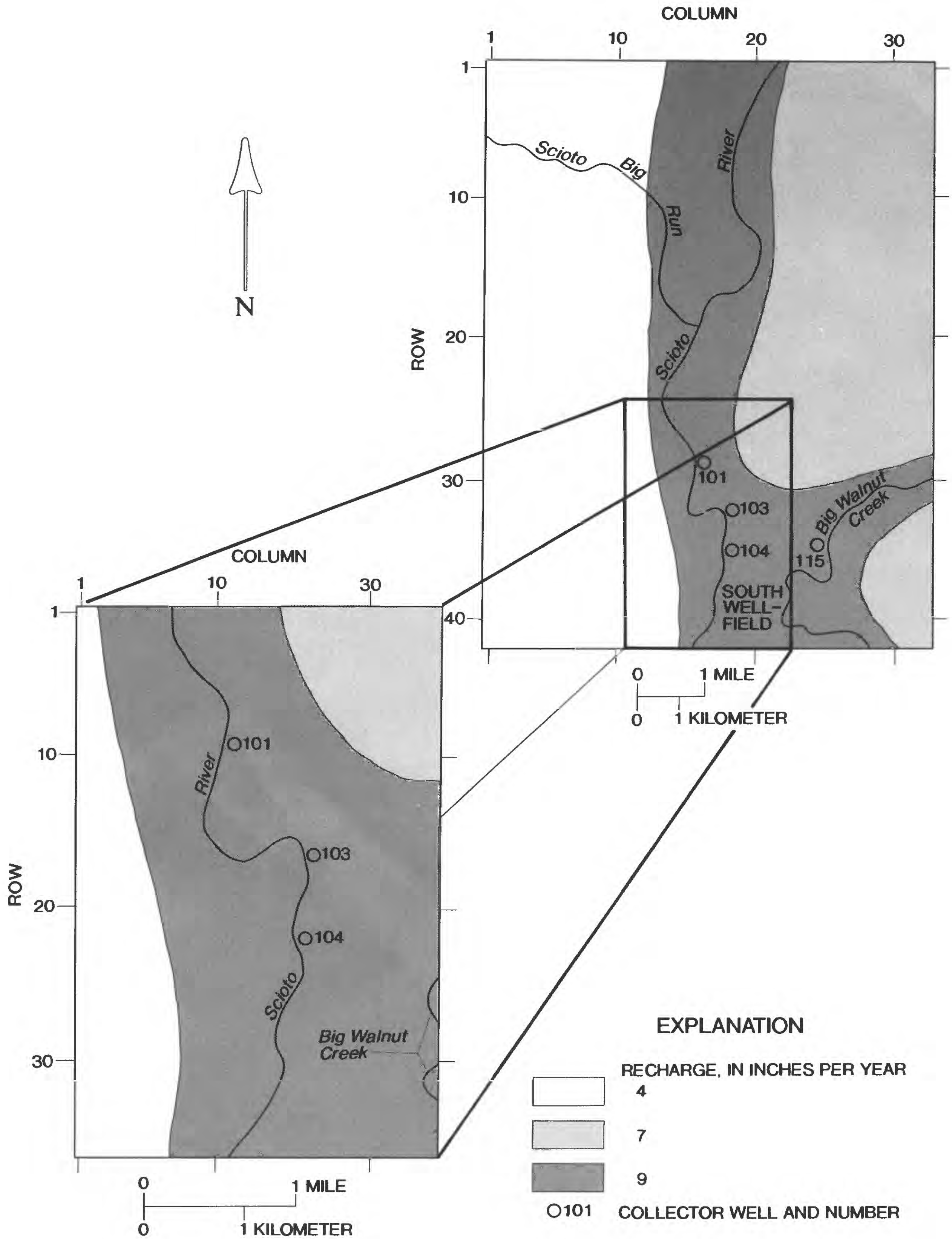


Figure 19.--Areal distribution of recharge used in the regional and subregional models.

Horizontal hydraulic conductivities and corresponding transmissivities assigned to the carbonate bedrock aquifer also are the same as those assigned in the regional model (fig. 18).

Vertical hydraulic conductivities for the two glacial drift layers in the subregional model were taken from values assigned in the regional model. The equation for vertical conductance (McDonald and Harbaugh, 1988, p. 138) is as follows:

$$Vcont_{i,j,k+1/2} = \frac{1}{\frac{(\Delta z_u)/2}{K_{z_u}} + \frac{(\Delta z_\ell)/2}{K_{z_\ell}}}$$

where Δz_u is the thickness of the upper layer,

Δz_ℓ is the thickness of the lower layer,

K_{z_u} is the vertical hydraulic conductivity of the upper aquifer,

K_{z_ℓ} is the vertical hydraulic conductivity of the lower aquifer,

i is the row,

j is the column, and

k is the layer.

For the regional model, when k = 1, Vcont is equal to the vertical conductance between the glacial drift and carbonate bedrock aquifer layers.

The glacial drift layer in the regional model is separated into two layers in the subregional model, so the vertical conductance between the two upper layers in the subregional model becomes:

$$Vcont_{i,j,k+1/2} = \frac{1}{\frac{(\Delta z_{u_1})/2}{K_{z_u}} + \frac{(\Delta z_{u_2})/2}{K_{z_u}}},$$

where k is 1,

Vcont is the vertical conductance between the two glacial drift layers,

Δz_{u_1} is the thickness of the upper glacial drift layer, and

Δz_{u_2} is the thickness of the lower glacial drift layer.

Rearranging this equation,

$$Vcont_{i,j,1.5} = \frac{K_{z_u}}{(\Delta z_u)/2},$$

where Δz_u is the entire thickness of glacial drift aquifer.

For the purpose of calibration to the regional model, horizontal hydraulic conductivities in the glacial drift were used for K_{z_u}, thus, these layers were treated as isotropic in the model. In this way, the two upper layers in the subregional model function as the one layer functioned in the regional model. A discussion of the sensitivity of this parameter in the subregional model is presented later in this report.

The vertical hydraulic conductivity between layers two and three of the subregional model can be derived from equation 2. Because layer 1 in the subregional model is thin compared with the total thickness of layers 1 and 2, regional-model values for Vcont were used to approximate the regional-model flow between the glacial drift and carbonate bedrock aquifers.

Vertical hydraulic conductivity of the riverbed (K_{rb}), measured by use of seepage meters in runs and riffles, was used to assess the accuracy of values used in previous models of the study area to assess the variability of K_{rb} and to attempt to correlate K_{rb} with riverine setting.

Commonly, the distinction as to where one riverine setting ends and another begins is not clear. Because streams are dynamic, the type of setting describing a particular reach can change in time and with changes in river stage; however, at low flow, the segment of Scioto River between I-270 and State Route 665 is dominated by runs and has fewer but nearly equal numbers of riffles and pools (fig. 4).

Measured K_{rb} values were adjusted to equivalent K_{rb} values at the mean annual water temperature of 12 °C (table 6) (William Cunningham, U.S. Geological Survey, written commun., 1989). The values range from 0.0036 to 3.75 ft/d. The median is 0.250 ft/d, and the interquartile range (from the 25th to the 75th percentile) is 0.053 to 1.08 ft/d. No relation between K_{rb} and riverine setting is apparent (table 6). The ranges and variations of K_{rb} for riffles and runs are considerable.

Table 6.--Summary of vertical hydraulic conductivity of the riverbed measured at three different riverine settings in Scioto River between Interstate Route 270 and State Route 665

[Site number refers to figure 5; N, number of observations; IQR, interquartile range.]

Site number	Location	Date	Temperature (degrees Celsius)	Vertical hydraulic conductivity of the riverbed (feet per day)	
				Measured	Adjusted[1]
RUNS (N = 16, median = 0.40, IQR = 0.055 - 0.90)					
7	Left bank	09/08/88	22.5	0.0025	0.055
	Right bank	09/08/88	22.5	.0042	.077
	Center	09/08/88	22.5	.0030	.038
1	Left bank	09/15/88	22.0	.67	.49
	Right bank	09/15/88	22.0	.075	.044
	Center	09/15/88	22.0	.15	.11
3	Left bank	09/23/88	22.0	.63	.47
	Right bank	09/23/88	22.0	.75	.55
	Center	09/23/88	22.0	.070	.049
5	Left bank	10/05/88	17.0	4.25	3.52
	Right bank	10/05/88	17.0	1.06	.90
2	Right bank	10/19/88	14.5	.19	.17
	Center	10/19/88	14.5	.35	.33
8	Left bank	10/29/88	11.5	1.50	1.62
	Right bank	10/29/88	11.5	2.75	3.01
	Center	10/29/88	11.5	3.70	3.75
RIFFLES (N = 5, median = 0.16, IQR = 0.01 - 0.69)					
4	Left bank	09/28/88	22.0	3.05	2.24
	Right bank	09/28/88	22.0	.053	.037
	Center	09/28/88	22.0	.22	.16
6	Left bank	10/14/88	12.5	.0036	.0036
	Right bank	10/14/88	12.5	.17	.17
POOLS (N = 1)					
3	Left bank	09/28/88	22.0	0.45	0.33

[1]Vertical hydraulic conductivity is adjusted to 12.0 degrees Celsius, assuming a 2.7-percent change in hydraulic conductivity per degree Celsius (Rorabaugh, 1957).

Furthermore, the medians of K_{rb} for runs (0.40 ft/d) and riffles (0.16 ft/d) do not differ appreciably from the K_{rb} of 0.22 ft/d used in the regional model. Thus, riverbed conductance in the subregional-model nodes containing rivers or streams was calculated from values for K_{rb} and thickness used by Sedam and others (1989). The reduced grid size of the subregional model nodes (500 x 500 ft) required that riverbed conductance be recomputed in the subregional model.

Recharge from precipitation was applied to nodes in the uppermost active cell in the subregional model. Recharge values were the same as those in the part of the regional model containing the subregion (fig. 19).

The subregional-model area encompasses only the three collector wells along Scioto River, as indicated in figure 15. These wells were simulated as pumped wells in the subregional model at an overall pumping rate of 7.5 Mgal/d, as assigned for these three wells in the regional model.

Calibration

Regional model.--The steady-state regional model was calibrated to two different steady-state conditions to increase the uniqueness of the solution. Simulated water levels from both layers of the regional model were compared with measured water levels for March 1986 and historic (pre-1967) pumping conditions. Gain-loss studies along Scioto River (de Roche, 1985) also were used in the calibration and compared well with simulated river losses and gains. Details of these calibration efforts, including the calculated ground-water budget, are described in Sedam and others (1989).

Subregional model.--The subregional model was calibrated to the same steady-state conditions as was the regional model. Measured water levels for the March 1986 and historic conditions compared well, generally within 5 ft. In addition to the comparison of water levels, the flow across each cell in the subregional model was compared with the corresponding cell area in the regional model. These flows compared favorably, except adjacent to the boundaries of the subregional model where a general-head-boundary (lake) node had been assigned in the regional model (node 30, 11 in the regional model; fig. 15). Only the outer subregional node was assigned as a general-head-boundary node. This boundary assignment caused locally anomalous flows of water that affected only adjacent nodes.

The distribution of head for layer 1 of the glacial drift aquifer after calibration is shown for the coupled regional-subregional model areas (fig. 20). The smaller grid size used in the subregional model results in a more detailed simulation of the cone of depression surrounding each collector well than is possible with the regional model.

During September 1987, the pumping rates at Scioto River collector wells totaled 18.4 Mgal/d. Because of the increased rate of pumping, heads were lowered near the collector wells (fig. 20c). The regional model could not accurately simulate the head changes associated with this pumping because of the size of the grid cells. These increased pumping rates were simulated in the subregional model, and the simulated heads were generally within 5 ft of measured heads near the collector wells.

A sensitivity analysis of the subregional model to changes in vertical hydraulic conductivity and of the riverbed (K_{rb}) and of the upper layer (K_{z_u}) was formed to examine the effect of the discretization of the glacial drift aquifer in this model. Specifically, K_{rb} was varied from 0.11 to 1.32 ft/d, and vertical hydraulic conductivity (K_{z_u}) of the upper layer was varied from values that were equal to the horizontal hydraulic conductivity (K_h) to values that were 1/100 of K_h. K_{rb} and K_{z_u} were varied to examine their effects on the percentage of waters pumped from the well field. Effects of varying these parameters on the total contribution of induced flow from Scioto River to the collector wells adjacent to the river is shown in figure 21.

The effect of decreasing K_{z_u} in the nodes containing the river is most evident at high values of K_{rb}(K_{rb} > 0.5 ft/d). A significant increase in the percentage of water contributed to the collector wells by the river takes place with an increase in pumping rate. At low values of K_{rb} (K_{rb} < 0.5 ft/d), an incremental increase in K_{rb} significantly increases the amount of contribution from the river, but a corresponding increase in K_{rb} above 0.5 ft/d does not result in a similar change in contribution.

These results have implications for the entire flow system. Under constant pumpage, an increase in the amount of flow induced from the river (greater K_{rb}) would result in a decrease in the proportion of water from the other two sources, the carbonate bedrock or glacial drift aquifers. Because the contribution from the carbonate bedrock aquifer is small in relation to the contribution from the glacial drift aquifer, any change in K_{rb} will result, primarily, in a change in the amount of flow derived from the glacial materials; hence, the area of the zone around the wells that contributes water to the collector wells will change.

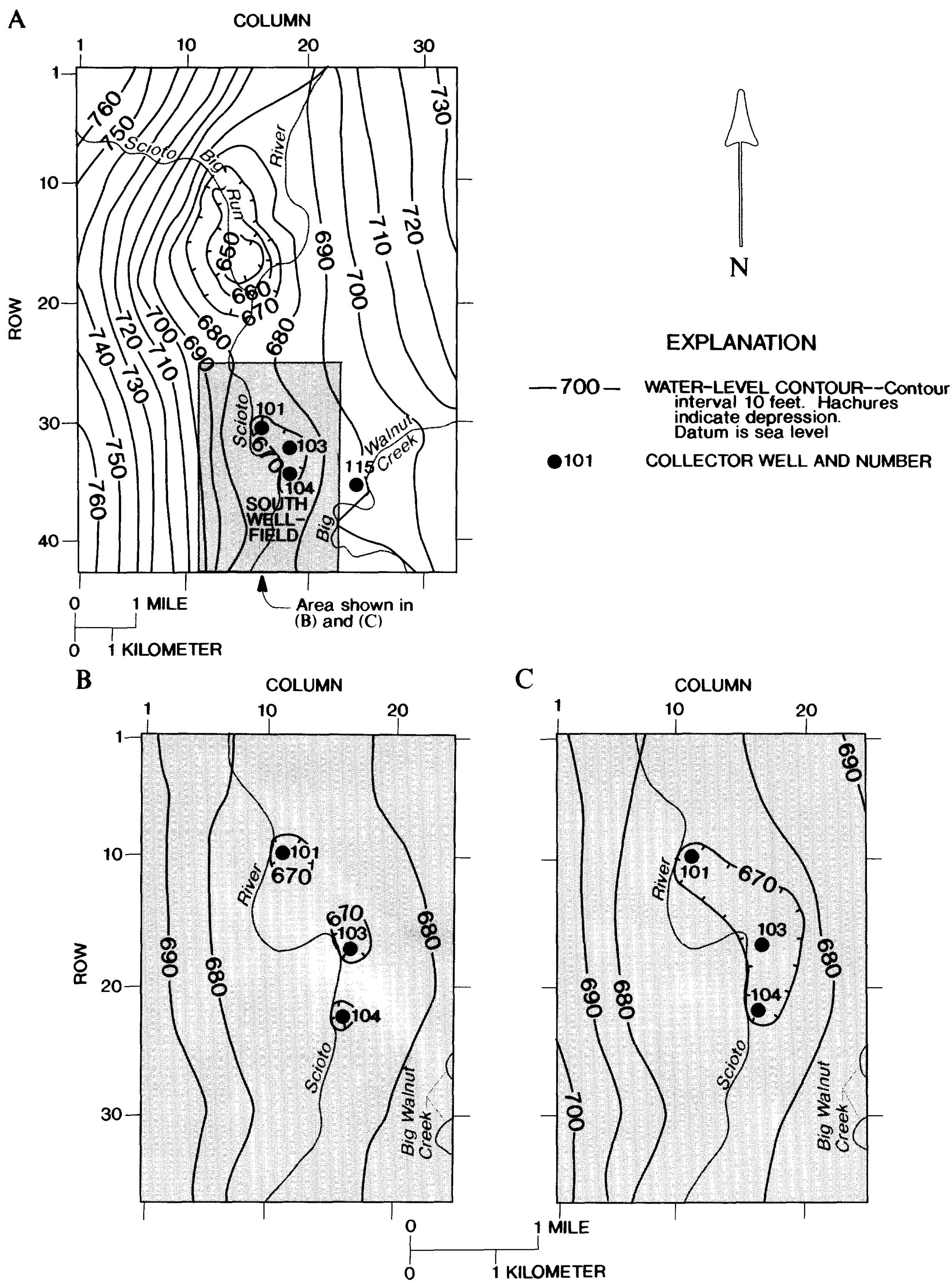
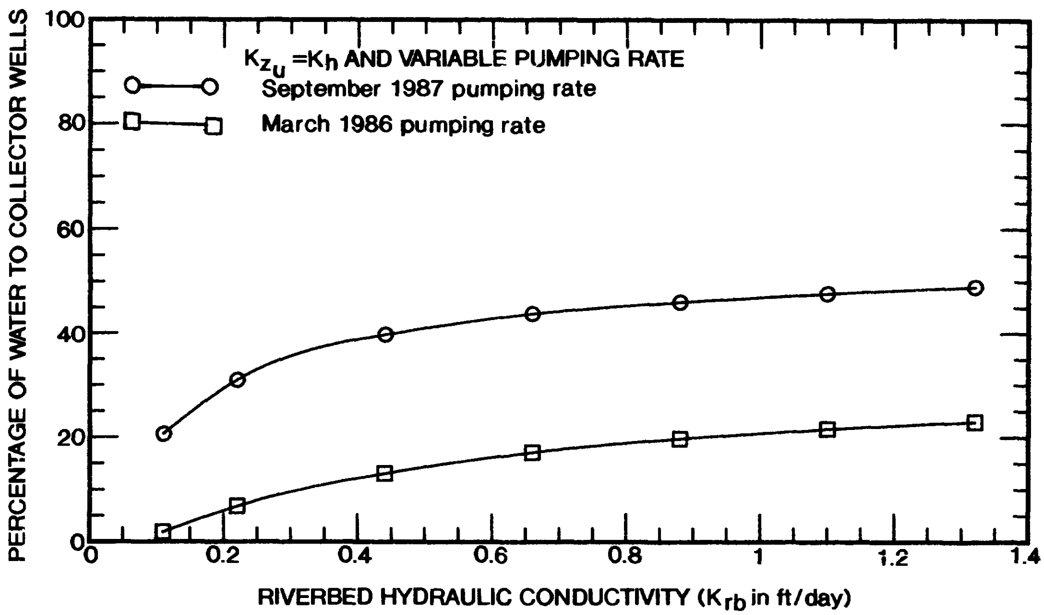


Figure 20.--Calibrated head distribution in the glacial drift aquifer for the (A) regional model area; (B) subregional model area, March 1986 pumping rates; and (C) subregional model area, September 1987 pumping rates.



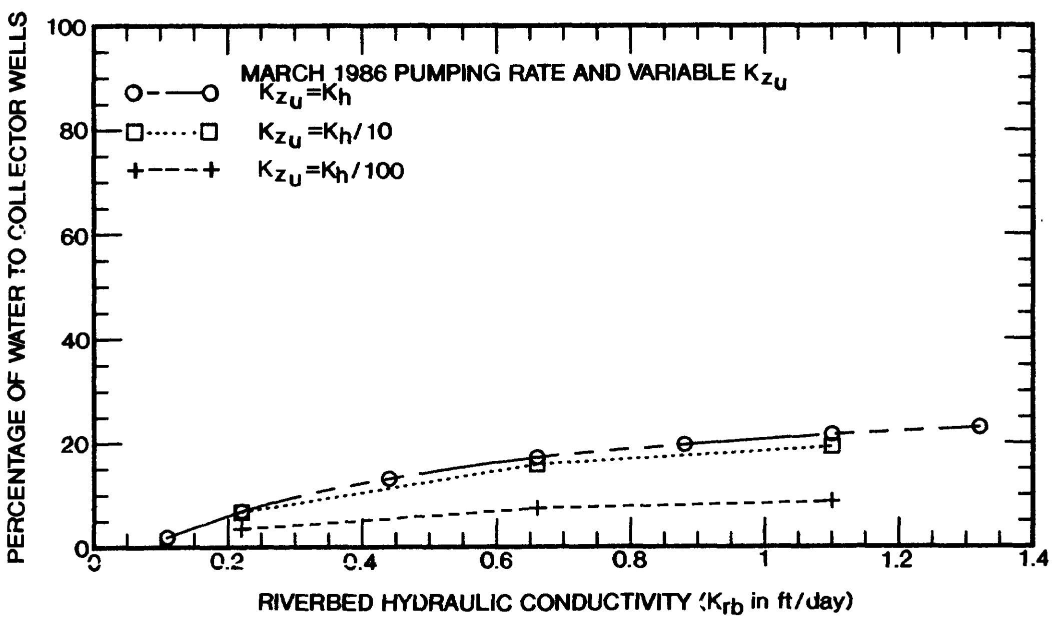


Figure 21.--Relation of the percentage of Scioto River water pumped from the collector wells to variations in riverbed hydraulic conductivity and vertical hydraulic conductivity of the upper glacial drift aquifer (K_{z_u}). K_h is the horizontal hydraulic conductivity of the upper glacial drift aquifer.

As pumpage increased to near the theoretical maximum, and the vertical hydraulic conductivity of the upper layer was decreased to 1/100 of the horizontal hydraulic conductivity, the simulations failed to converge because nodes at collector well 103 dried up. This effect is a result of the wells not getting enough water from the glacial drift and carbonate bedrock aquifers to fulfill the demand for water.

Other factors also affect the contribution of Scioto River water to the collector wells. The vertical hydraulic gradient across the riverbed between the river and the underlying glacial drift aquifer increases as river stage increases. Variations in the stage of Scioto River at the streamflow-gaging station at Columbus during the 1987 water year is shown in figure 22. Stage ranged from 685.33 to 697.88 ft above sea level. Hydraulic conductivity is a property of the porous medium and the transmitted fluids; thus, K_{rb} is greatest during the summer, when water is less viscous than at low temperatures. For example, a range in temperature of 28 °C (fig. 23) corresponds to a decrease in viscosity of the river water from 170 centipoise at 2 °C to 80 centipoise at 30 °C. Because hydraulic conductivity increases approximately 2.7 percent for every increase of 1 °C in temperature, within the practical range of surface-water temperatures, K_{rb} would decrease by a factor of approximately 75 percent.

Interaction of Scioto River and Ground Water

Three sources of water contribute to production from the collector wells--induced infiltration from Scioto River, induced upflow from the carbonate bedrock aquifer, and the glacial drift aquifer. The quantity provided by each source is controlled by the design of the wells and by the hydraulic gradients and hydraulic conductivities of the glacial drift aquifer, the carbonate bedrock aquifer, and the riverbed. The quality of the water produced by the collector wells depends on the proportion and water quality of the individual sources. Scioto River potentially has the most variable water quality because of changes in amount of runoff and quality of effluent from Jackson Pike WTF.

The design specifications indicate that the South Well Field should be capable of producing about 50 Mgal/d (Stilson and Associates, 1976). Typical pumpage from the four collector wells in 1990 was about 20 Mgal/d (William Eitel, City of Columbus, oral commun., 1990). During the drought in 1988, the well field was pumped at approximately 25 Mgal/d, a greater rate than had previously been used. Excessive drawdown in collector well 103 during the drought indicated that the capacity of the well field is less than 50 Mgal/d, perhaps as low as 30 Mgal/d.

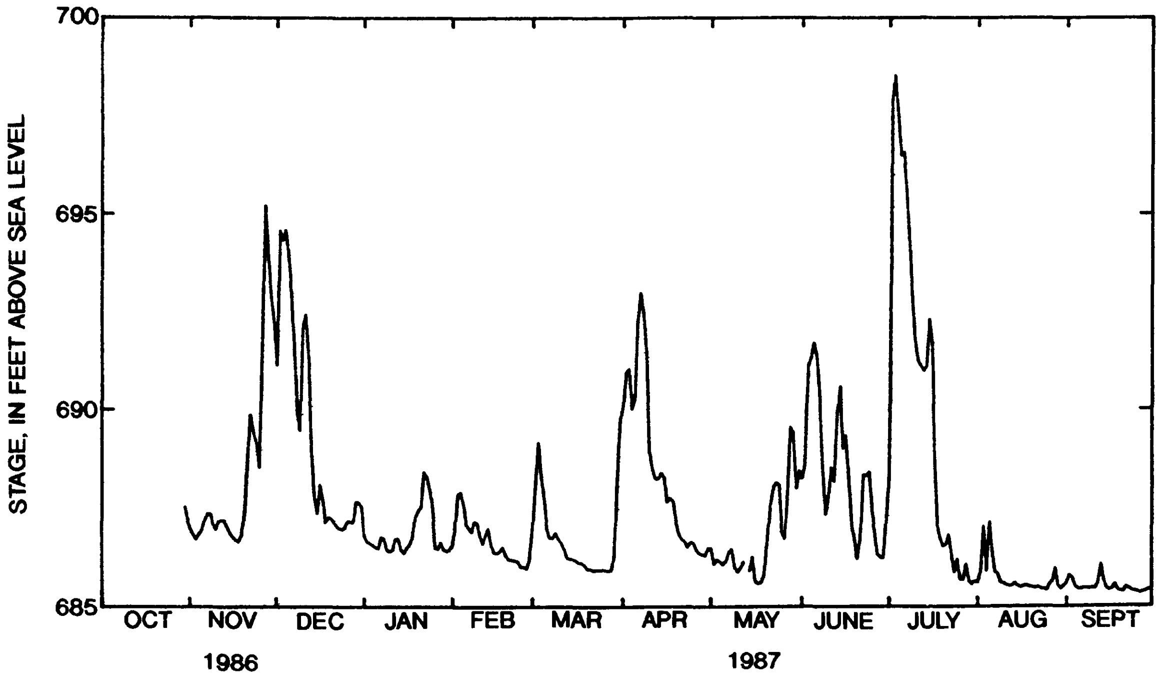


Figure 22.--Daily mean stage for Scioto River at Columbus, Ohio, 1987 water year.

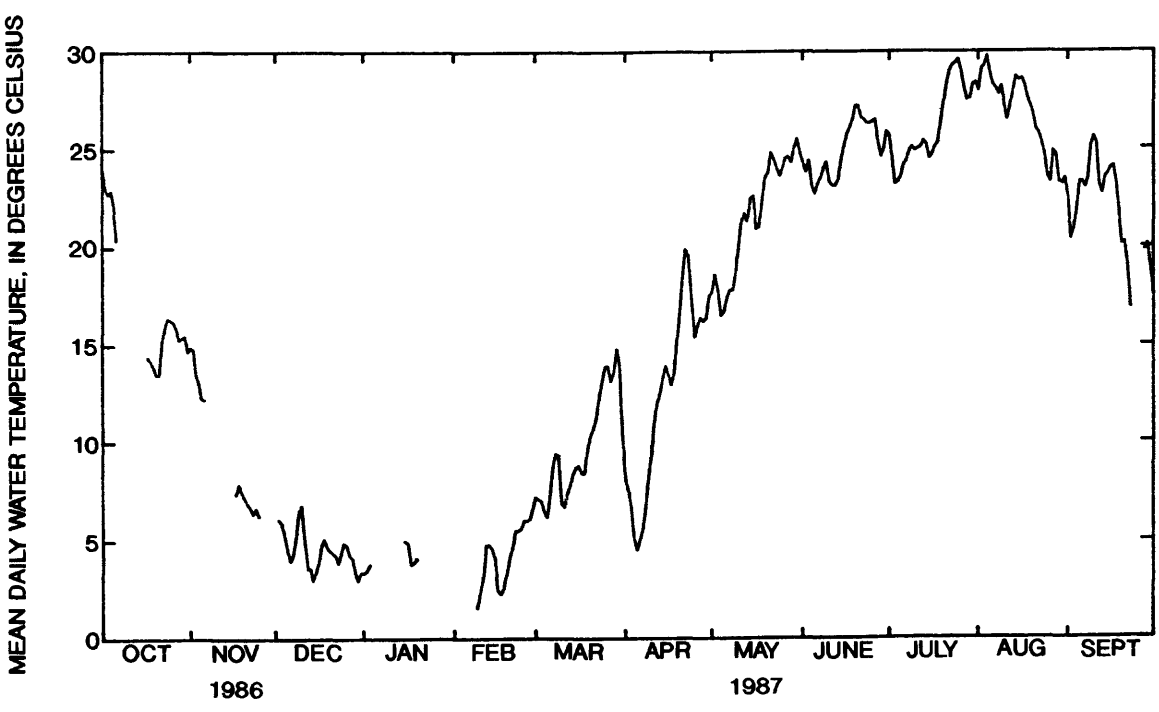


Figure 23.--Daily mean water temperature for Scioto River at Chillicothe, Ohio, 1987 water year.

Eberts and Bair (1990), using a two-layer ground-water model to examine cell-by-cell flow, calculated that approximately 13 percent of the water pumped from the collector wells was derived from induced stream infiltration; the rest was from the glacial drift and carbonate bedrock aquifers. This model was based on ground-water levels measured in March 1986, an average river stage of 4 ft for Scioto River, and a K_{rb} of 0.22 ft/d for the reach of Scioto River adjacent to the collector wells.

Subregional-model simulations of March 1986 and September 1987 pumping scenarios were used to quantify the relative contributions of these three sources by examining the computed cell-by-cell flow terms. Because the subregional model includes two layers to represent the glacial drift aquifer (fig. 16), stresses from wells could be assigned to a different layer than stresses from streams.

At the river nodes, the cell-by-cell flow through the bottom of layer 1 can be examined for the effects of induced infiltration by subtraction of flow that would normally enter the glacial drift aquifer (under historic or no-pumping conditions) from flow that would result from normal pumping of the collector wells. The resulting flow loss along the reach of Scioto River affected by the collector wells is then divided by the total pumping rate of the three collector wells to determine the percentage of collector-well pumpage derived from the river.

The contribution of water from the carbonate bedrock aquifer also can be calculated similarly. Unstressed flow through the bottom of layer two in the model (the glacial drift/bedrock interface) is subtracted from the flow calculated for cells affected by cell collector-well pumpage.

The contribution of water from the glacial drift aquifer is calculated by subtracting the calculated amounts from the river and the carbonate bedrock aquifer from the total pumpage at the collector wells.

The following table summarizes these calculations for March 1986 and September 1987 pumping scenarios.

Collector-well pumpage source	March 1986 Flow, in millions of gallons per day	March 1986 Percent	September 1987 Flow, in millions of gallons per day	September 1987 Percent
Scioto River-------	1.2	16	7.7	42
Carbonate bedrock aquifer----------	.7	9	1.3	7
Glacial drift aquifer----------	5.6	75	9.4	51
Total--------------	7.5	100	18.4	100

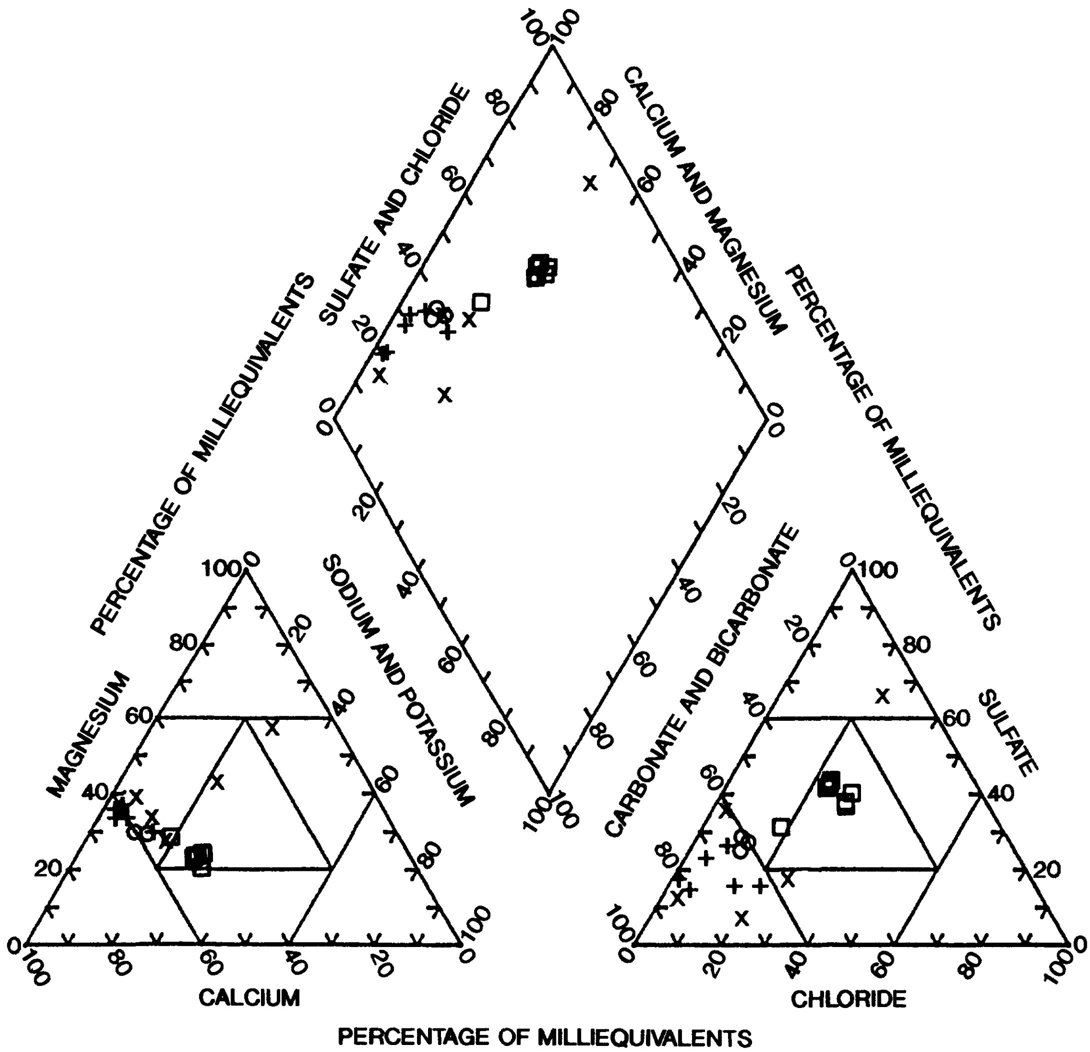
Results of the subregional steady-state model presented herein indicate that, for a range in pumping rate of 7.5 to 18.4 Mgal/d, approximately 16 to 42 percent of the water pumped by the collector wells is derived from induced stream infiltration, 51 to 75 percent is derived from underflow in the glacial-drift aquifer, and 7 to 9 percent is derived from upflow from the carbonate bedrock aquifer, respectively. These estimates are based solely on hydrologic modeling by use of the water-level, river-stage, and K_{rb} data previously discussed. The pumpage attributed to induced infiltration from Scioto River under the March 1986 pumping scenario (7.5 Mgal/d) agrees well with the proportion of 13 percent calculated by Eberts and Bair (1990) under the same pumping rate. An increase in total pumpage resulted in an increase in induced infiltration.

Corroboration of ground-water-flow model results was sought by use of water-quality data (tables 1 and 2) collected as part of this study. In a previous study (de Roche and Razem, 1984), a model of the chemical reactions between minerals and water indicated that 80 percent of the water pumped from the collector wells was derived from the glacial drift aquifer, whereas 20 percent was derived from Scioto River. The collector wells were pumped at a rate of 10.3 Mgal/d. This analysis did not account for upflow (vertical leakage) from the underlying carbonate bedrock aquifer as a possible source of water.

On the basis of constraints imposed by the hydraulics of the ground-water-flow system in the area of the well field, water chemistry of collector-well pumpage is believed to be controlled by a two-step mixing of three water types (fig. 24). In the first step, river water mixes with water in the glacial drift aquifer. In the second step, this mixture combines with water flowing upward from the carbonate bedrock aquifer before entering the laterals of the collector wells.

These processes are limited to the area surrounding the well field where water flows upward from the carbonate bedrock aquifer to the glacial drift aquifer and to areas along Scioto River where leakage is downward through the riverbed into the glacial drift aquifer. The areas of flow are centered on the collector wells where vertical hydraulic gradients are the largest and decrease outward; thus, areas of upflow correspond to the cone of depression associated with each collector well.

This two-step mixing model, if it is a correct interpretation of the hydrodynamic processes controlling water chemistry near the collector wells, can be examined by use of plots of conservative-ion concentration from samples representing each step of the mixing process. In the first step (fig. 25), water from Scioto River mixes with water from the glacial drift aquifer near the collector wells. Water from the glacial drift aquifer near the collector wells is mixed with river water,



EXPLANATION

X CARBONATE BEDROCK AQUIFER

\+ GLACIAL DRIFT AQUIFER

□ SCIOTO RIVER

O COLLECTOR WELLS

Figure 24.--Relative concentrations of major anions and cations in waters from glacial drift and carbonate bedrock aquifers, the collector wells, and Scioto River.

whereas water from the glacial drift aquifer distant from the collector wells is unmixed glacial drift aquifer water; thus, the composition of glacial drift aquifer water from wells near the collector wells should be intermediate compared with that of glacial drift aquifer water from wells distant from the collector wells and that of water from Scioto River.

In the second step (figs. 26 and 27), the mixed glacial drift aquifer and river water produced in step one mixes with water from the carbonate bedrock aquifer. Thus, the composition of water from the collector well should be intermediate compared with the composition of water from the carbonate bedrock aquifer and from the glacial drift aquifer near the collector wells.

Concentrations of two conservative constituents, sodium and chloride, illustrate this mixing process. In the first step (fig. 25), samples collected from Scioto River near the collector wells and wells FR-73 and FR-120--completed in the glacial drift aquifer distant from the collector wells--are the mixing components. Samples from wells FR-147 and FR-TH73--completed in the glacial drift aquifer near collector wells 101 and 104, respectively--are the mixing product.

The mixing product should fall approximately on the straight line drawn between the two mixing components. The contribution that each mixing component makes to the mixing product is proportional to the distance, along the line, from each mixing component to the mixing product. Samples from the glacial drift aquifer near the collector wells contain approximately 7 and 30 percent river water, respectively (fig. 25).

Mixing product	Approximate percentage contribution from each mixing component	
	Scioto River	Glacial drift aquifer
FR-147 (near collector well 101)-------------	30	70
FR-TH73 (near collector well 104)-------------	7	93

These ratios are consistent with the measured K_{rb} data, which indicates that the vertical hydraulic conductivity of the Scioto River bed is greater near collector well 101 than near collector well 104.

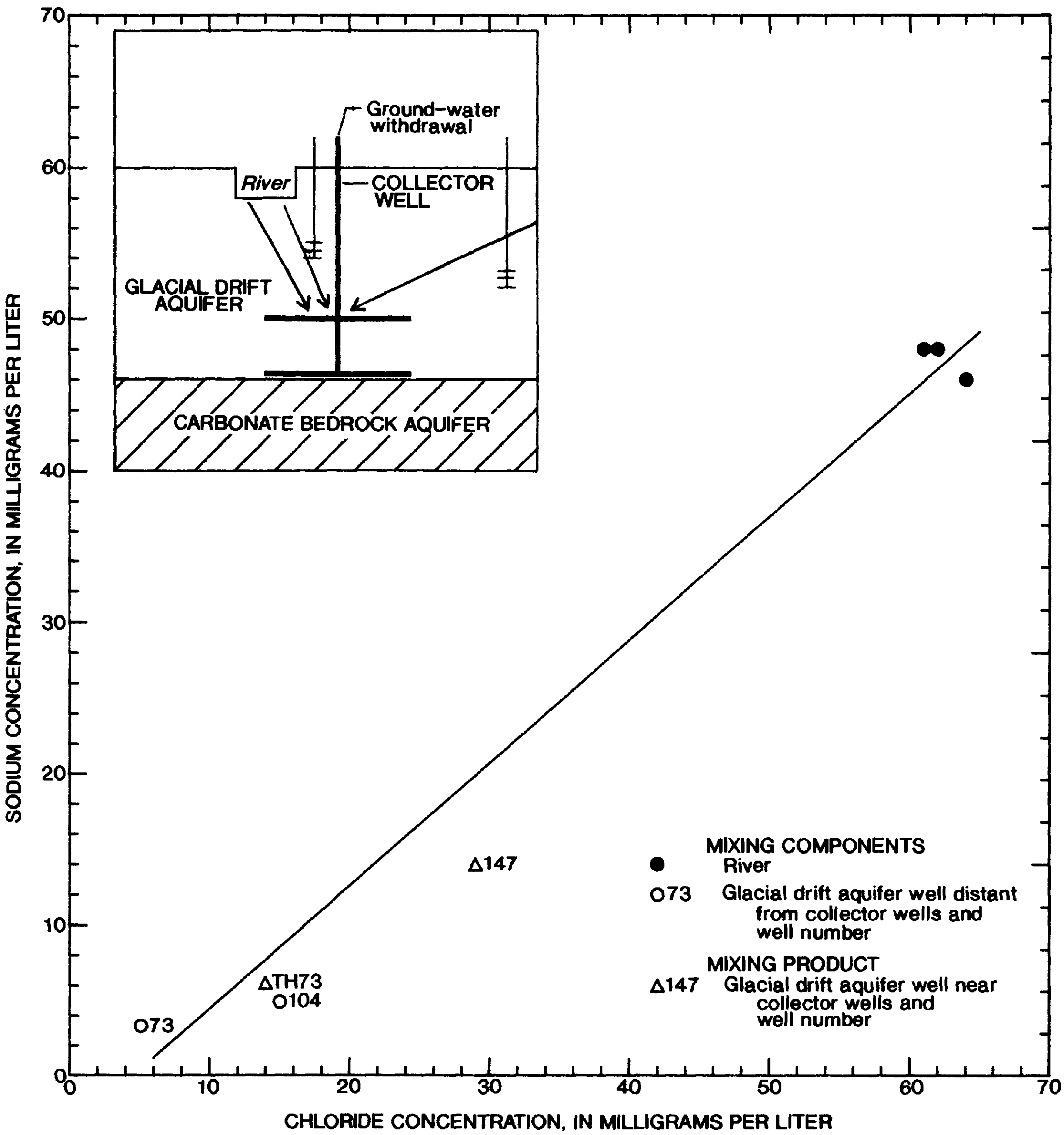


Figure 25.--First stage of chloride and sodium mixing in waters from the glacial drift aquifer distant from the collector wells and Scioto River and a schematic diagram showing the mixing process, wells, and flow lines.

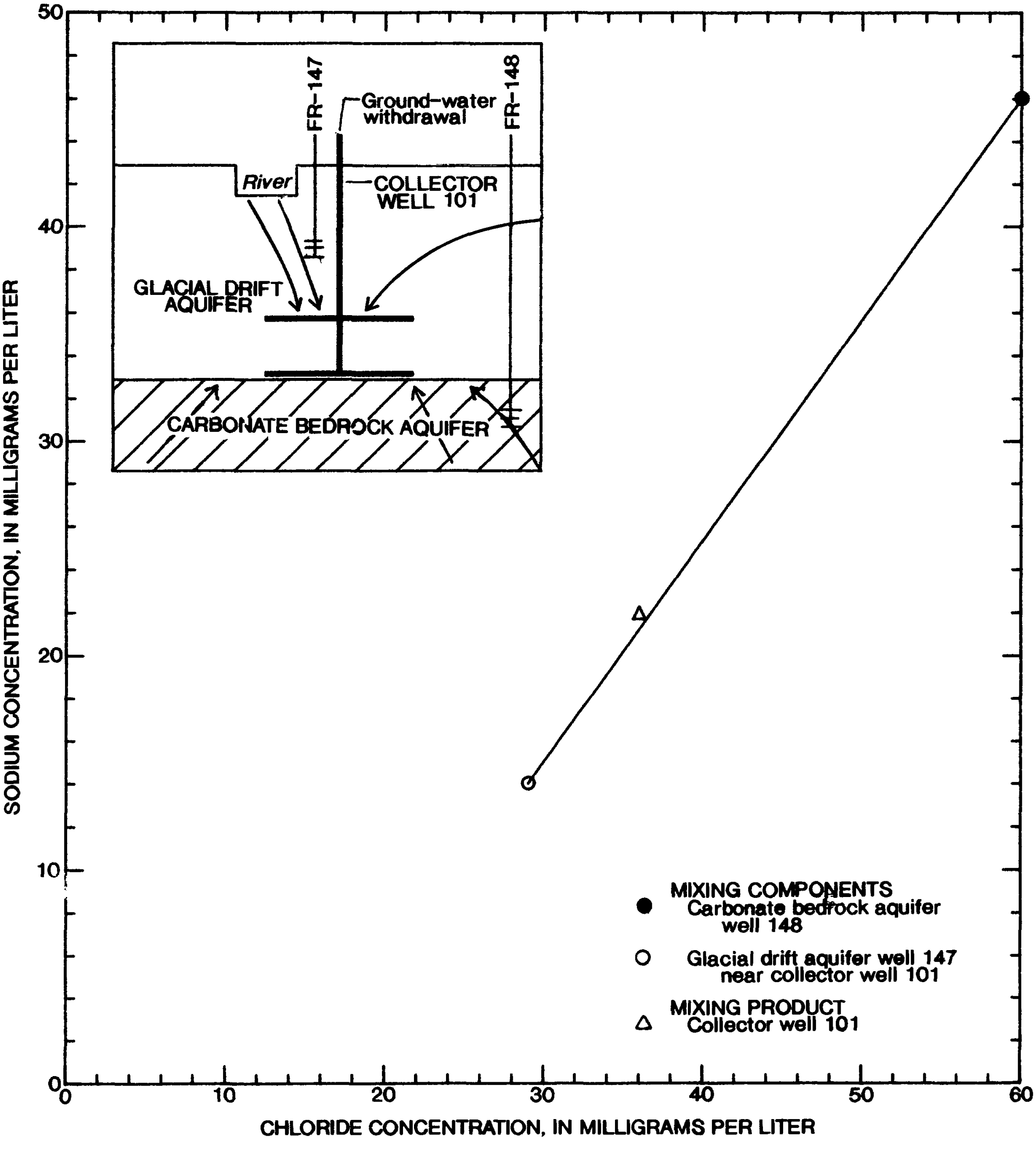


Figure 26.--Second stage of chloride and sodium mixing in waters of the carbonate bedrock and glacial drift aquifers near collector well 101 and a schematic diagram showing the mixing process, wells, and flow lines.

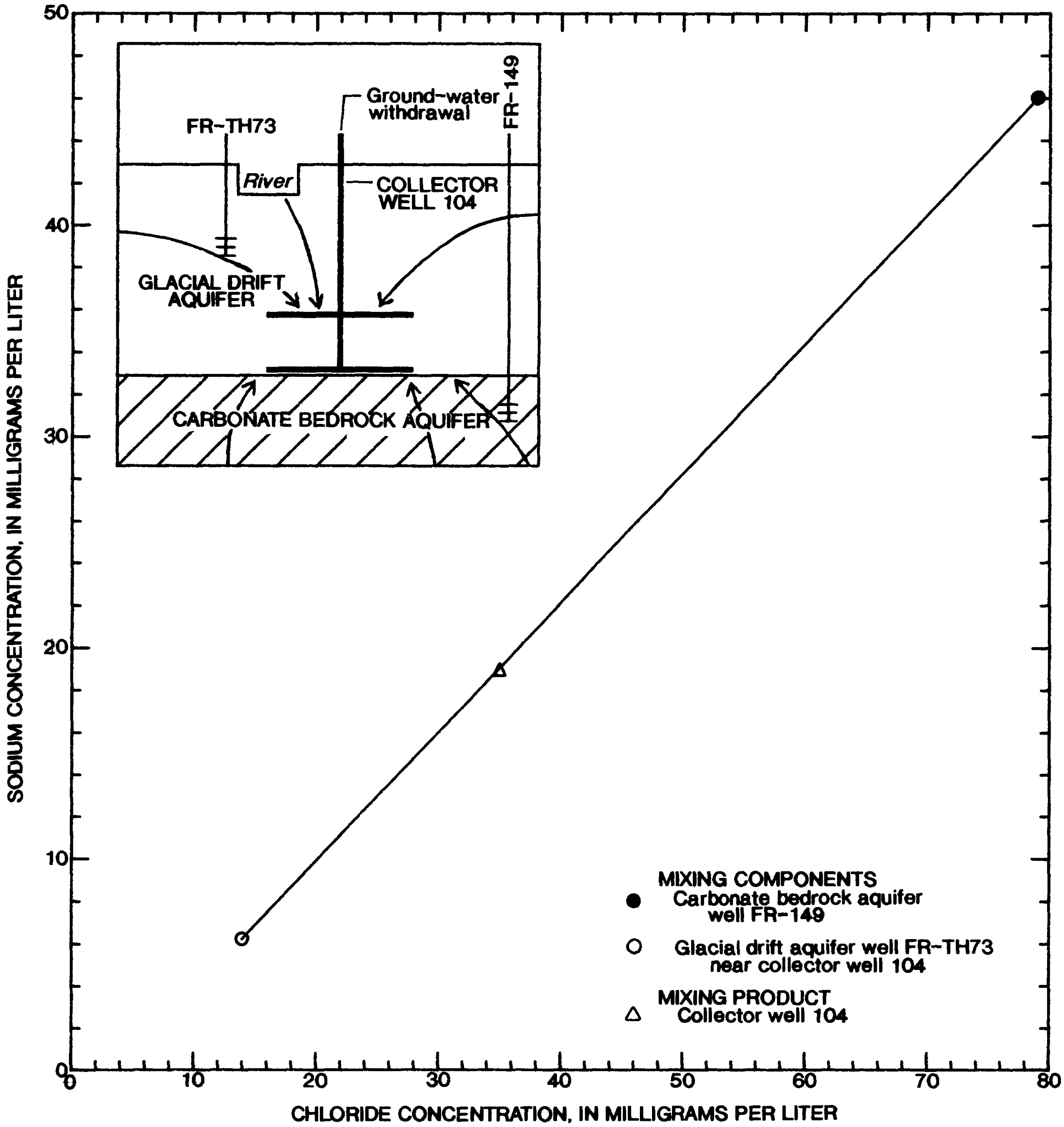


Figure 27.--Second stage of chloride and sodium mixing in waters of the carbonate bedrock and glacial drift aquifers near collector well 104 and a schematic diagram showing the mixing process, wells, and flow lines.

In the second step of the mixing process, upward-flowing water from the carbonate bedrock aquifer is mixed with mixed Scioto River/glacial drift aquifer water. Results of the mixing analysis for water from collector well 101 (fig. 26) and collector well 104 (fig. 27) are shown below.

Mixing product	Approximate percentage contribution from each mixing component	
	Carbonate bedrock aquifer	Glacial drift aquifer/ river mixture
Collector well 101------	23	77
Collector well 104------	32	68

The percentage of collector-well water that originates from each of the three potential sources can be derived by combining the results of the two mixing steps, as shown in the following table.

Water source	Approximate percentage of collector-well water from each source, by calculation method (pumping rate[1], in millions of gallons per day)			
	Chemical mixing	Sub-regional ground-water-flow model		Regional ground-water-flow model
	(15.8)	(18.4)	(7.5)	(7.5)
Scioto River----------------	5-23	42	16	13
Glacial drift aquifer-------	54-63	51	75	--
Carbonate bedrock aquifer---	23-32	7	9	--

[1] Combined pumping rate for collector wells 101, 103, and 104.

The mixing analysis generally corroborates the proportion of pumpage from the glacial drift aquifer that was predicted by the ground-water-flow model; however, the mixing analysis indicates more pumpage from the carbonate bedrock aquifer than does the ground-water-flow model. Some of the difference can be attributed to differences in pumping rate; sources of error associated with each calculation method also could be significant. For example, few wells are completed in the carbonate bedrock aquifer in southern Franklin County. Water analyses that are available to characterize water quality in the carbonate bedrock aquifer differed considerably in chemical character (fig. 24). In addition, the values for vertical hydraulic conductivity between the carbonate bedrock and glacial drift aquifers are based on simulated values taken from Sedam and others (1989) and have not been verified in the field.

SUMMARY AND CONCLUSIONS

At present (1990), about 15 percent of the total water supply for the City of Columbus, Ohio, is provided by ground-water withdrawals from the South Well Field in southern Franklin County. Four radial collector wells, completed in the glacial drift aquifer along Scioto River (three wells) and Big Walnut Creek (one well), are designed to induce stream infiltration. Much of the flow of Scioto River at the South Well Field originates from the Jackson Pike Wastewater Treatment Facility one of two municipal wastewater-treatment plants operated by the City of Columbus. The Jackson Pike WTF discharges effluent into Scioto River about 6 miles upstream from the South Well Field.

Simulations of surface-water transport and ground-water flow were examined along with surface-water and ground-water quality to describe the relation between the quantity and quality of flow in Scioto River; the nature of the ground-water-flow system; and the quantity, quality, and sources of water pumped from the South Well Field.

Under low-flow conditions, Scioto River above the Jackson Pike WTF receives discharge primarily from the glacial drift aquifer. The river below the Jackson Pike WTF is dominated by effluent from the plant, as evidenced by a marked increase in concentrations of dissolved solids, chloride, sodium, nitrate, phosphorus, and several trace elements.

The surface-water transport of a conservative substance was modeled by use of the one-dimensional Lagrangian transport model. The study area was discretized into 11 unevenly spaced grids. Three point sources of inflow were identified--the Jackson Pike WTF, the quarry, and Scioto Big Run. There were no significant nonpoint sources, but a nonpoint sink of 0.00078 $(ft^3/s)/ft$ was measured in Scioto River near the collector wells. This sink represents a loss of approximately 6.5 Mgal/d over a 2.1-mile-long segment.

Traveltimes, under varying flow conditions, were examined by use of the model. At a discharge of 93 ft^3/s from the Jackson Pike WTF, traveltime in Scioto River from Frank Road to the South Well Field during a 7-day, 2-year low-flow period would be 35 hours. If the Jackson Pike WTF discharged no effluent, traveltime would increase to approximately 94 hours.

Ground water in the study area is classified as hard, calcium bicarbonate-type water. Concentrations of trace metals generally are below detection levels, and the combined concentration of all nitrogen species generally is less than 1 mg/L. On the basis of relative percentage of major cations and anions, ground waters from the carbonate bedrock aquifer can be distinguished from ground waters from the glacial drift aquifer by their greater dissolved-solids, sulfate, and calcium concentrations.

The dynamics of the ground-water-flow system were simulated by use of a three-dimensional finite-difference flow model. The three components of ground-water flow--leakage from Scioto River, lateral flow within the glacial drift aquifer, and upflow from the carbonate bedrock aquifer into the glacial drift aquifer--were modeled for an area of approximately 7.7 mi^2 near the collector wells. The model was calibrated to steady state by use of water levels measured in March 1986 and historic (pre-1967) water levels.

Simulations of ground-water flow for two different pumping rates show that 7 to 9 percent of the pumpage from three collector wells in the South Well Field originates from the carbonate bedrock aquifer, 51 to 75 percent originates from the glacial drift aquifer, and 16 to 42 percent originates from Scioto River. A sensitivity analysis of model input parameters shows that, at increased pumping rates, the proportion of pumpage that is derived from the river is increased. In addition, when vertical hydraulic conductivity of the riverbed (K_{rb}) is less than 0.5 ft/d, the quantity of infiltration from the river significantly increases. An increase in K_{rb} at values greater than 0.5 ft/d does not result in a significant increase in infiltration from the river. Variations in river stage and water temperature also can significantly affect the contribution of water from the river to the collector wells.

A mixing analysis of collector-well pumpage generally corroborates the percentage contributions derived from the ground-water-flow model for the glacial drift aquifer and Scioto River. A two-step mixing analysis shows that approximately 50 to 60 percent of pumpage was derived from the glacial drift aquifer and 5 to 25 percent was derived from Scioto River. At the time that water-quality samples were collected in August 1987, the pumping rate from the collector wells was approximately 15.8 Mgal/d. The contribution from the carbonate bedrock aquifer, 23 to 32 percent, is greater than that calculated by the ground-water-flow model. This difference could be due to a combination of factors, including variable data on chemical quality of the carbonate bedrock aquifer and uncertainties associated with estimates of vertical hydraulic conductivity of the glacial drift and carbonate bedrock aquifers.

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Table 1.--Surface-water-quality and discharge data collected at sites on Scioto River and tributaries, Frank Road to Southerly Wastewater Treatment Facility, August 1987 and 1988

[°C, degrees Celsius; ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; mL, milliliter; µg/L, micrograms per liter; --, missing data; K, based on a nonideal colony count; <, less than the detection limit; WTF, wastewater-treatment facility; N, nitrogen; E, estimated]

Date	Time	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Air temperature (°C)	Water temperature (°C)	Dissolved oxygen (mg/L)	Fecal coliform bacteria (colonies per 100 mL)	Total hardness (mg/L as $CaCO_3$)	Total noncarbonate hardness (mg/L as $CaCO_3$)
Site 1--Scioto R at Frank Rd										
Aug 1987										
18...	0630	73	550	8.1	17.0	24.5	4.2	K1100	230	88
Aug 1988										
25...	0645	74	525	7.8	17.0	23.0	3.2	--	200	94
Site 2--Jackson Pike WTF outfall										
Aug 1987										
18...	0820	114	980	7.4	22.0	24.5	4.1	K2	250	83
Aug 1988										
25...	0820	77	880	7.8	18.0	25.0	6.4	--	230	110
Site 2a--American Aggregates quarry discharge										
Aug 1988										
25...	1000	--	1840	8.1	--	26.0	--	--	980	820
Site 3--Scioto R below Jackson Pike WTF										
Aug 1987										
18...	1630	201	950	7.6	29.5	29.0	5.5	K30	330	180
Aug 1988										
25...	1540	175	--	8.0	30.0	27.5	7.9	--	310	190
25...	0715	164	850	7.4	20.0	22.0	4.1	--	310	190
Site 4--Kian Run										
Aug 1987										
18...	1230	0.80	700	8.0	29.5	18.5	7.7	660	260	140
Site 5--Scioto R 2.4 mi below Frank Road										
Aug 1987										
18...	2145	207	790	7.0	--	27.0	5.4	--	330	170
Aug 1988										
25...	2030	186	850	8.0	25.5	26.0	6.5	--	330	210
25...	1200	168	770	7.6	27.0	22.0	5.1	--	310	190
Site 5a--Scioto R at Interstate Route 270 south										
Aug 1987										
19...	0345	206	910	6.8	17.0	24.5	4.7	--	330	180
Aug 1988										
25...	1715	157	860	8.0	28.0	23.0	8.6	--	310	190
Site 6--Scioto Big Run										
Aug 1987										
19...	0415	6.6	1050	7.4	16.0	21.5	6.7	--	500	220
Aug 1988										
25...	1515	9.0	860	7.8	24.0	23.0	8.6	--	330	160
Site 7--Scioto R below Scioto Big Run										
Aug 1987										
18...	0630	208	840	6.9	23.0	25.5	5.9	K100	300	150

Dissolved calcium (mg/L)	Dissolved magnesium (mg/L)	Dissolved sodium (mg/L)	Dissolved potassium (mg/L)	Alkalinity, (mg/L as $CaCO_3$)	Bicarbonate, (mg/L as $CaCO_3$)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved fluoride (mg/L)	Dissolved bromide (mg/L)
59	19	20	4.6	--	--	83	34	0.50	<0.010
48	19	27	3.4	106	129	80	39	.30	.024
73	15	75	12	--	--	120	110	1.0	.52
62	17	86	10	114	139	130	96	.90	.87
260	78	55	5.1	158	193	810	100	1.1	.60
93	23	57	9.2	--	--	190	93	.90	.32
80	25	54	7.4	117	143	190	69	.70	.32
82	26	51	6.7	123	150	190	67	.60	.41
71	21	42	3.4	--	--	140	57	.80	.048
92	23	56	9.1	--	--	180	92	.90	.33
86	27	55	7.2	115	140	200	70	.70	.36
80	25	50	6.5	120	146	190	65	.60	.45
92	23	56	9.2	--	--	170	92	.90	--
82	26	49	6.3	128	156	190	63	.60	.42
130	43	51	6.7	--	--	220	90	.30	.17
87	27	36	4.4	168	205	150	57	.30	.086
80	24	47	7.9	--	--	180	63	.70	.50

Table 1.--Surface-water-quality and discharge data collected at sites on Scioto River and tributaries, Frank Road to Southerly Wastewater Treatment Facility, August 1987 and 1988--Continued

Date	Dissolved silica (mg/L)	Dissolved solids residue at 180 °C (mg/L)	Dissolved NO_2+NO_3 (mg/L as N)	Dissolved ammonia (mg/L as N)	Dissolved ammonia plus organic N (mg/L as N)	Dissolved phosphorus (mg/L)	Dissolved barium (µg/L)	Dissolved beryllium (µg/L)	Dissolved boron (µg/L)	Dissolved cadmium (µg/L)
Site 1--Scioto R at Frank Road										
Aug 1987										
18...	3.8	334	0.100	0.070	0.80	0.030	43	<0.5	160	<1
Aug 1988										
25...	3.2	317	.600	.370	1.0	.070	51	.5	70	1
Site 2--Jackson Pike WTF outfall										
Aug 1987										
18...	10	529	4.10	8.00	13	5.60	19	<.5	280	<1
Aug 1988										
25...	8.5	556	9.50	.100	1.9	4.20	25	.8	210	1
Site 2a--American Aggregates quarry discharge										
Aug 1988										
25...	.17	1530	<.100	.080	.80	.021	25	<.5	320	5
Site 3--Scioto R below Jackson Pike WTF										
Aug 1987										
18...	6.8	574	3.20	5.40	10	1.80	31	<.5	230	1
Aug 1988										
25...	4.8	537	3.80	.180	.70	1.80	37	<.5	150	<1
25...	4.8	539	3.60	.290	.90	1.40	90	<.5	150	<1
Site 4--Kian Run										
Aug 1987										
18...	10	427	<.100	.080	.50	.040	27	<.5	90	2
Site 5--Scioto R 2.4 mi below Frank Road										
Aug 1987										
18...	6.6	582	3.30	5.40	5.4	2.10	30	<.5	230	<1
Aug 1988										
25...	4.7	566	3.90	.130	.90	1.70	38	<.5	160	2
25...	4.7	542	3.40	.220	.50	1.30	42	<.5	150	<1
Site 5a--Scioto R at Interstate Route 270 south										
Aug 1987										
19...	6.6	527	3.20	5.00	5.4	2.30	31	<.5	--	<1
Aug 1988										
25...	4.9	527	3.00	.140	.90	1.10	44	<.5	140	<1
Site 6--Scioto Big Run										
Aug 1987										
19...	10	754	.910	.340	1.1	.090	100	<.5	170	<1
Aug 1988										
25...	7.2	492	--	--	1.0	.040	79	<.5	100	1
Site 7--Scioto R below Scioto Big Run										
Aug 1987										
18...	6.2	509	3.40	3.80	4.5	2.50	33	<.5	190	<1

Dis- solved cobalt (µg/L)	Dis- solved copper (µg/L)	Dis- solved iron (µg/L)	Dis- solved lead (µg/L)	Dis- solved lithium (µg/L)	Dis- solved manga- nese (µg/L)	Dis- solved molyb- denum (µg/L)	Dis- solved stron- tium (µg/L)	Dis- solved vana- dium (µg/L)	Dis- solved zinc (µg/L)
<3	<10	25	<10	13	6	<10	1200	<6	16
<3	20	14	<10	7	38	10	1700	<6	34
<3	10	59	<10	43	40	20	870	<6	65
<3	20	59	<10	68	5	50	840	<6	100
<3	10	7	<10	62	12	<10	8500	<6	30
<3	<10	37	<10	25	29	20	1900	<6	63
<3	<10	14	<10	33	20	20	2200	<6	37
<3	<10	31	<10	43	22	20	2200	<6	45
<3	10	21	10	10	56	10	340	<6	62
<3	<10	28	<10	27	29	20	1900	<6	41
<3	<10	8	10	37	13	20	2300	<6	35
<3	<10	92	<10	45	25	20	2200	<6	53
<3	<10	29	<10	26	28	20	1900	<6	40
<3	<10	22	<10	42	13	20	2100	<6	36
<3	<10	17	<10	16	36	10	2500	<6	11
<3	<10	19	<10	10	20	10	1500	<6	6
<3	<10	28	<10	15	22	10	1800	<6	37

Table 1.--Surface-water-quality and discharge data collected at sites on Scioto River and tributaries, Frank Road to Southerly Wastewater Treatment Facility, August 1987 and 1988--Continued

Date	Time	Discharge (ft^3/s)	Specific conductance (µS/cm)	pH	Air temperature (°C)	Water temperature (°C)	Dissolved oxygen (mg/L)	Fecal coliform bacteria (colonies per 100 mL)	Total hardness (mg/L as $CaCO_3$)	Total noncarbonate hardness (mg/L as $CaCO_3$)
Site 8--Scioto R below Interstate Route 270 south										
Aug 1987										
18...	1000	207	820	7.6	24.0	24.5	--	560	300	150
Aug 1988										
25...	2100	--	787	8.0	21.0	--	--	--	310	180
Site 8a--Unnamed tributary to Scioto R										
Aug 1987										
18...	0845	.23	740	6.5	--	20.5	6.8	140	360	89
Site 9--Scioto R at CW-101										
Aug 1987										
18...	1140	198	810	6.9	--	25.5	4.6	--	310	160
Aug 1988										
26...	0300	147	780	7.8	18.0	23.0	8.6	--	320	200
Site 9a--Grant Run										
Aug 1987										
18...	1400	.0	--	--	--	--	--	--	--	--
Site 10--Scioto R near CW-103										
Aug 1987										
18...	1445	178	800	7.2	32.0	27.5	6.3	200	300	160
Aug 1988										
26...	0650	171	792	7.8	19.0	21.0	9.7	--	320	180
Site 11--Scioto R at CW-104										
Aug 1987										
18...	0630	203	860	7.5	18.0	25.0	2.2	K86	320	180
18...	1715	187	790	7.0	31.0	27.5	8.6	--	310	160
Aug 1988										
26...	0830	134	--	7.8	19.0	23.0	5.6	--	320	190
Site 12--Scioto R at Shadeville										
Aug 1987										
18...	0830	208	860	7.5	20.0	25.0	8.6	K150	310	160
Aug 1988										
26...	1130	E134	--	8.0	--	24.0	7.2	--	320	200
Site 13--Scioto R near Shadeville										
Aug 1987										
18...	0945	203	860	7.5	22.0	25.5	3.9	K30	320	160
Site 14--Scioto R above Columbus Southerly WTF outfall										
Aug 1987										
18...	1230	197	850	7.5	24.0	26.0	3.8	100	310	170
Site 14a--Plum Run										
Aug 1987										
18...	1345	.16	780	8.1	28.0	24.0	8.8	280	380	100

Dissolved calcium (mg/L)	Dissolved magnesium (mg/L)	Dissolved sodium (mg/L)	Dissolved potassium (mg/L)	Alkalinity (mg/L as $CaCO_3$)	Bicarbonate (mg/L as $CaCO_3$)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved fluoride (mg/L)	Dissolved bromide (mg/L)
80	24	46	7.9	--	--	170	62	0.70	0.50
81	26	48	6.4	--	--	190	63	.50	.53
94	30	23	2.8	--	--	99	36	.40	<.010
81	25	48	7.8	--	--	180	62	.70	.52
84	26	49	6.3	115	140	190	64	.60	.40
--	--	--	--	--	--	--	--	--	--
81	24	48	8.2	--	--	170	61	.70	.53
83	26	49	6.3	135	165	180	64	.50	98
87	25	46	8.2	--	--	190	64	.70	1.0
82	24	47	7.5	--	--	190	62	.70	.57
83	26	49	6.3	128	156	190	64	.50	.40
83	24	46	7.7	--	--	170	88	.60	1.0
84	27	50	6.3	127	155	190	65	.50	.40
86	24	45	8.1	--	--	180	63	.70	1.0
85	24	46	8.2	--	--	180	63	.70	1.2
97	34	9.3	2.2	--	--	63	28	.40	.014

Table 1.--Surface-water-quality and discharge data collected at sites on Scioto River and tributaries, Frank Road to Southerly Wastewater Treatment Facility, August 1987 and 1988--Continued

Date	Dis- solved silica (mg/L)	Dis- solved residue at 180 °C (mg/L)	Dis- solved NO_2+NO_3 (mg/L as N)	Dis- solved ammonia (mg/L as N)	Dis- solved ammonia plus or- ganic N (mg/L as N)	Dis- solved phos- phorus (mg/L)	Dis- solved barium (μg/L)	Dis- solved beryl- lium (μg/L)	Dis- solved boron (μg/L)	Dis- solved cadmium (μg/L)
Site 8--Scioto R below Interstate Route 270 south										
Aug 1987										
18...	6.2	519	3.30	3.70	3.8	2.50	33	<0.5	190	<1
Aug 1988										
25...	4.7	513	2.80	.070	.80	1.10	53	<.5	140	2
Site 8a--Unnamed tributary to Scioto R										
Aug 1987										
18...	5.5	467	<.100	.080	.40	.020	100	<.5	50	<1
Site 9--Scioto R at CW-101										
Aug 1987										
18...	6.1	522	3.50	3.40	3.6	2.40	35	<.5	190	<1
Aug 1988										
26...	4.7	530	3.00	.080	.60	1.10	48	<.5	140	<1
Site 9a--Grant Run										
Aug 1987										
18...	--	--	--	--	--	--	--	--	--	--
Site 10--Scioto R near CW-103										
Aug 1987										
18...	5.8	536	3.60	3.20	3.6	2.50	34	<.5	190	<1
Aug 1988										
26...	4.6	530	3.00	.070	.90	1.10	47	<.5	140	<1
Site 11--Scioto R at CW-104										
Aug 1987										
18...	6.2	517	3.80	3.90	4.3	2.60	34	<.5	190	<1
18...	5.3	519	4.10	2.70	3.8	2.40	34	<.5	200	<1
Aug 1988										
26...	4.4	524	--	--	.60	1.10	47	<.5	140	<1
Site 12--Scioto R at Shadeville										
Aug 1987										
18...	6.0	546	3.80	3.90	4.2	2.70	33	<.5	100	<1
Aug 1988										
26...	4.3	536	--	--	.60	1.10	47	<.5	150	<1
Site 13--Scioto R near Shadeville										
Aug 1987										
18...	6.0	514	3.80	3.80	3.9	2.60	34	<.5	190	<1
Site 14--Scioto R above Columbus Southerly WTF outfall										
Aug 1987										
18...	5.7	522	3.80	3.70	4.1	2.50	34	<.5	200	<1
Site 14a--Plum Run										
Aug 1987										
18...	12	418	1.40	.090	.50	.040	170	<.5	30	<1

Dissolved cobalt (µg/L)	Dissolved copper (µg/L)	Dissolved iron (µg/L)	Dissolved lead (µg/L)	Dissolved lithium (µg/L)	Dissolved manganese (µg/L)	Dissolved molybdenum (µg/L)	Dissolved strontium (µg/L)	Dissolved vanadium (µg/L)	Dissolved zinc (µg/L)
<3	<10	25	<10	15	32	20	1700	<6	19
<3	10	37	<10	40	14	10	2000	<6	54
<3	<10	22	<10	10	220	10	1900	<6	4
<3	<10	24	<10	15	27	10	1800	<6	33
<3	<10	15	<10	40	11	20	2100	<6	23
--	--	--	--	--	--	--	--	--	--
<3	<10	25	<10	14	26	10	1800	<6	23
<3	<10	20	<10	40	13	20	2100	<6	30
<3	<10	19	<10	15	16	<10	1800	<6	22
<3	<10	21	<10	11	17	10	1800	<6	20
<3	<10	26	<10	40	10	20	2100	<6	30
<3	<10	16	<10	11	21	10	1800	<6	28
<3	<10	15	<10	40	9	10	2100	<6	26
<3	<10	16	<10	41	22	10	1800	<6	21
<3	<10	21	<10	11	24	<10	1800	<6	16
<3	<10	47	<10	4	270	10	800	<6	<3

Table 2.--Ground-water-quality data collected in September 1987 and August 1988 at wells completed in the glacial drift and carbonate bedrock aquifers, Southern Franklin County, Ohio

[ft, feet; °C, degrees Celsius; μS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; μg/L, micrograms per liter; cols./100 mL, colonies per 100 milliliters; N, nitrogen; <, less than the detection limit; ft, foot; K, based on non-ideal colony count; --, data not available]

Local identifier	Station number	Date	Total well depth (ft)	Specific conductance (μS/cm)	pH	Water temperature (°C)	Dissolved oxygen (mg/L)	Fecal coliform (cols./100 mL)	Dissolved calcium (mg/L)	Dissolved magnesium (mg/L)	Dissolved sodium (mg/L)
				WELLS COMPLETED IN GLACIAL DRIFT							
FR-141	395020083014400	09-08-87	64.00	894	7.3	14.0	0.3	<1	120	43	6.6
FR-147	395108083010600	09-04-87	78.80	896	7.5	13.0	.3	K1	120	40	14
FR-120	395117083011600	09-11-87	72.00	672	7.4	12.5	.5	K1	99	32	4.9
FR-73	395132083001200	09-04-87	--	699	7.3	14.5	--	<1	100	34	3.3
FR-18	394956083002700	09-08-87	--	1010	7.0	12.5	.2	K1	120	38	34
FR-104-TH-73	395020083003700	09-09-87	67.00	742	7.7	12.0	1.3	>60	100	37	6.2
				WELLS COMPLETED IN BEDROCK							
FR-202	395314083021900	09-08-87	220.00	986	7.3	14.0	.3	<1	120	44	27
		08-22-88	220.00	1020	7.4	13.0	--	--	120	47	27
FR-149	395024083003000	09-04-87	144.00	952	7.5	13.0	.3	<1	70	51	46
		08-22-88	144.00	--	7.2	15.5	--	--	110	72	55
FR-148	395114083010200	09-03-87	140.00	744	10.4	14.0	.5	<1	24	54	46
FR-270	395116083024500	08-18-88	180.00	757	7.4	13.0	.2	--	93	39	8.5
FR-269	395323083014000	08-18-88	90.00	--	7.1	13.5	.6	--	170	51	61
				COLLECTOR WELLS							
CW-101	395114083010405	09-03-87	74.00	774	7.3	15.5	.2	<1	100	31	22
CW-103	395046083003105	09-03-87	--	793	7.2	14.0	.3	<1	110	33	18
CW-104	395020083003405	09-03-87	--	788	7.4	13.5	.3	<1	110	33	19

Table 2.--Ground-water-quality data collected in September 1987 and August 1988 at wells completed in the glacial drift and carbonate bedrock aquifers, Southern Franklin County, Ohio--Continued

Local identifier	Date	Dissolved potassium (mg/L)	Alkalinity (mg/L)	Bicarbonate (mg/L)	Carbonate (mg/L)	Dissolved sulfate (mg/L)	Dissolved chloride (mg/L)	Dissolved fluoride (mg/L)	Dissolved bromide (mg/L)	Dissolved silica (mg/L)	Dissolved solids (mg/L)
					WELLS COMPLETED IN GLACIAL DRIFT						
FR-141	09-08-87	1.2	--	--	--	72	53	0.50	0.050	17	507
FR-147	09-04-87	1.8	310	378	--	120	29	.70	.17	15	542
FR-120	09-11-87	1.7	300	366	0	53	15	.30	.026	14	396
FR-73	09-04-87	1.4	--	--	--	63	5.1	.30	.033	16	400
FR-18	09-08-87	2.2	365	445	--	88	87	.20	.12	14	482
FR-104-TH-73	09-09-87	1.5	293	358	--	90	14	.40	.037	14	460
					WELLS COMPLETED IN BEDROCK						
FR-202	09-08-87	2.2	--	--	--	190	9.8	1.7	.034	16	637
	08-22-88	2.2	350	427	--	190	13	1.5	.043	16	658
FR-149	09-04-87	7.8	390	476	--	38	79	1.6	.90	7.8	512
	08-22-88	8.8	590	720	--	32	130	1.4	.76	9.9	727
FR-148	09-03-87	5.3	34	18	12	230	60	1.0	.70	180	474
FR-270	08-18-88	1.4	360	439	--	52	10	1.0	.028	17	438
FR-269	08-18-88	2.7	--	--	--	130	150	.60	.10	17	922
					COLLECTOR WELLS						
CW-101	09-03-87	3.0	250	305	--	110	36	.40	.20	12	483
CW-103	09-03-87	2.7	265	323	--	120	32	.50	.14	12	500
CW-104	09-03-87	2.1	265	323	--	100	35	.40	.12	12	429

Table 2.--Ground-water-quality data collected in September 1987 and August 1988 at wells completed in the glacial drift and carbonate bedrock aquifers, Southern Franklin County, Ohio--Continued

Local identifier	Date	Dissolved NO_2+NO_3 (mg/L as N)	Dissolved ammonia (mg/L as N)	Dissolved NH_4 + organic nitrogen (mg/L as N)	Dissolved phosphorus (mg/L)	Dissolved barium (µg/L)	Dissolved beryllium (µg/L)	Dissolved boron (µg/L)	Dissolved cadmium (µg/L)	Dissolved cobalt (µg/L)
				WELLS COMPLETED IN GLACIAL DRIFT						
FR-141	09-08-87	<0.10	0.16	0.30	<0.01	270	<0.5	20	<1	<3
FR-147	09-04-87	<.10	.29	.60	<.01	30	<.5	80	<1	<3
FR-120	09-11-87	<.10	.19	.30	<.01	210	<.5	20	<1	<3
FR-73	09-04-87	<.10	.14	.70	<.01	310	<.5	10	5	<3
FR-18	09-08-87	<.10	.22	<.20	<.01	270	<.5	40	<1	<3
FR-104-TH-73	09-09-87	<.10	.19	.20	<.01	250	<.5	40	<1	<3
				WELLS COMPLETED IN BEDROCK						
FR-202	09-08-87	<.10	.60	.30	<.01	26	<.5	190	<1	<3
	08-22-88	--	--	--	--	29	<.5	180	1	<3
FR-149	09-04-87	<.10	1.40	1.7	.02	16,000	<.5	1,400	<1	<3
	08-22-88	--	--	--	--	31,000	<.5	1,900	1	<3
FR-148	09-03-87	<.10	.03	.40	<.01	6	<.5	330	<1	<3
FR-270	08-18-88	--	--	--	--	110	<.5	50	<1	<3
FR-269	08-18-88	--	--	--	--	110	<.5	110	2	<3
				COLLECTOR WELLS						
CW-101	09-03-87	<.10	.24	.60	<.01	87	<.5	90	<1	<3
CW-103	09-03-87	<.10	.09	.50	<.01	60	<.5	70	<1	<3
CW-104	09-03-87	<.10	.16	.30	<.01	130	<.5	70	<1	<3

Table 2.--Ground-water-quality data collected in September 1987 and August 1988 at wells completed in the glacial drift and carbonate bedrock aquifers, Southern Franklin County, Ohio--Continued

Local iden-tifier	Date	Dis-solved copper (µg/L)	Dis-solved iron (µg/L)	Dis-solved lead (µg/L)	Dis-solved lithium (µg/L)	Dis-solved manga-nese (µg/L)	Dis-solved molyb-denum (µg/L)	Dis-solved stron-tium (µg/L)	Dis-solved vana-dium (µg/L)	Dis-solved zinc (µg/L)
				WELLS COMPLETED IN GLACIAL DRIFT						
FR-141	09-08-87	<10	3,500	10	<4	38	10	1,100	<6	14
FR-147	09-04-87	<10	730	<10	18	43	<10	2,000	<6	6
FR-120	09-11-87	<10	2,000	<10	5	57	<10	630	<6	46
FR-73	09-04-87	<10	2,500	<10	5	37	<10	200	<6	10
FR-18	09-08-87	<10	470	20	<4	86	10	480	<6	10
FR-104-TH-73	09-09-87	<10	1,100	<10	10	120	<10	1300	<6	12
				WELLS COMPLETED IN BEDROCK						
FR-202	09-08-87	<10	3,100	<10	13	35	50	19,000	<6	<3
	08-22-88	<10	3,100	<10	27	30	50	21,000	<6	11
FR-149	09-04-87	<10	240	<10	59	200	<10	4,400	<6	8
	08-22-88	<10	200	10	85	180	<10	6,800	<6	<3
FR-148	09-03-87	<10	5	<10	49	22	<10	5,100	<6	<3
FR-270	08-18-88	<10	380	<10	22	7	10	5,100	<6	5
FR-269	08-18-88	<10	7,100	<10	27	200	20	8,500	<6	27
				COLLECTOR WELLS						
CW-101	09-03-87	<10	1,200	<10	8	100	<10	880	<6	<3
CW-103	09-03-87	<10	460	<10	8	100	<10	680	<6	<3
CW-104	09-03-87	<10	1,300	<10	8	100	<10	740	<6	<3