GROUND-WATER LEVELS, WATER QUALITY, AND POTENTIAL EFFECTS OF TOXIC-SUBSTANCE SPILLS OR CESSATION OF QUARRY DEWATERING NEAR A MUNICIPAL GROUND-WATER SUPPLY, SOUTHERN FRANKLIN COUNTY, OHIO

By Alan C. Sedam, Sandra M. Eberts, and E. Scott Bair

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 88-4138

Prepared in cooperation with the

CITY OF COLUMBUS, OHIO

Columbus, Ohio

1989

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.4	millimeter (mm)
square inch ($in.^2$)	645.2	square millimeter (mm^2)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09290	square meter (m^2)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot (ft^3)	0.02832	cubic meter (m^3/s)
gallon (gal)	0.003785	cubic meter (m^3)

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.

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

$$F = 1.8(^{\circ}C) + 32$$

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

GROUND-WATER LEVELS, WATER QUALITY, AND POTENTIAL EFFECTS OF TOXIC-SUBSTANCE SPILLS OR CESSATION OF QUARRY DEWATERING NEAR A MUNICIPAL GROUND-WATER SUPPLY, SOUTHERN FRANKLIN COUNTY, OHIO

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ABSTRACT

A newly completed municipal ground-water supply that produces from a sand and gravel aquifer in southern Franklin County, Ohio, may be susceptible to potential sources of pollution. Among these are spills of toxic substances that could enter recharge areas of the aquifer or be carried by surface drainage and subsequently enter the aquifer by induced infiltration. Ground water of degraded quality also is present in the vicinity of several landfills located upstream from the municipal supply.

Local dewatering by quarrying operations has created a ground-water divide which, at present, prevents direct movement of the degraded ground water to the municipal supply. In addition, the dewatering has held water levels at the largest landfill below the base of the landfill. Should the dewatering cease, concern would be raised regarding the rise of water levels at this landfill and transport of contaminants through the aquifer to the Scioto River and subsequently by the river to the well field.

From June 1984 through July 1986, the U.S. Geological Survey, in cooperation with the City of Columbus, Ohio, investigated the relations among the ground-water supply and potential sources of contamination by means of an observation-well network and a program of measuring water levels and sampling for water quality. Sample collections included those made to determine the baseline levels of organic chemicals and metals, as well as periodic sampling and analysis for common constituents to evaluate any changes taking place in the system. Finally, a steady-state, three-dimensional numerical model was used to determine ground-water flow directions and average ground-water velocities to assess potential effects of toxic-substance spills. The model also was used to simulate changes in the ground-water flow system that could result if part or all of the quarry dewatering ceased.

Few of the organic-chemical and metal constituents analyzed for were present at detectable levels. With respect to chemical analyses of water and soil materials reported in earlier studies, no new problem areas were discovered as a result of either the baseline or periodic samplings. Model simulations suggest that, under March 1986 conditions, a toxic-substance spill along the major highways in the northern two-thirds of the study area eventually could discharge into one of the two quarries being dewatered or into the Scioto River.

A toxic-substance spill in the southern one-third of the study area ultimately may discharge into the Scioto River, Big Walnut Creek, or possibly into the municipal ground-water supply. Model simulations also indicate that concentrated landfill leachate probably would not reach the municipal ground-water supply under current or increased well-field pumping conditions if dewatering ceased at either or both of the quarries.

INTRODUCTION

The "South Well Field" of the City of Columbus, Ohio, is constructed in a highly permeable sand and gravel aquifer, which is underlain by a carbonate bedrock aquifer. The water supply comes from four radial-collector wells located between the Scioto River and Big Walnut Creek (fig. 1). The well field uses these streams as part of its water source by means of induced stream infiltration. The four collector wells, designated CW-101, -103, -104, and -115 (fig. 1), were designed for a maximum combined yield of 45.6 Mgal/d (million gallons per day). The well field serves the southern part of Columbus and its suburbs and accounts for about 15 percent of the City's total water supply.

The glacial aquifer in the vicinity of the well field is vulnerable to contamination from (1) toxic-substance spills along any of the major highways that cross the project area, and (2) toxic-substance spills or other uncontrolled discharges into or near the Scioto River or Big Walnut Creek upstream from the well field. Toxic substances could be transported to the well-field area not only by the streams but also by runoff that infiltrates the recharge area for the well field.

Previous studies of the well-field area conducted by the U.S. Geological Survey in cooperation with the City of Columbus, Ohio, have identified potential water-quality problems caused by landfills near the Scioto River upstream from the water supply. A steady-state digital ground-water flow model of the area (Weiss and Razem, 1980) indicated that a part of the recharge to the glacial aquifer may come from areas adjacent to these landfills. A transient-state model of the same area (Razem, 1983) showed that infiltration through the riverbed would account for 28 to 33 percent of the pumpage of the collector wells. A report on ground-water quality in the vicinity of the landfills (de Roche and Razem, 1981) notes several areas of low-level contamination and indicates that the direction of ground-water flow is towards the Scioto River. Most recently, de Roche (1985) provides evidence of continued degradation of ambient water quality near the landfills and presents a ground-water-level map showing a large, asymmetrical cone of depression centered on a limestone quarry (fig. 1), which has created an unsaturated zone beneath the base of one of the landfills.

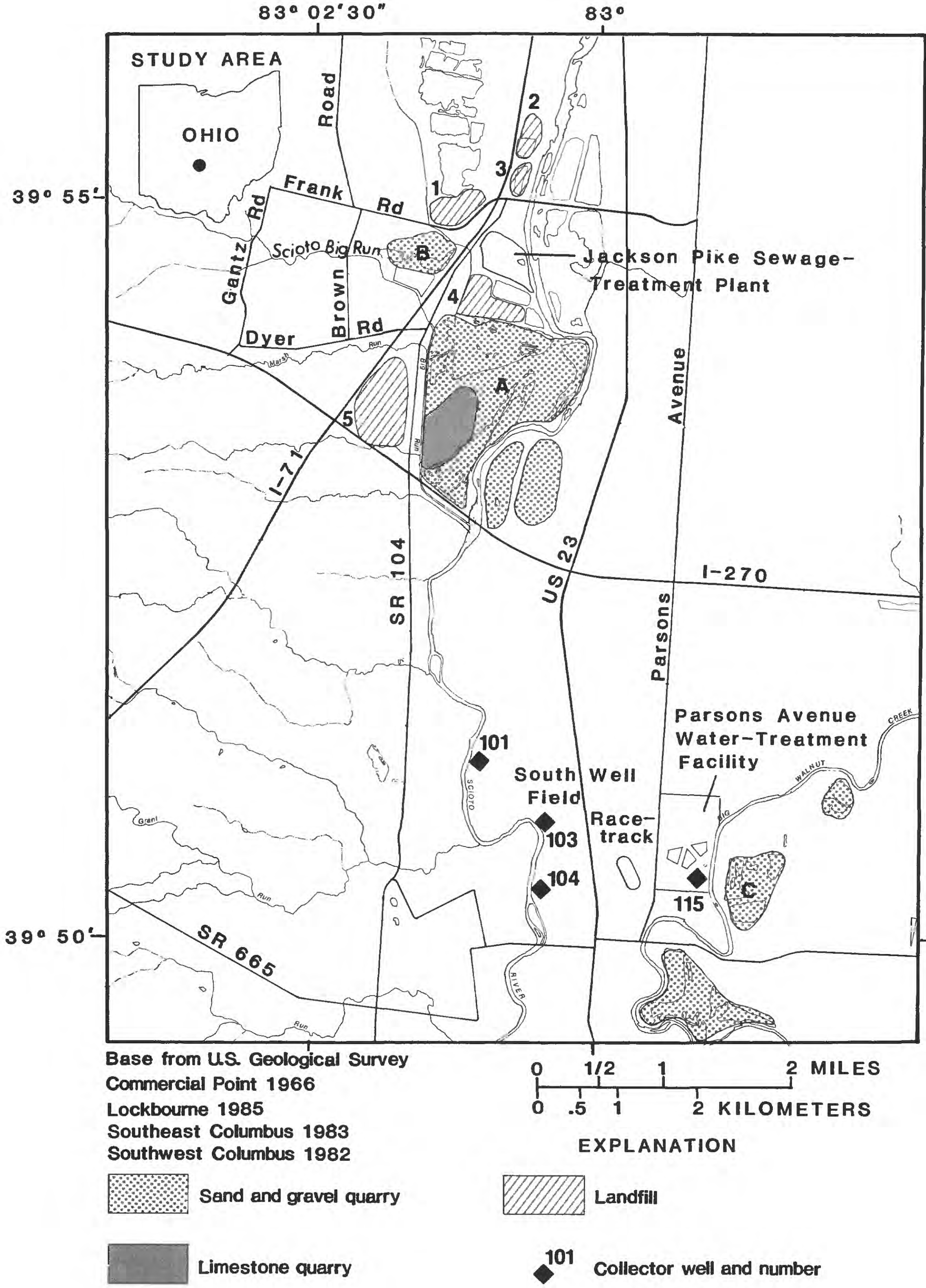


Figure 1.--Location of study area, principal quarries and landfills, and South Well Field (quarries and landfills having alphabetic or numeric designations are specifically discussed in report).

From June 1984 through July 1986, the U.S. Geological Survey, in cooperation with the City of Columbus, Ohio, conducted a study to further describe ground-water levels and water quality and to evaluate the potential effects of toxic-substance spills or cessation of quarry dewatering near the South Well Field. This study contributes to the understanding of potential effects of diverse land uses on municipal ground-water supplies.

Purpose and Scope

This report presents the results of the 1984-86 study. Specifically, the report discusses:

(1) Ground-water levels near the quarries;

(2) ground-water levels near the well field and potential sources of contamination;

(3) background levels of organic and metal constituents in surface and ground water;

(4) results of periodic water-quality sampling;

(5) potential effects of toxic-substance spills in terms of ground-water flow directions and approximate traveltimes; and

(6) potential effects of cessation of quarry dewatering on movement of landfill leachate toward the South Well Field.

Although the principal data-collection phase of this project was from June 1984 through July 1986, this report also incorporates water-level and water-quality data collected between 1982 and 1984 in support of other projects of the U.S. Geological Survey. McDonald and Harbaugh's (1984) modular three-dimensional ground-water flow model was used to assess the potential effects of toxic-substance spills and cessation of quarry dewatering on the glacial aquifer.

Study Area

The area containing the well and stream network (fig. 1) covers approximately 48 square miles, within which the Scioto River meanders approximately 10 miles. A 2-mile reach of Big Walnut Creek extends through the southeastern part of the area. The four collector wells that comprise the Columbus South Well Field are located within the southern half of the study area, three along the Scioto River and one adjacent to Big Walnut Creek. Topography of the study area generally is flat to gently rolling; slopes are 50 to 70 feet per mile toward the Scioto River. The area receives approximately 36 inches of precipitation per year.

Several sand and gravel quarries and one quarry mining both limestone and sand and gravel operate within the study area. Quarries A and B (fig. 1) maintain large dewatering systems to mine below the natural water table within the area. Additionally, five landfills located in abandoned sand and gravel quarries are adjacent to the active quarries (fig. 1). Demolition waste (stone, masonry, concrete, and miscellaneous metal) and solid waste have been deposited in these landfills. Single-family residences, commercial buildings, and manufacturing establishments also are present within the northern half of the study area, whereas agriculture is the primary land use in the southern half of the study area near the South Well Field.

Acknowledgments

The authors appreciate the cooperation of the Division of Water of the Ohio Department of Natural Resources, the American Aggregates Company, the JP Sand and Gravel Company, AggRok Materials, Waste Management, Inc., and residents and other commercial enterprises of southern Franklin County who permitted access to their wells.

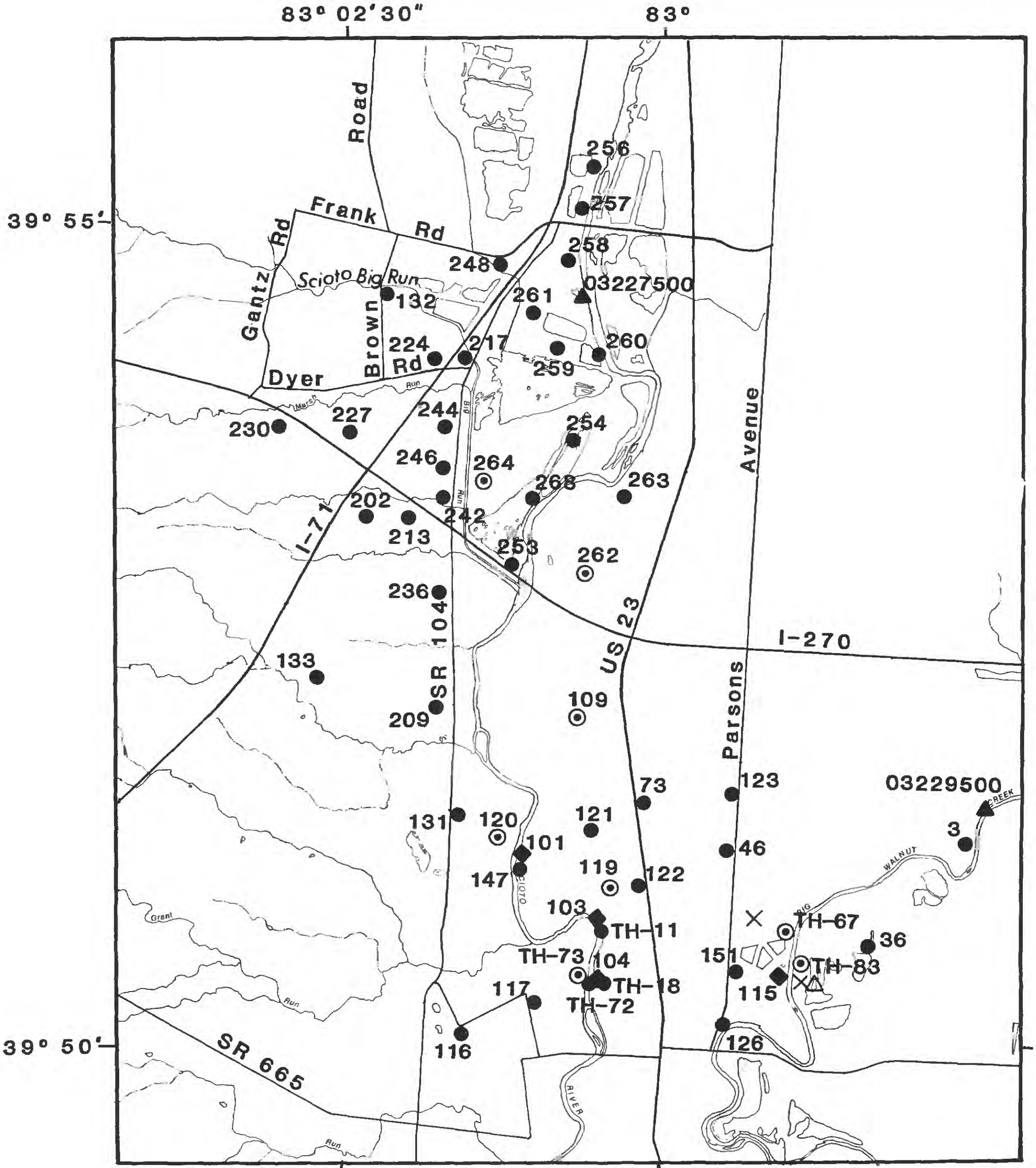
METHODS OF STUDY

Data-Collection Network

A data-collection network (fig. 2) includes all of the sites where ground-water levels, surface-water stages, or precipitation accumulations were measured. A separate map (fig. 3) shows locations of ground-water and surface-water sites where samples were collected for water-quality analysis. Also shown are locations where streambed sediment and soil-core samples were collected for analysis. Most of the data collected during the study (1982-86) have appeared in the U.S. Geological Survey's annual water-data reports (Shindel and others, 1983-87).

Water-Level Measurement

Locations of water-level measurement sites are shown in figure 2. Eight wells were instrumented to collect continuous water-level data. Seven were in glacial material and one was in bedrock. An additional 40 wells were measured every 2 months.



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

0 1/2 1 2 MILES

0 .5 1 2 KILOMETERS

EXPLANATION

254 ● Ground-water-level measurement site

◎109 Well equipped with water-level recorder

101 ◆ Collector well and number

▲03229500 USGS stream gage

△ Pond-level measurement site

✕ Precipitation gage

Figure 2.--Location of water-level measurement sites and precipitation gages (the county-code prefix FR- has been omitted from well numbers).

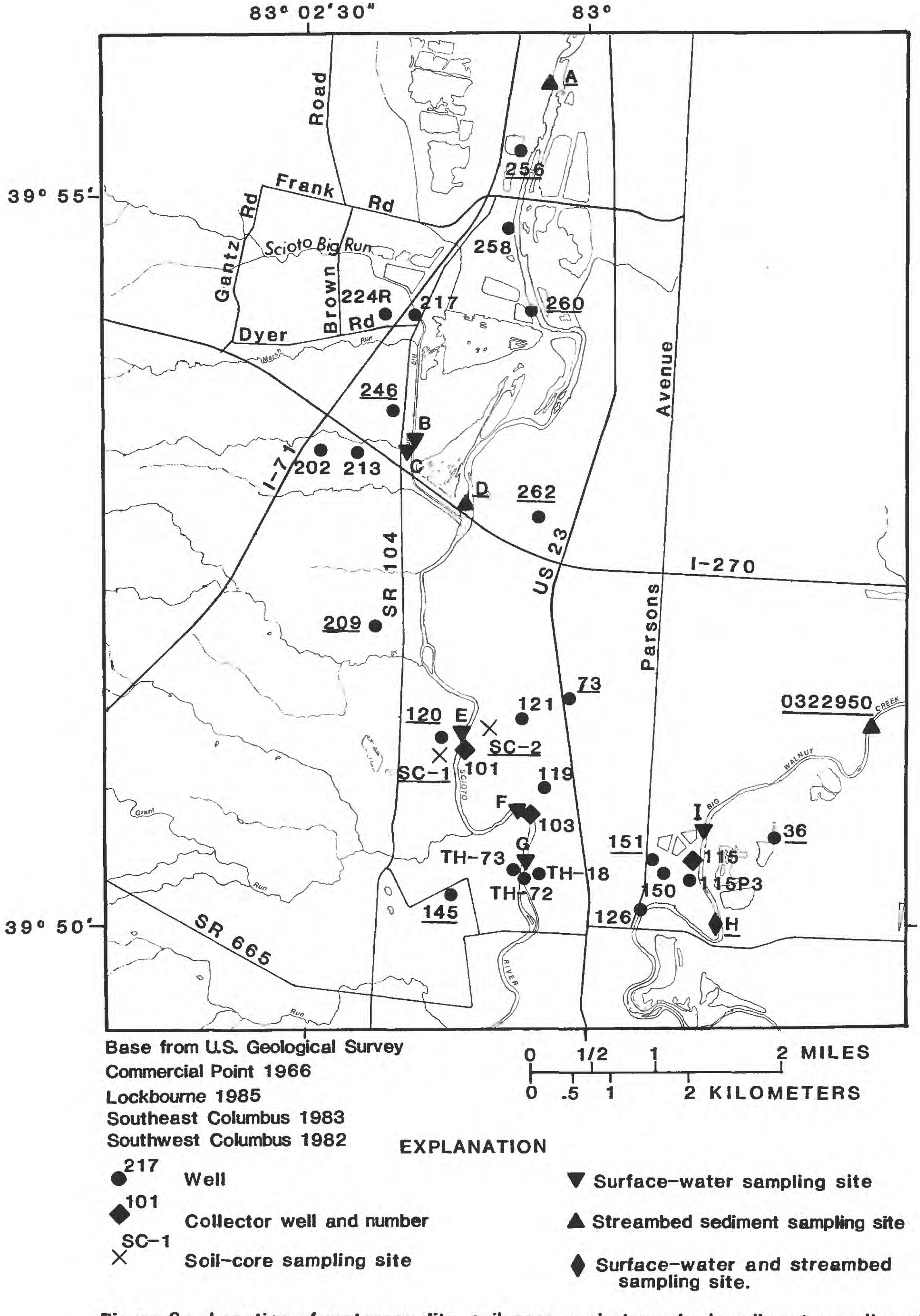


Figure 3.—Location of water-quality, soil-core, and streambed-sediment sampling sites (underlined sites were sampled during the baseline assessment; the county-code prefix FR- has been omitted from well numbers).

A stilling well was used to record changes in a pond believed to be affected by ground-water withdrawals. Streamflow records for the Scioto River and Big Walnut Creek were used to study ground-water and surface-water relations. Midday stage readings for the Scioto River at collector well 104 were recorded daily by the City of Columbus beginning in May 1984.

Water-Quality Sampling

Baseline Sampling for Organics and Metals

In order to measure the effects of a toxic-substance spill in the study area, it would first be necessary to have knowledge of the ambient level of toxic substances already present in water, streambed materials, and soil. For the purpose of providing baseline data, a comprehensive sampling for organics and metals was done once only in June 1984.

Table 1 lists organic and metal constituents for which samples from 10 wells, four surface-water and stream-bottom-material sites, and two soil-test sites (fig. 3) were analyzed. Most of these constituents are on the USEPA Priority Pollutant list (Keith and Telliard, 1979). Four of the sampled wells were drilled for water supply and are presently in use. The others were drilled as observation wells in support of previous studies conducted over the past decade.

To obtain a representative sample from the aquifer, the observation wells were pumped until the water was clear, and at least several well volumes were removed before samples were collected. All wells, whether observation or supply, were pumped until specific conductance and temperature had stabilized before sampling. Alkalinity and dissolved oxygen also were measured in the field. Dissolved oxygen was measured using a flowthrough device to minimize exposure of the sample to the air. Samples collected for analysis of volatile organic compounds were obtained through a spigot on the flow-through chamber to minimize degassing.

The surface-water samples were depth-integrated except for one site where the flow was well mixed. The bed-material samples were collected at the same sites in sections where stream velocity was low and bottom material was fine-grained. A U.S. Geological Survey BMH-53 sampler was used to collect the upper 4 inches or less of bottom material. The material was then wet-sieved to retain the medium silt and smaller-sized fractions for analysis. Procedures for handling and cleaning equipment used to obtain water and bed-material samples were similar to those discussed by de Roche (1985, p. 7-11).

Criteria for selecting the soil-test sites included places that (1) at one time or another were flooded by the Scioto River, (2) were not affected by accumulations of vegetation or trash, and (3) were not under recent cultivation. The two sites selected, on either side of the river, had been covered by flood waters at least once in each of the past several years. The most recent inundation before sampling was in late March 1984. The soil cores were collected using the same device used to sample streambed material. The samples were wet-sieved with distilled water to retain medium silt and smaller-sized fractions for analysis. All baseline samples were analyzed at the U.S. Geological Survey's National Water Quality Laboratory.

Periodic Sampling

The purpose of the periodic sampling program was to monitor water quality within the study area and to determine if ground-water quality in the vicinity of the landfills has continued to degrade since 1983. Several wells sampled during the current study were sampled in earlier studies.

In addition, the sampling program was used to evaluate effects of the leaching of landfills by surface water. Runoff from landfill sites could transport a variety of undesirable constituents to the Scioto drainage system, which, in turn, could contribute these constituents to the ground-water system through induced infiltration.

Water samples were collected eight times, approximately once each quarter between June 1984 and April 1986. Constituents for which the samples were analyzed are listed in table 2.

The sampling network usually consisted of eight wells and two surface-water sites. The wells and surface-water sites from which samples were collected varied throughout the course of the study. Samples were collected from a total of 19 wells and 5 surface-water sites during the periodic sampling. No single well was sampled more than seven times. Several miscellaneous water samples also were collected from wells and surface-water sites between August 1983 and March 1984. Constituents for which miscellaneous samples were analyzed are mostly the same as those listed in table 2. In all, 25 wells and 7 surface-water sites were sampled between August 1983 and April 1986, excluding the sites involved in the baseline sampling. Locations of all sites sampled for water quality are shown in figure 3.

The samples were analyzed at the U.S. Geological Survey's National Water-Quality Laboratory except for fecal coliform and hydrogen sulfide, which were determined at the Columbus office. Whenever samples collected during the periodic sampling were submitted for analysis, a replicate sample was included for quality assurance.

Table 1.--*Organic-chemical and metal constituents selected for the baseline sampling*

[µg/kg, micrograms per kilogram]

Base/neutral extractable compounds (Detection level: 10 µg/kg)	
Acenaphthene	Di-n-butyl phthalate
Acenaphthylene	2,4-Dinitrotoluene
Anthracene	2,6-Dinitrotoluene
Benzo(a)anthracene	Di-n-octyl phthalate
Benzo(b)fluoranthene	bis(2-ethylhexyl) phthalate
Benzo(k)fluoranthene	Fluoranthene
Benzo(ghi)perylene	Fluorene
Benzo(a)pyrene	Hexachlorobenzene
4-Bromophenyl phenyl ether	Hexachlorobutadiene
Butyl benzyl phthalate	Hexachlorocyclopentadiene
bis(2-chloroethoxy)methane	Hexachloroethane
bis(2-chloroethyl) ether	Indeno(1,2,3-cd)pyrene
bis(2-chloroisopropyl) ether	Isophorone
2-chloronaphthalene	Napthalene
4-chlorophenyl phenyl ether	Nitrobenzene
Chrysene	N-Nitrosodimethylamine
Dibenzo(ah)anthracene	N-Nitrosodi-n-propylamine
1,2-Dichlorobenzene	N-Nitrosodiphenylamine
1,3-Dichlorobenzene	Phenanthrene
1,4-Dichlorobenzene	Pyrene
Diethyl phthalate	1,2,4-Trichlorobenzene
Dimethyl phthalate	

Acid-extractable compounds (Detection level: 20 µg/kg)	
4-Chloro-3-methylphenol	2-Nitrophenol
2-Chlorophenol	4-Nitrophenol
2,4-Dichlorophenol	Pentachlorophenol
2,4-Dimethylphenol	Phenol
4,6-Dinitro-2-methylphenol	2,4,6-Trichlorophenol
2,4-Dinitrophenol	

Volatile organic compounds (Detection level: 30 µg/kg)	
Benzene	1,2-Dichloropropane
Bromoform	1,3-Dichloropropene
Carbon tetrachloride	Ethylbenzene
Chlorobenzene	Methylbromide
Chloroethane	Methylene chloride
2-Chloroethylvinyl ether	1,1,2,2-Tetrachloroethane
Chloroform	Tetrachloroethylene

Table 1.--*Organic-chemical and metal constituents selected for the baseline sampling*--Continued

Volatile organic compounds--Continued	
Dibromochloromethane	Toluene
Dichlorobromomethane	1,1,1-Trichloroethane
1,1-Dichloroethane	1,1,2-Trichloroethane
1,2-Dichloroethane	Trichloroethylene
1,1-Dichloroethylene	Vinyl chloride
1,2-trans-Dichloroethylene	
Metals	
Aluminum	Iron
Antimony	Lead
Arsenic	Manganese
Barium	Mercury
Beryllium	Nickel
Cadmium	Selenium
Chromium	Silver
Copper	Strontium
Cyanide	Zinc

Table 2.--*Properties and constituents selected for the periodic sampling*

Specific conductance	Chloride, dissolved
pH	Fluoride, dissolved
Temperature	Silica, dissolved
Oxygen, dissolved	Dissolved solids, sum of constituents
Fecal coliform bacteria	Nitrogen, ammonia, dissolved, as N
Hardness, as $CaCO_3$	Nitrogen, ammonia plus organic, dissolved, as N
Hardness, noncarbonate	Nitrite, dissolved, as N
Calcium, dissolved	Nitrite plus nitrate, dissolved, as N
Magnesium, dissolved	Phosphorus, dissolved orthophosphate, as P
Sodium, dissolved	Aluminum, dissolved
Potassium, dissolved	Iron, dissolved
Alkalinity, total, as $CaCO_3$	Manganese, dissolved
Carbon dioxide	Carbon, organic, total
Sulfide, total as S	Phenols, total
Sulfate, dissolved	

During the periodic samplings the same procedures described for baseline sampling were used to obtain samples representative of the aquifer. However, the flow-through device used for the baseline sampling was not always available when the periodic sampling was done; thus, reliable measurements of dissolved oxygen could not always be made.

Two stream sites were sampled regularly under a variety of climatic conditions. One of the sites (C, fig. 3) was on an unnamed tributary to Scioto Big Run, which receives surface drainage from an operating landfill. The other site (B, fig. 3), which served as a control, was located nearby on Scioto Big Run but just upstream from the tributary described above.

A depth-integrated method was used to collect the surface-water samples at site B. Although the flow at site C was usually small, there was a spot where the flow was channelized, well mixed, and easily collected with a bucket. Discharge measurements were not made during any of the samplings.

Collection of Precipitation Data

Rainfall data were collected at two sites (fig. 2) to help compute the hydrologic budget in the study area. The U.S. Geological Survey rain gage (east of Big Walnut Creek, fig. 2), which was operated May 1982 to July 1986, consisted of a 50-square-inch collecting tray connected to a 3-inch pipe. The gage was equipped to record the rainfall collecting in the pipe in amounts as little as 0.01 inch as hourly values on punched-paper tape. The second gage (west of Big Walnut Creek, fig. 2) was operated by City of Columbus personnel at the Parsons Avenue Water Treatment Facility from November 1983 through the end of the study. It consisted of a U.S.-Weather-Bureau-type collector, which was read daily at 8 a.m. The two stations, although only about one-half mile apart, showed minor discrepancies in monthly totals, which are attributed to natural variations of rainfall distribution.

By using alcohol to prevent freezing in the collecting tube, the U.S. Geological Survey was able to collect rainfall data during the winter months. However, during periods of heavy snowfall, the record is less reliable because the Survey's gage was not equipped to measure snowfall. The City of Columbus gage was read daily; thus, the winter record collected there is more complete.

A composite of the precipitation is shown in figure 4. For the 53 months of record, the average amount was 3.00 inches per month, with monthly extremes ranging from 0.45 inches in

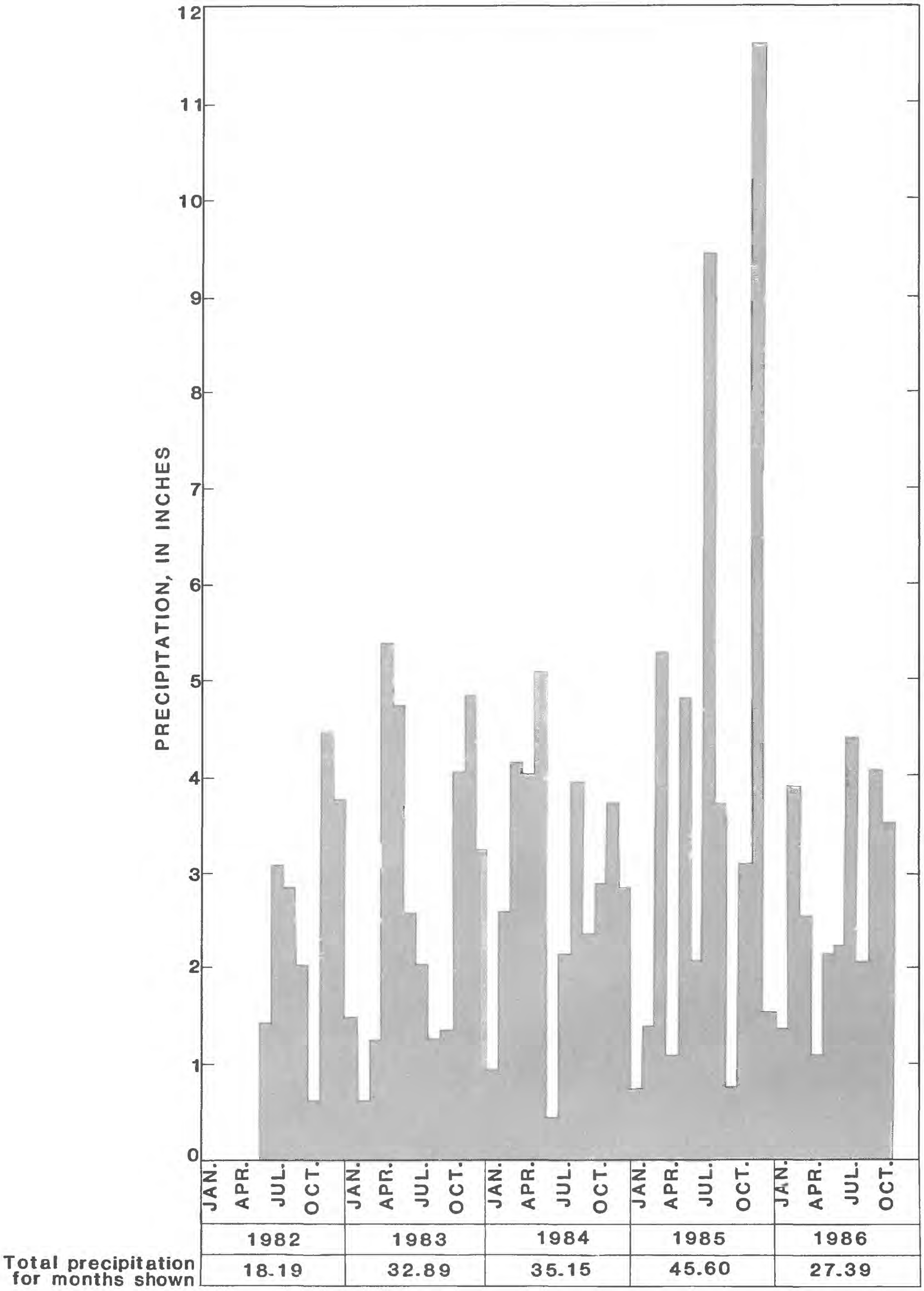


Figure 4.--Monthly precipitation, June 1982 through October 1986.

June 1984 to 11.58 inches in November 1985. For water years[1] 1983 through 1986, the average annual rainfall was 36.6 inches.

Compilation of Pumpage Data

Pumpage data, as well as records of large transfers of surface water to and from quarry lakes, were needed to construct the ground-water flow model. Sources of such data include the Ohio Environmental Protection Agency and the various industrial and commercial users within the project area.

It was not feasible or necessary to obtain exact pumpage figures for the individual collector wells. Daily records indicating which pumps were operated on any given day have been kept since May 1984, thus, approximate pumpage of any of the collector wells on a given day can be estimated from the rated capacity of the pumps. During the period of study, the average daily pumping period at any of the collector wells was about 7 hours.

HYDROLOGIC FRAMEWORK

An assemblage of unconsolidated materials, largely of glacial origin, and the underlying consolidated-rock section constitute the two aquifers in the study area. In the ground-water model discussed later in the report, the unconsolidated aquifer, hereafter referred to as the "glacial aquifer," comprises "layer 1," and the underlying bedrock system comprises "layer 2." Figure 5 gives locations of several geologic sections (figs. 6-10), which show the relation between the two aquifers.

Glacial Aquifer

The glacial aquifer in southern Franklin County is composed of sand, gravel, and clay from at least two major glacial stages. In places, meltwaters from the receding glaciers left thick outwash deposits, which have been exploited for sand and gravel in several areas and which are important sources of ground water in the study area. The heterogeneity of the glacial deposits is demonstrated in the geologic sections (figs. 6-10). Saturated thickness is about 60 feet where the collector wells are located. The unconsolidated deposits in the northwestern part of the area are thinner, less permeable, and have been dewatered in places.

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[1]Water year in U.S. Geological Survey reports is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1980, is called the "1980 water year."

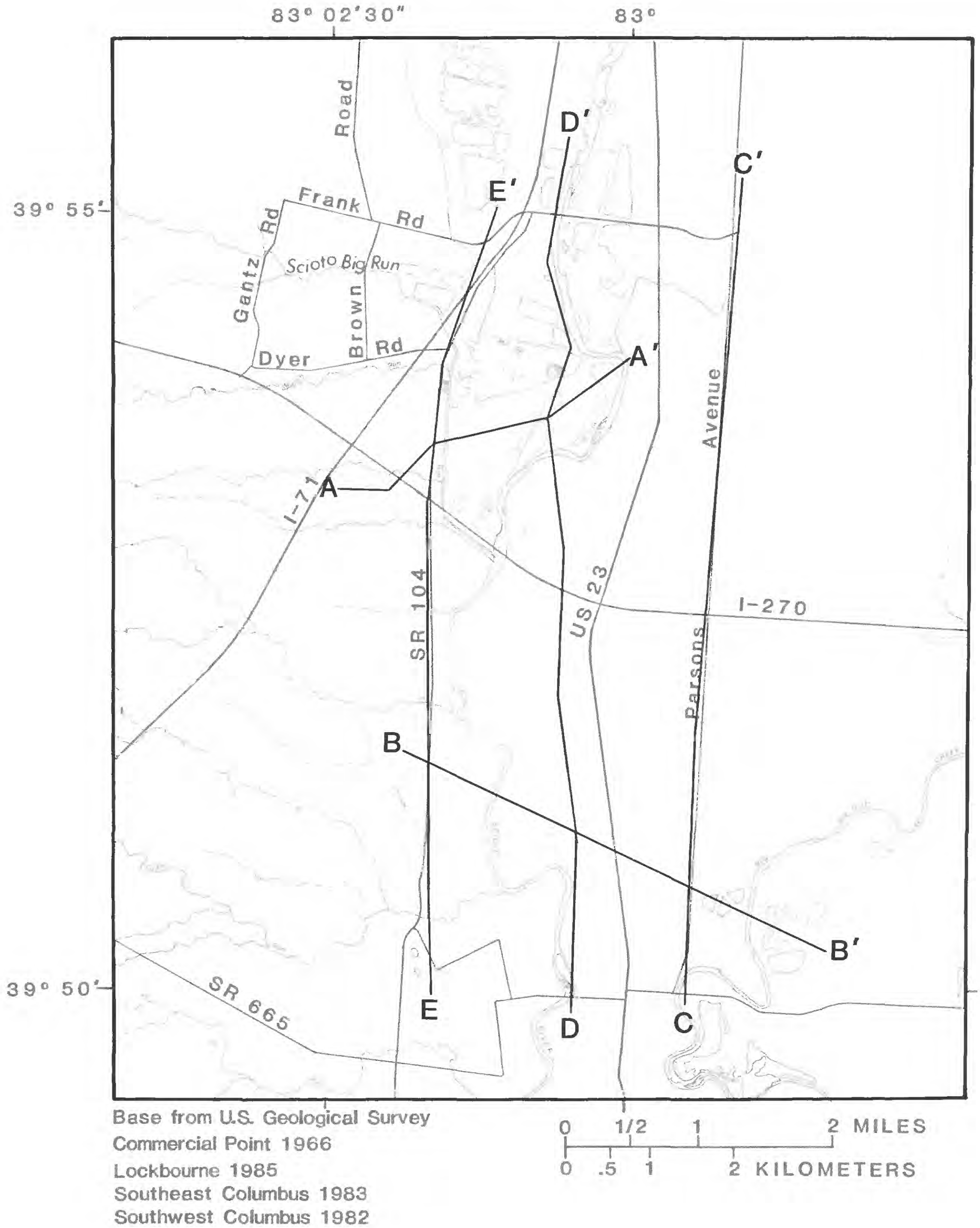


Figure 5.--Location of geologic sections shown in figures 6-10.

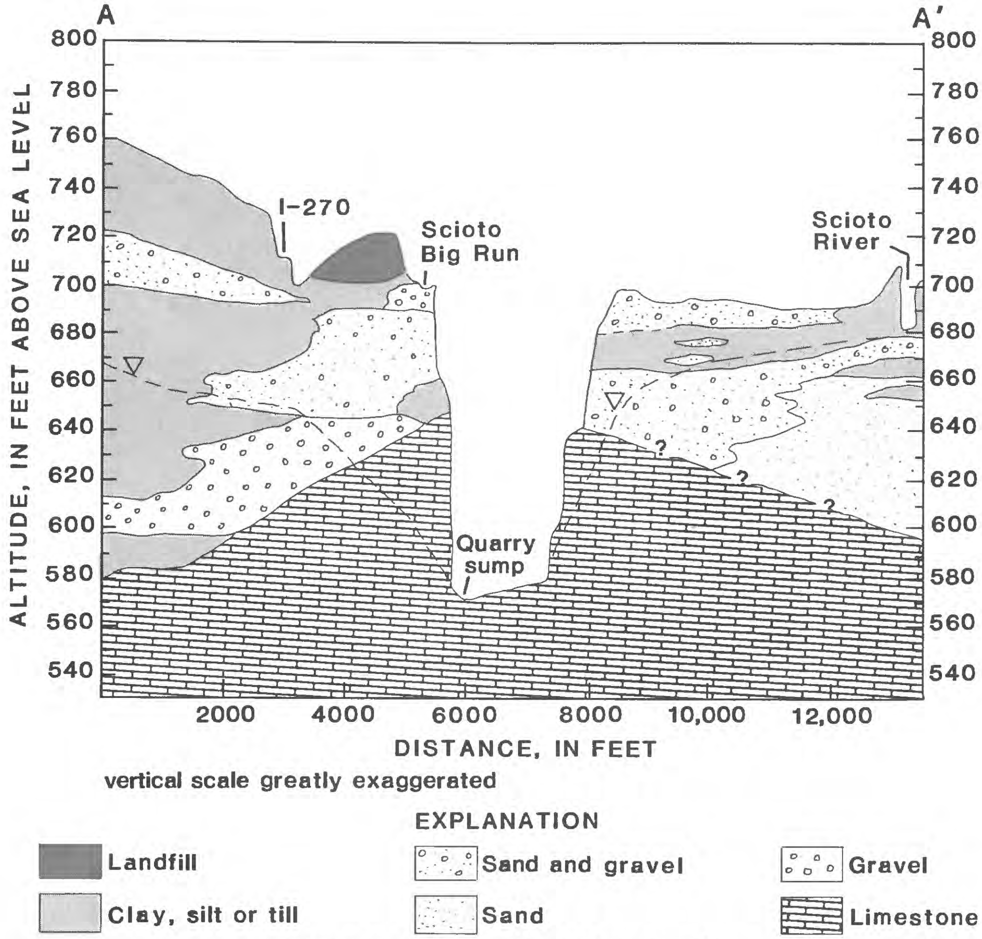


Figure 6.--Geologic section A-A′.

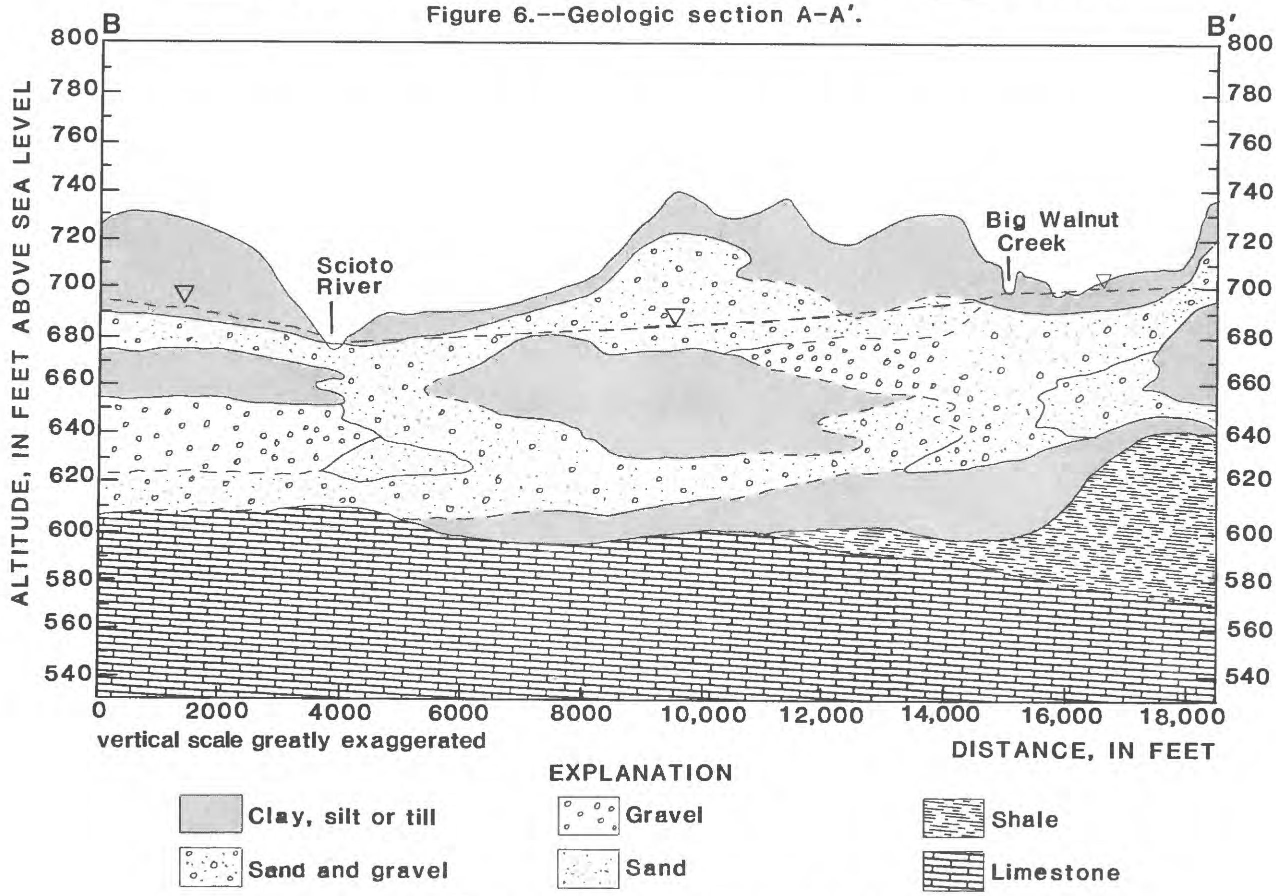


Figure 7.--Geologic section B-B′.

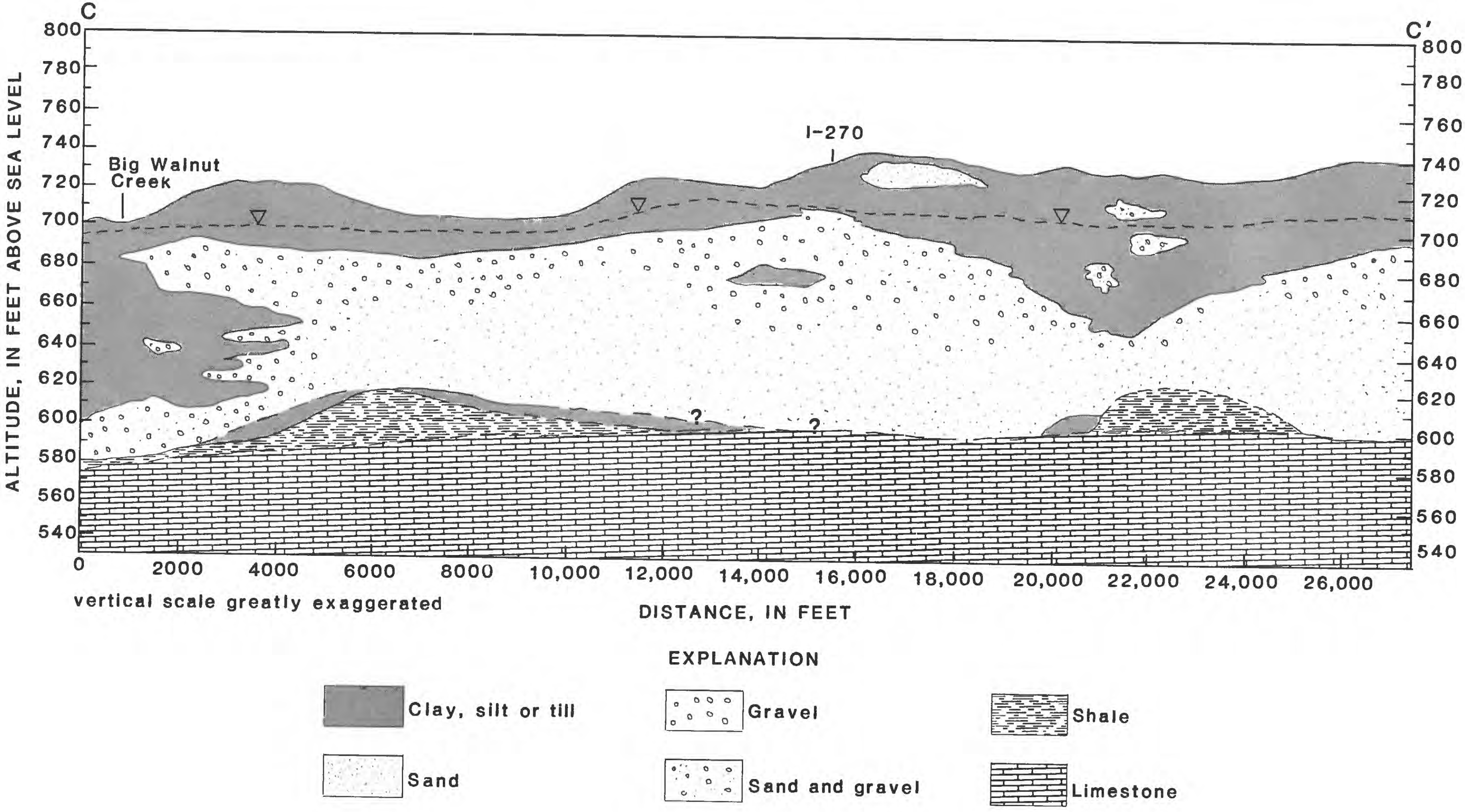
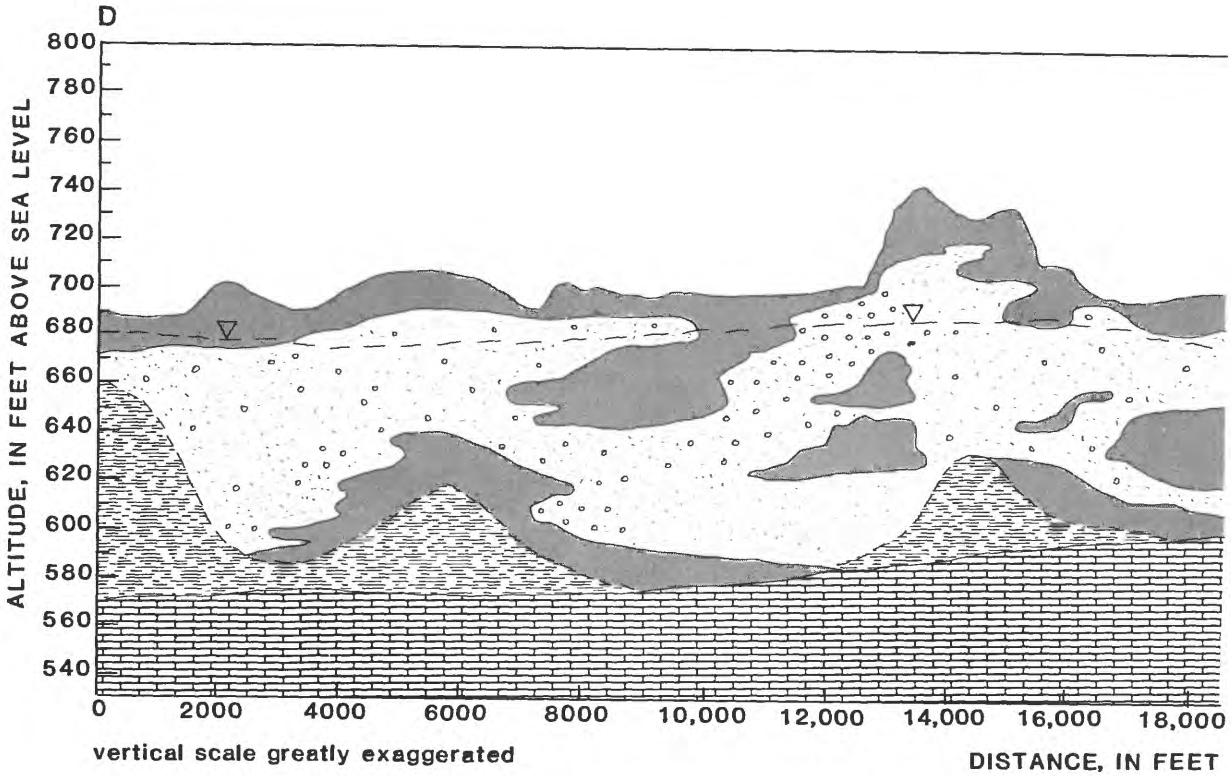


Figure 8.--Geologic section C-C′.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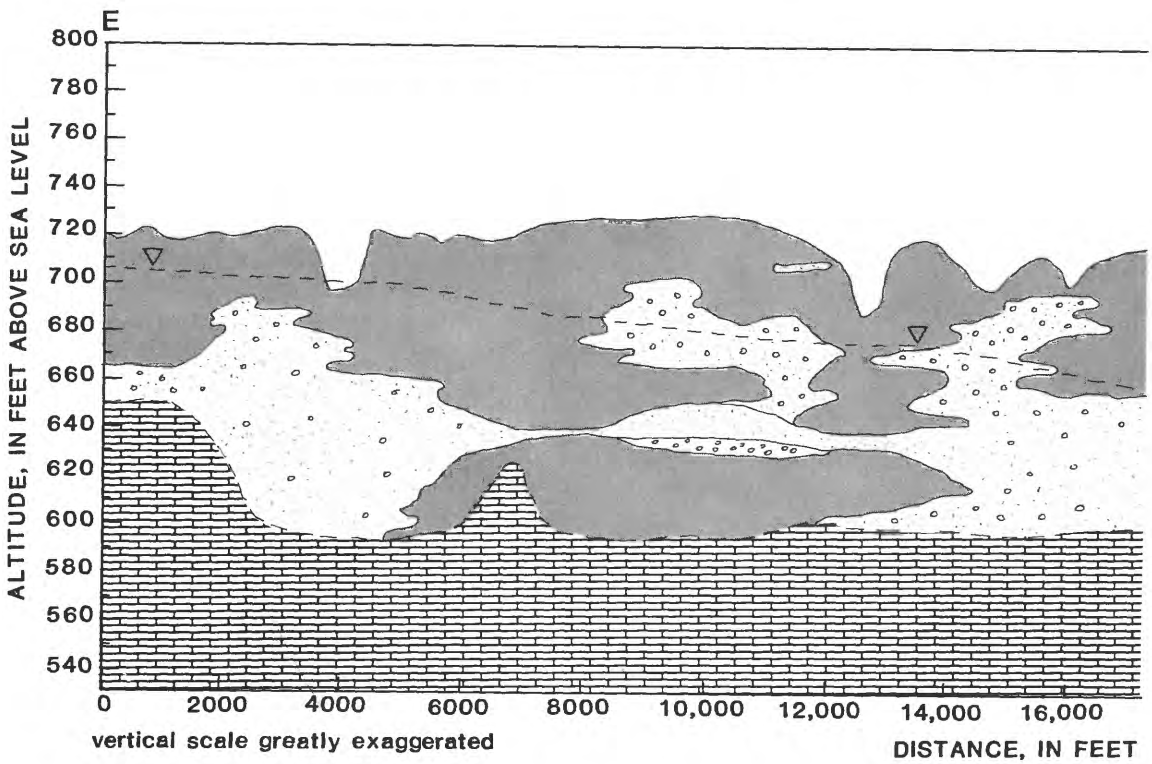
vertical scale greatly exaggerated
DISTANCE, IN FEET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vertical scale greatly exaggerated
DISTANCE, IN FEET

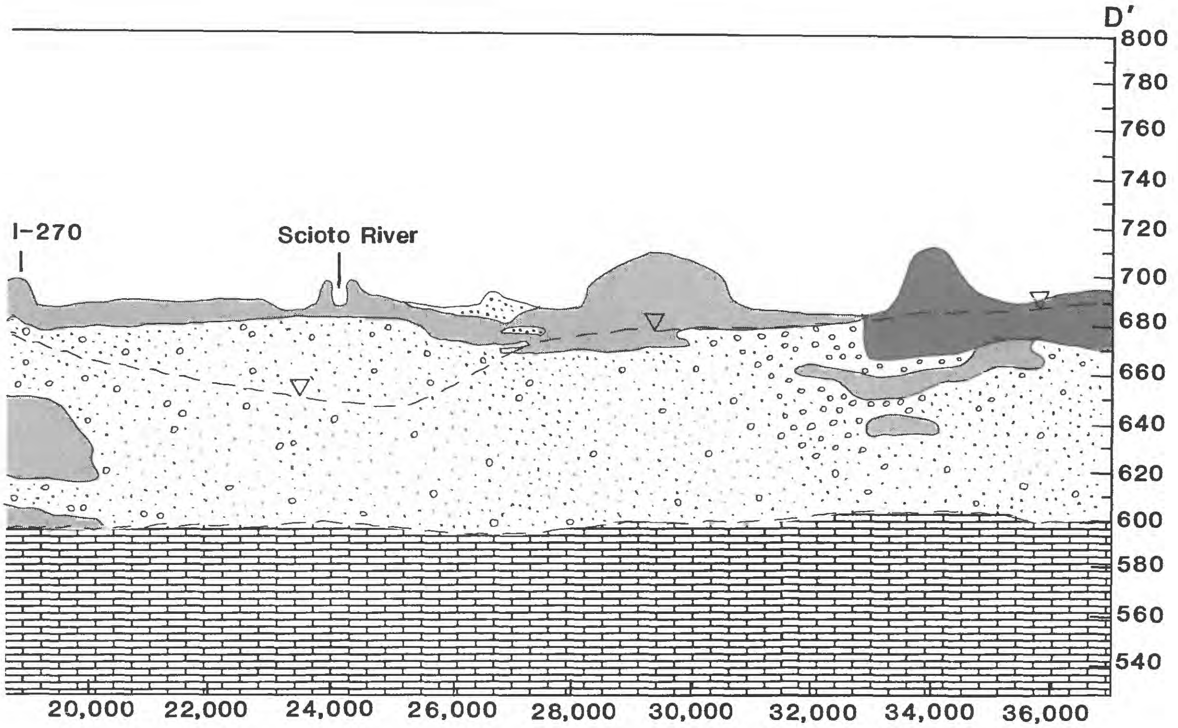

Figure 9.--Geologic section D-D′.

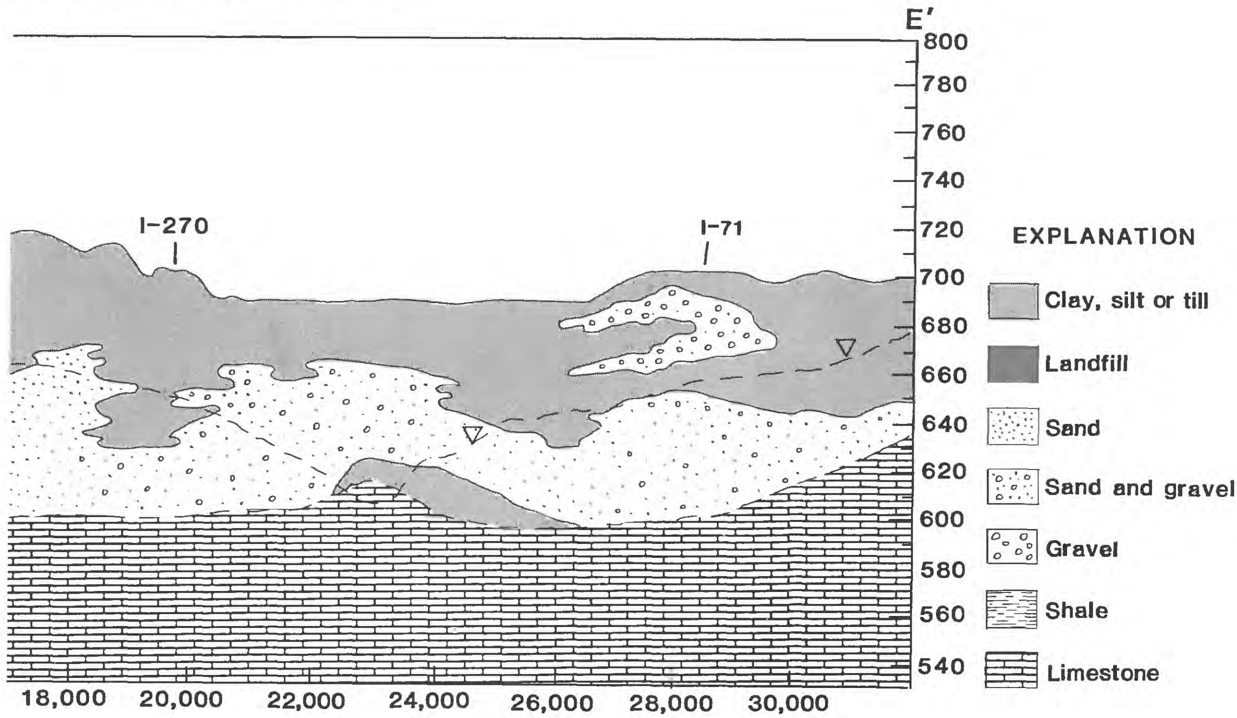

Figure 10.--Geologic section E-E′.

Most of the glacial cover on the bedrock highs west of the Scioto River is composed of poorly permeable till. The area is drained by several small tributaries to the Scioto River, some of which have no flow during dry weather. East of the Scioto River flood plain, much of the surficial material is composed of relatively permeable outwash material, some of it characteristic of glacial kame deposits. There is little or no surface drainage in this section between Big Walnut Creek and the Scioto River.

Bedrock Aquifer

Carbonate rocks of Upper Silurian and Lower Devonian age underlie the glacial material west of the Scioto River. The bedrock surface is irregular in places. East of the Scioto River, the carbonate rock is capped by Devonian shales that thicken eastward. The carbonate section in the northwestern part of the area is a source of water for domestic and commercial uses. Water-level data indicate an artesian head in the bedrock in most places throughout the study area, although, in some places, the levels are not far above the top of bedrock.

The study area in its original state (before quarrying began in 1967) had no bedrock exposures, although in the northern fringes of the modeled area bedrock is very close to land surface. At present, about 100 acres of limestone bedrock has been exposed by quarrying (fig. 1).

Stream-Aquifer Relations

Several reaches of the Scioto River, Scioto Big Run, and Big Walnut Creek in the study area are known to be losing part of their flow to the ground-water system; however, reliable quantitative data on these streamflow losses do not exist. The relations of streams and aquifers in the study area are complicated somewhat by the presence of numerous lakes resulting from quarrying operations.

In the northern part of the study area, a gain/loss study of the Scioto River in October 1982 showed an estimated loss of at least 6 ft^3/s (cubic feet per second) between the U.S. Geological Survey gage at the Jackson Pike Sewage Treatment Plant (station 03227500) and a site about 0.5 mile north of I-270 (fig. 2). A precise value of the loss was impossible to determine because of variation in the amount of effluent released by the sewage-treatment plant and long time-of-travel conditions (de Roche, 1985, p. 22). At quarry A (fig. 1), the limestone has been excavated to approximately 110 feet below the bed of the Scioto River. Because of leakage into the pit from the Scioto River, Scioto Big Run, and quarry lakes, as well as flow from the aquifer, pumping is required in order to maintain desired water levels for quarry operations.

Loss of Scioto River streamflow due to induced infiltration near the South Well Field probably is not great enough to be detected given the approximately 5-percent error expected in gain/loss studies. Assuming the amount of water from streambed infiltration to be as much as 30 percent of the total pumped by each of the three collector wells adjacent to the Scioto River(de Roche and Razem, 1984, p. 28), the amount of flow induced would range from 1.6 to 2.8 Mgal/d, depending on which of the wells was pumping. The higher figure is equivalent to about 2.7 percent of the base flow (the stream discharge that is equaled or exceeded 90 percent of the time).

The approximate flow of 10.2 ft^3/s measured for Scioto Big Run east of SR 104 (de Roche, 1985, p. 23) comes mainly from a breach in the levee at the southeastern corner of an unnamed lake covering about 21 acres south of quarry B and west of I-71 (fig. 1). The lake is being used to convey water pumped from excavations at quarry B to Scioto Big Run. Although the excavations have reached levels approximately 50 feet below the base of the lake, the lake bed has accumulated silt, and there is little if any leakage directly from the lake to the sump at quarry B. At a rate of 10 ft^3/s, drainage through the breach could lower the lake surface about 1 foot per day if there were no sources to replenish the lake.

As reported by de Roche (1985), Scioto Big Run immediately upstream from the breach is, noticeably, a losing stream. After heavy rains fell in mid-July 1986, streamflow, which was initially strong, diminished, and some reaches became dry within a few days. On July 28, 1986, the following was observed:

(1) At the breach, the lake level was about 1 foot higher than the surface of Scioto Big Run. Although not measured, the flow from the lake to Scioto Big Run was estimated at 10 ft^3/s.

(2) The bed of Scioto Big Run upstream from the breach was dry for about 1 mile, almost to Gantz Road (fig. 1).

(3) The only other noticeable discharge from the lake was a small pathway of seepage from the southwestern corner of the lake toward the dry channel of Scioto Big Run. The water disappeared into the intervening gravel bank before reaching the stream channel.

Although no gain/loss measurements have been made, there is evidence that Big Walnut Creek is a losing stream in the vicinity of collector well 115. At well FR-3, which is located along Big Walnut Creek near the U.S. Geological Survey gaging station at Reese (03229500) (fig. 2), ground-water levels, except for occasional peak stages, are usually above creek levels (fig. 11).

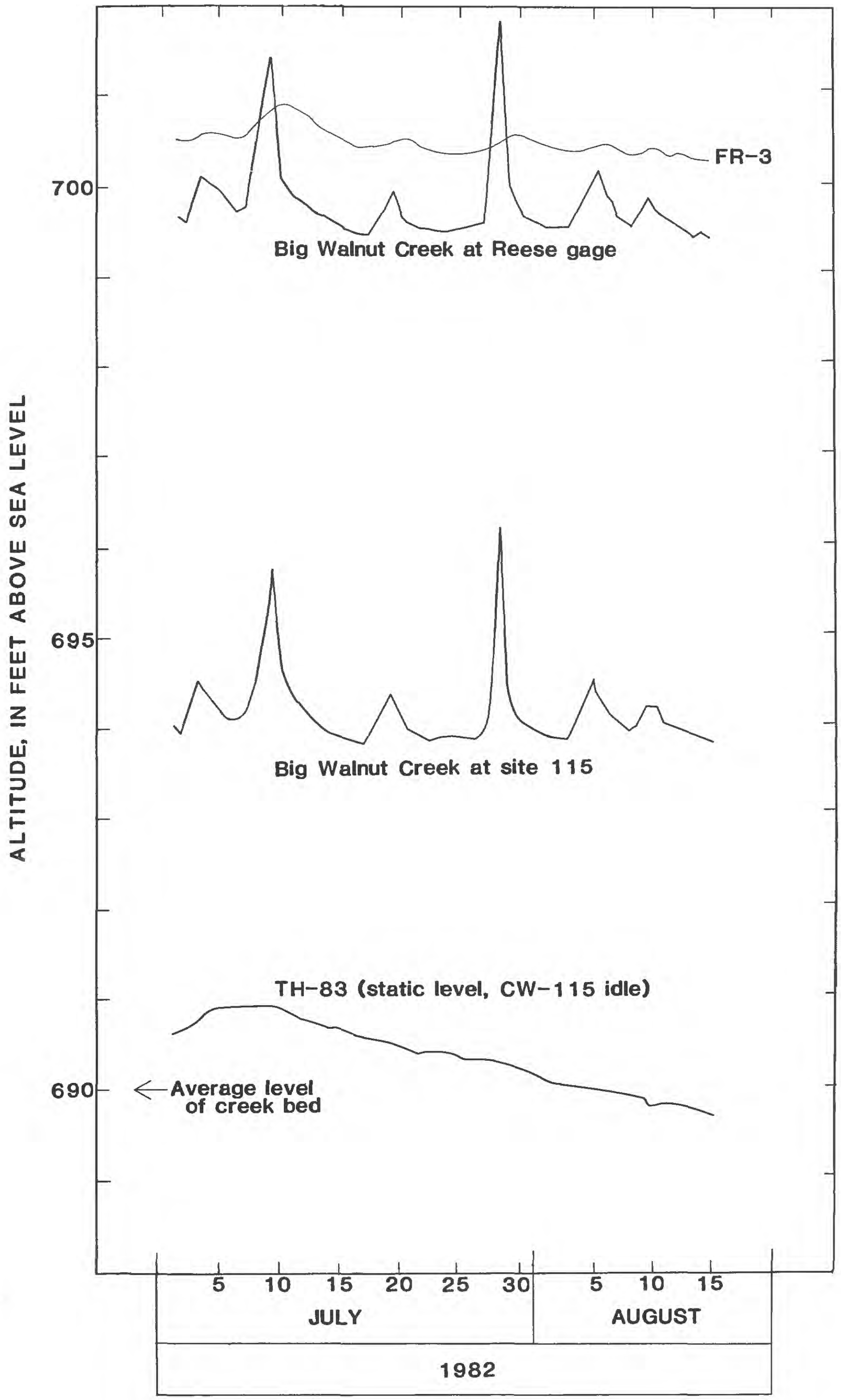

Figure 11.--Relation of ground-water levels to stage of Big Walnut Creek.

In contrast, at well TH-83, which is about 50 feet east of Big Walnut Creek and 420 feet east of CW-115, water levels are below creek levels even when CW-115 is idle (fig. 11). There are also times when the static water level at TH-83 is below the bed of Big Walnut Creek. Farther north, at well TH-67 (fig. 2), a similar relation between ground water and stream levels suggests that Big Walnut Creek also loses water to the aquifer near TH-67.

Hydrographs (fig. 12) of stream records collected during an aquifer test at site 115 (Stilson and Associates, 1977) show that, for relatively low flows, Big Walnut Creek stages between the Reese gage (03229500) and site 115 differ by a consistent 5.6 feet. On the basis of stage records available for the Reese gage during the current study, this difference of 5.6 feet was used to calculate stream-level elevations needed to compare ground-water/surface-water relations at site 115.

Recharge

In southern Franklin County, before large-scale pumping began, recharge to the ground-water system was mostly by precipitation, ground-water flow into the study area, and infiltration from flood waters. Within the study area, ground-water discharge was principally along the major streams. Natural infiltration from losing streams such as that described earlier for a part of Big Walnut Creek probably was minimal. Essentially, the drainage network was made up of gaining streams.

Large-scale ground-water withdrawals have caused stream infiltration to the aquifer induced by pumping to become a locally important form of recharge. The effect of this is visible along dried-up sections of Scioto Big Run and is demonstrated by gain/loss measurements (de Roche, 1985) that show that the Scioto River is losing to the ground-water system near quarry A.

Recharge from rainfall is controlled largely by the permeability of the surficial materials. Recharge also is influenced by slope of the ground, seasonal variations of temperature, plant growth, and evapotranspiration, all of which affect soil moisture.

Estimates of recharge from precipitation were made by Stowe (1979, p. 70-78) for four areas of differing surficial geology in southern Franklin County. These estimates were based on generic recharge rates calculated for various glacial materials using base-flow separation of stream hydrographs. Annual equivalents of Stowe's estimates range from 4.2 inches for areas covered chiefly with till to 9.4 inches for areas covered with alluvium, outwash, and kames. The average for Stowe's study area of 74 mi^2, which includes much of the current study area, is 6.5 inches annually.

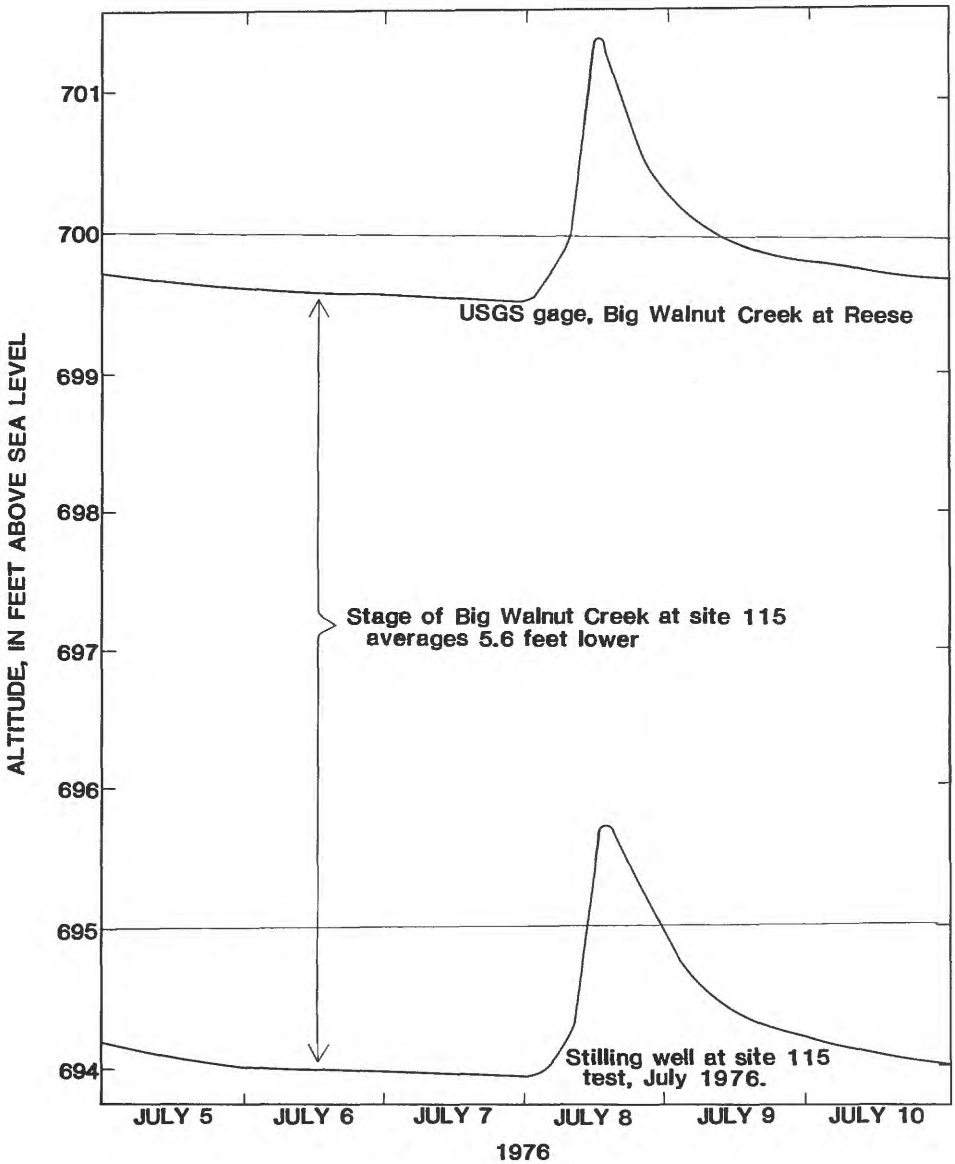

Figure 12.—Relation of stage of Big Walnut Creek between gage at Reese and site 115, 2 miles downstream.

The average annual precipitation during the current study was 36.6 inches or about the average annual amount cited by Stowe (37 inches). Thus, estimates of recharge from precipitation considered in this investigation range from one ninth to one fourth of the annual rainfall.

Weiss and Razem (1980, p. 9-11) used an annual recharge rate from precipitation of 12 inches in their digital model of southern Franklin County. This estimate was based on hydrograph fluctuations of well FR-109 (fig. 2). Their calculation assumed a specific yield of 10 percent and used water-level rises in FR-109, which totaled 10 feet during the period January through December 1977. The rate postulated by Weiss and Razem is reasonable, except that part of it may be attributed to flooding along the Scioto River.

Water levels in well FR-109, which is located 3,000 feet from the Scioto River on terrain slightly upland from the flood plain adjacent to the river, indicate the effects of flooding on recharge. The sharp rises shown by the hydrograph of FR-109 in figure 13 for the period following November 10, 1985, are responses to flood stages of the Scioto River rather than to precipitation alone. In summer and early fall, when river stages are low, the hydrograph of FR-109 usually exhibits little response to rainfall such as is shown in figure 13 for the period prior to November 9, 1985. Even an unusual event such as the 5.7 inches of rain measured at the Parsons Avenue Water Plant during a cloudburst on July 15, 1985, caused the water level to rise only 0.6 foot at FR-109.

Several periods of pronounced water-level rises at FR-109 that were accompanied by relatively abundant precipitation (fig. 13) also were times when the Scioto was known to have spilled out of its banks onto the bordering flood plains. On five occasions, between November 10, 1985, and March 13, 1986, the Scioto River flooded several hundred acres of lowland to the east of its channel between I-270 and collector well 103 (fig. 1). Each time the lake came within several hundred feet of well FR-109. Estimated levels for three of the flood lakes, which are based on high-water marks observed in the vicinity of collector well 103, are plotted on figure 13.

The peak stages for the Scioto River[2] plotted against the hydrograph for FR-109 (fig. 13) indicate that ground-water levels usually crest at FR-109 a couple of days after the Scioto River crests. The comparisons clearly show that whenever the bottom lands are soaked by floodwaters for any length of time, ground-water levels rise abruptly at FR-109, but recede very slowly com-

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[2]Determined from stage records of the Scioto River at collector well 104, in conjunction with mean gage-height values recorded at the U.S. gaging station at Jackson Pike Sewage Treatment Plant (03227500, fig. 2).

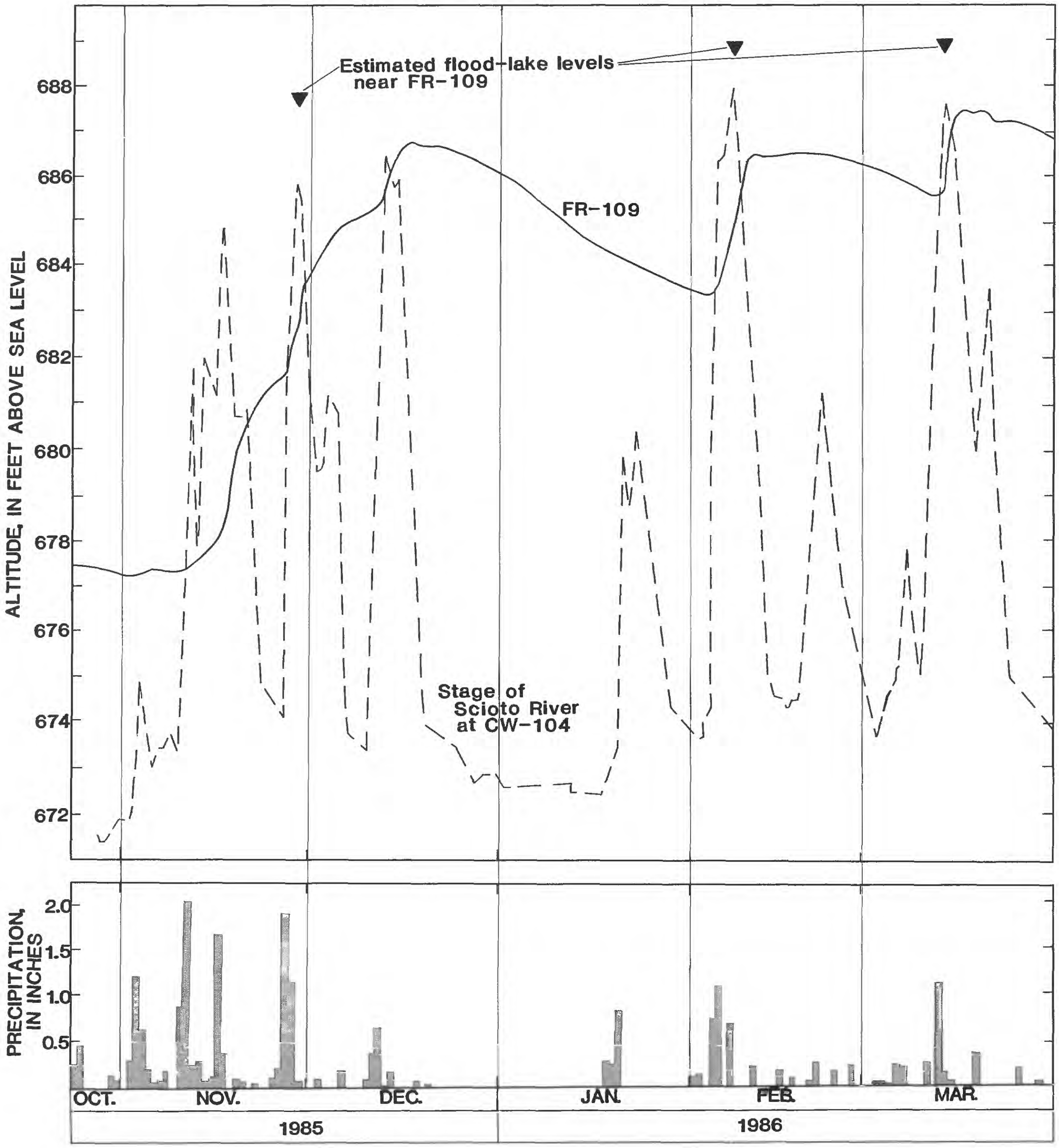


Figure 13.--Relation of ground-water levels, precipitation, and stage of Scioto River during recharge season, 1985-86.

pared with recession of the river stages. The recessional trend in FR-109 is useful as a background when computing water-level fluctuations in other wells.

The following table summarizes recharge estimates calculated with the technique used by Weiss and Razem (1980) for well FR-109.

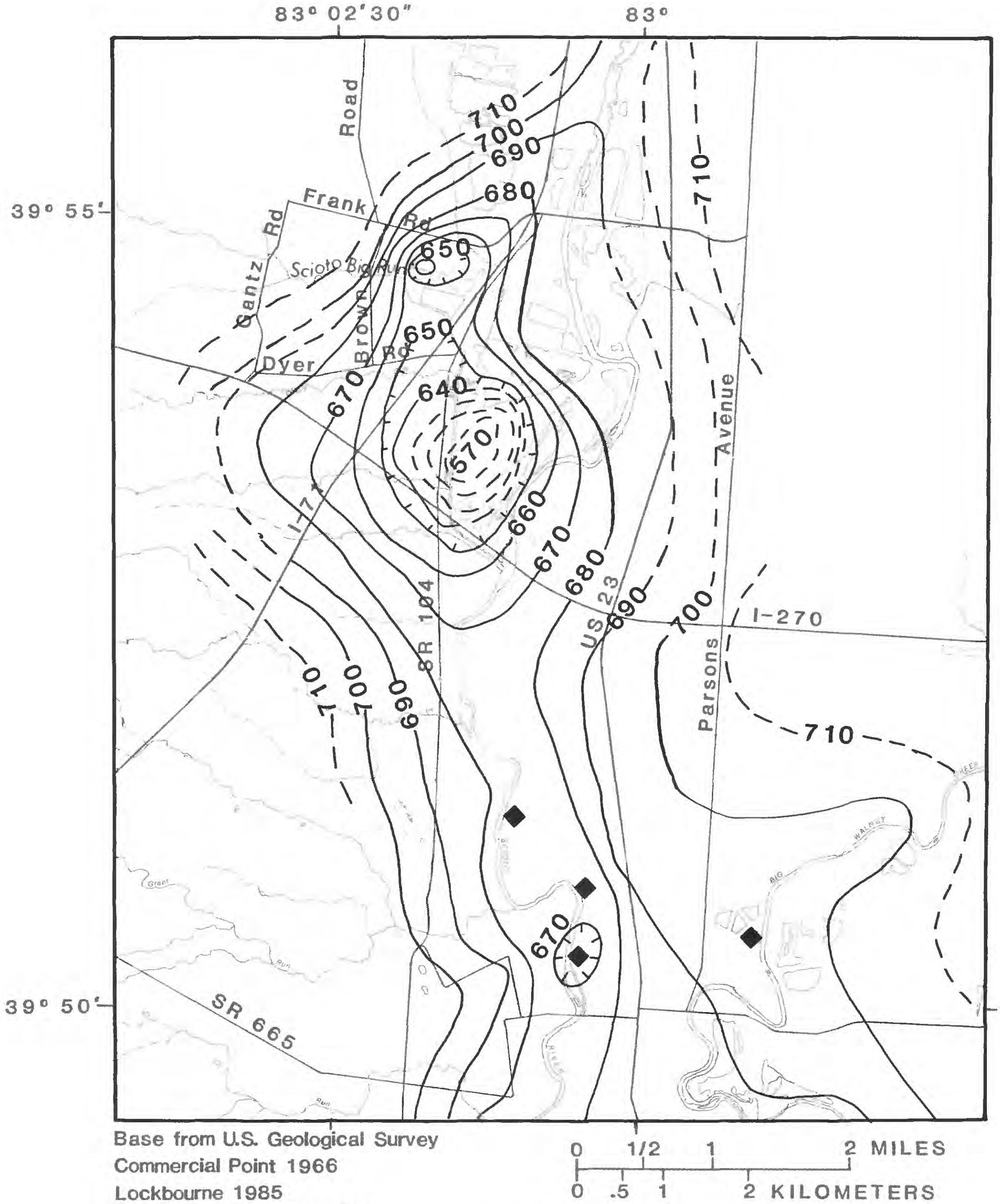
			Annual recharge based on 10 percent specific yield		
Water year	Precipitation (inches)	Total of incremental rises at FR-109 (in feet)	in feet	in inches	as a percentage of annual precipitation
1983	29.60	11.05	1.10	13.2	45
1984	37.81	14.10	1.41	16.9	45
1985	38.85	12.45	1.24	14.9	38
1986	40.08	16.81	1.68	20.2	50

The percentage values in the last column of the table show that recharge calculated by this method varies more widely than the annual precipitation. Moreover, the percentage values are considerably higher than the highest recharge-rate estimates (one-fourth of annual precipitation) discussed earlier. The conclusion is that flooding by the Scioto River is largely responsible for recharge at FR-109.

Hydrographs of the other recorder-equipped wells were examined for noticeable recharge events caused by precipitation. In general, such events in the wells were masked by the effects of pumping or stream fluctuations, depending on location.

GROUND-WATER LEVELS

The water-level maps for the glacial aquifer (fig. 14) and the bedrock aquifer (fig. 15) represent conditions in March 1986. In general, bedrock water levels near the Scioto River tended to be slightly higher (usually less than 1.0 foot) than levels in the glacial aquifer. In areas of considerable dewatering, the difference was not apparent.

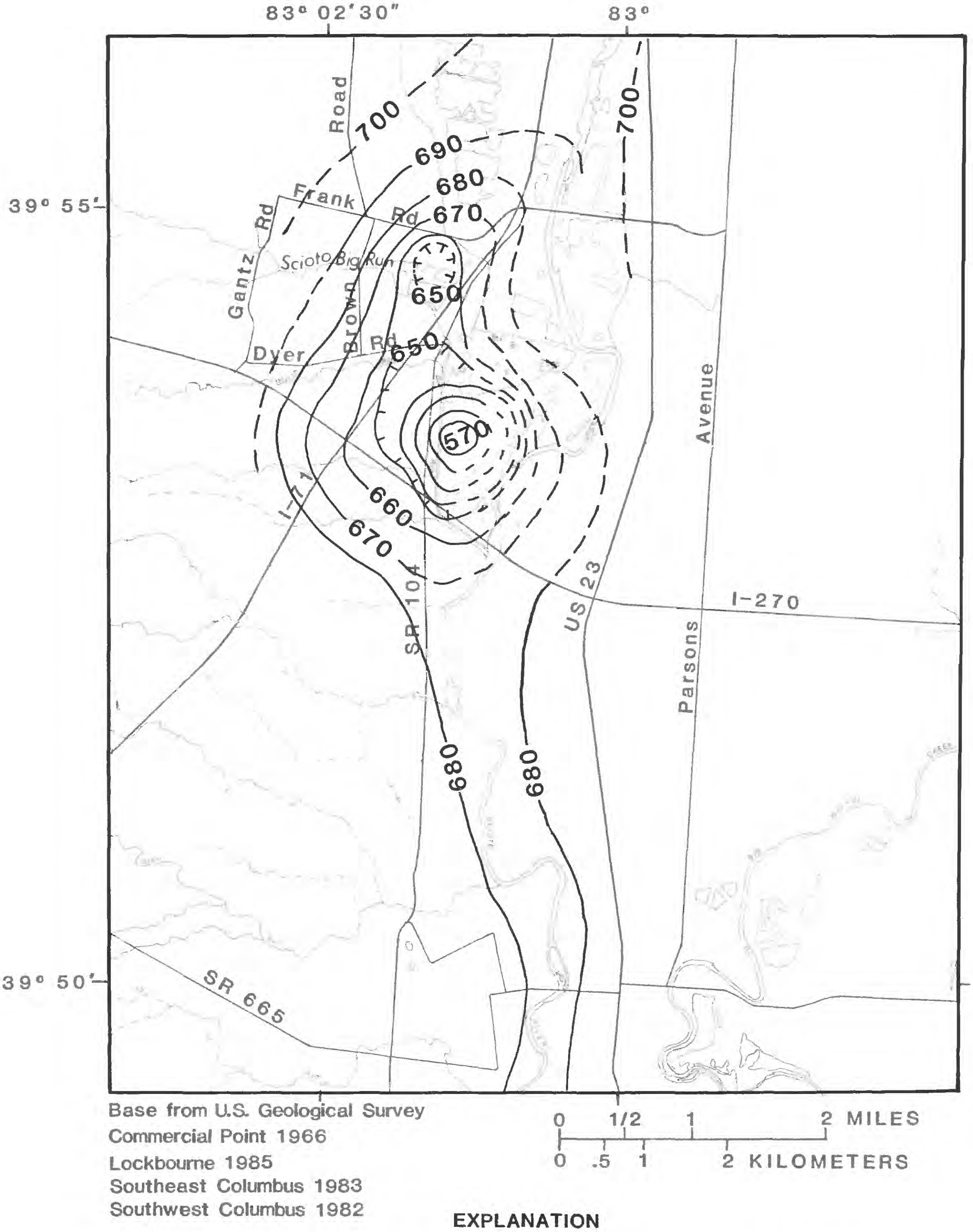


EXPLANATION

—690— Line of equal altitude of water level in glacial aquifer (layer 1), dashed where approximately located. Interval 10 feet except near large water-level depression. Datum is sea level.

◆ Collector well

Figure 14.--Ground-water levels in glacial aquifer, March 1986.



EXPLANATION

——680—— Line of equal altitude of potentiometric surface in bedrock aquifer (layer 2), dashed where approximately located. Interval 10 feet except near large water-level depression. Datum is sea level.

Figure 15.--Potentiometric surface in the bedrock aquifer, March 1986.

Water-level maps constructed from measurements made every 2 months show that the northern half of the study area is characterized by two persistent, deep depressions. Pumping-center depressions caused by operation of the collector-well system in the southern half of the area are subdued compared with those in the northern half of the study area.

Water levels in the study area are subject to seasonal variations. During the period of study, water levels generally were lowest in late January 1985 when conditions of extreme cold and little recharge from precipitation prevailed. Levels generally were highest in mid-March 1986 after a mild winter with abundant rainfall.

Water-Level Trends near Quarries

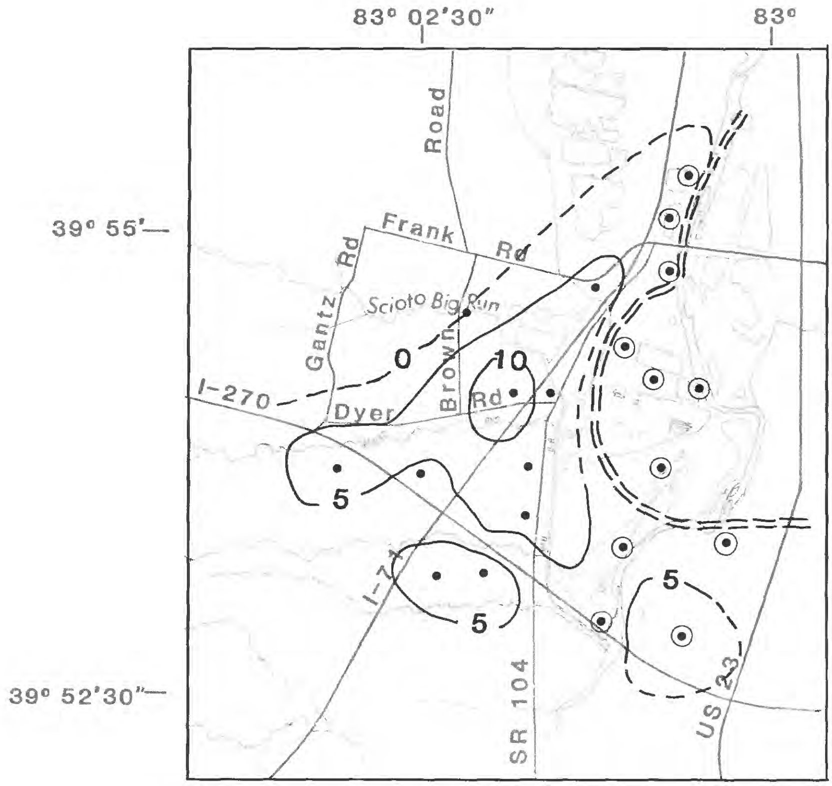
Ground-water flow in the northern half of the area converges toward quarries A and B as mapped (figs. 14 and 15). De Roche (1985) mapped water-level changes in the vicinity of the quarries between 1979 and 1982. Most of the same wells were measured in this study; figure 16 illustrates water-level changes from July 1982 through January 1985. The declines shown are for all wells in the area regardless of aquifer type. Water levels in wells tapping the bedrock aquifer north of Frank Road along Brown Road did not change much during this period, whereas farther south, in the area of Dyer and Brown Roads, water levels declined steadily in both the glacial and bedrock aquifers. In places, the glacial aquifer had been dewatered. Elsewhere, differences in water levels between the two aquifer types were inconsequential.

The map shows an area of wells drilled in 1982 for the landfill-effects study (de Roche, 1985) in which water levels by January 1985 were higher than in 1982. Several of the same wells reached their highest levels in May 1983 and March 1984, when peak flows of the Scioto River occurred. Several of the wells drilled in 1982 are located south and southeast of the limestone quarry (quarry A, fig. 1), and are within the area in which water levels continued declining through January 1985. These wells are under the influence of pumping from ponds on both sides of the river in connection with the quarry operations.

It should be noted that, in general, water levels in many of the wells located in the area of greatest declines rose to some extent by March 1986 after a winter season of abundant recharge. Even at FR-264, a well in the limestone nearest quarry A, the water level was 4.6 feet higher than it was on January 31, 1985.

Water-Level Trends near the South Well Field and Scioto River

Ground water in the southern part of the study area generally flows toward the Scioto River or Big Walnut Creek, and locally converges toward each of the collector-well sites.



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

0 1 2 MILES
0 1 2 KILOMETERS

EXPLANATION

— 5 — Line of equal water-level decline, 1982-85. Contour interval, 5 feet: dashed where approximately located.

⊙ Location of test wells drilled in 1982 for landfill effects study.

• Well locations measured in 1982-85.

= = = Line separating area where water levels generally declined during 1982-85 from area (on the east) where water levels generally rose during 1982-85.

Figure 16.--Water-level changes in northern part of study area.

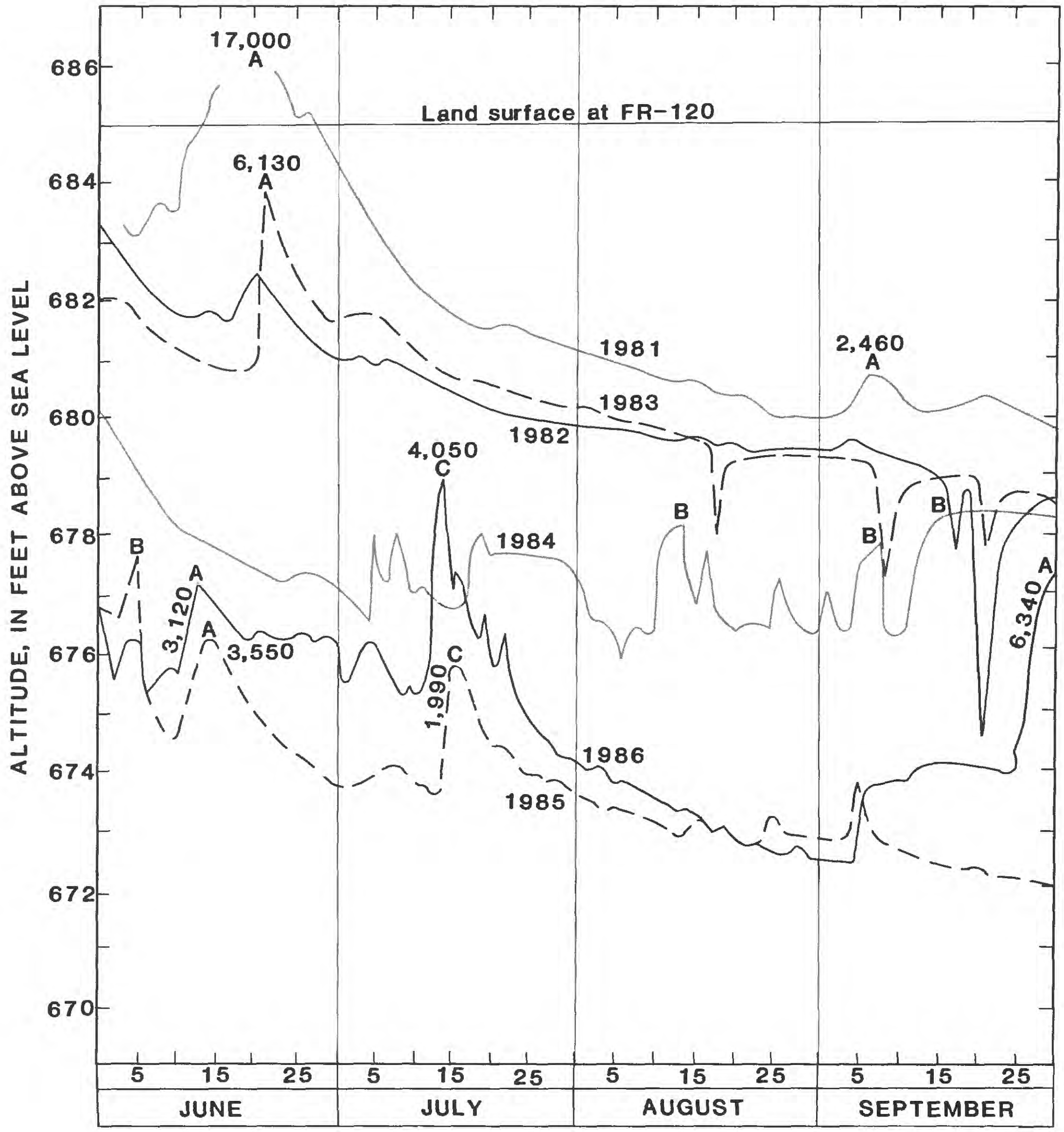
At times, the flow pattern may be modified by rising river stages, especially during periods of peak streamflow in winter and spring.

Figure 17 shows water levels in well FR-120 during the summer months for 1981 through 1986. This well was equipped with a continuous recorder and was chosen for the comparison of summer water levels because of its length of record (1981 to present) and its response to the Scioto River and collector well 101 (CW-101). The water-level peaks shown in figure 17 are a result of peak river flows, cessation of pumping at CW-101, or a combination of both. The sharpest declines occurred whenever pumping resumed at CW-101. Peak values of daily mean discharge measured at station 03227500 are indicated in the figure at points where the hydrograph for FR-120 is believed to have been strongly influenced by the river.

FR-120, located across the river about 1,000 feet from CW-101, is close enough to respond quickly to CW-101 but is not as "flashy" as other wells such as TH-73, TH-67, and TH-83 (fig. 2), which are closer to pumping centers. The July-September interval is normally a period of recession that follows the main recharge period during spring, much of which may result from flooding. In some years, such as 1981 (fig. 17), considerable recharge continues into June, after which seasonal recession of water levels usually prevails. At other times, such as late September 1986 (fig. 17), increased streamflow may override the effects of pumping and cause a reversal in what is normally a recessional trend of ground-water levels.

Monthly discharge totals of the Scioto River at the Survey's gage near the Jackson Pike Sewage Treatment Plant for the June-September period for 1981 through 1986 are as follows:

Total of daily mean discharges, in ft^3/s				
Year	June	July	August	September
1981	124,407	16,015	6,371	25,122
1982	34,740	10,347	5,376	5,180
1983	30,350	14,769	6,092	5,105
1984	12,329	7,628	7,552	5,602
1985	29,441	15,696	8,074	5,946
1986	29,686	45,462	1,732	33,153



EXPLANATION

A Water-level peaks caused by peak river flows.

B Water-level peaks caused by recovery from pumping at CW-101.

C Water-level peaks caused by a combination of A and B.

3,120 Peak value of daily mean discharge, in cubic feet per second, of Scioto River at station 03227500.

Figure 17.—Ground-water-level trends at FR-120 during summer recession periods, 1981-86.

It can be concluded from the stream-discharge data, pumping records, and information contained in figure 17 that stream discharge is an important control on ground-water levels at FR-120 and site 101. At FR-120 the hydrographs for 1982 and 1983 are nearly coincident because stream discharge for the June through September period was similar, and pumping at CW-101 was only incidental. The trends for both years are closely parallel to the trend for 1981, a year of considerably higher stream discharge. Except for brief periods of pumping, the water levels for 1981 through 1983 reflect natural conditions.

Although flow conditions of the Scioto River during July through September 1984 were similar for the same periods of 1982 and 1983, less recharge at FR-120 occurred in June 1984, and pumping at CW-101 helped to hold water levels lower at FR-120 than in previous years for the same months. Pumping records compiled by the City of Columbus show that in the summer of 1984 one pump was running at CW-101 on most days until September 12, when CW-101 was idled in preparation for a stress test that was conducted from October 4 through November 15, 1984. After the pumping ceased in September, water levels at FR-120 rose nearly to those that prevailed for the same period of 1982 and 1983. These comparisons show that, through September 1984, pumping at CW-101 had not inflicted a permanent downward trend on local water levels.

Compared with the summer of 1984, streamflow was greater in the summer of 1985. However, because two pumps were operated at CW-101 on most days in the summer of 1985, water levels were lower. Water levels in 1986 at FR-120 were mostly higher than in 1985, partly because pumping was lessened somewhat, but also because of increased flow of the Scioto River in July and, especially, in late September. The strong upward trend in early September 1986 can be attributed to operation of just one pump at CW-101. The abrupt rise after September 25, despite pumping, was a result of abundant rainfall that continued into October and caused local flooding.

Water Levels near Collector Wells during Stress Tests

During the period December 1983 through December 1985, the City of Columbus conducted four collector-well stress tests in which each of the collector wells was subjected to continuous pumping at the maximum design rate for at least 30 days. The U.S. Geological Survey, with its network of observation wells, used the opportunity to measure the extent of the cone of depression produced in each test and the effect of the pumping on local ground-water levels. Figure 18 shows the estimated extent to which the cone in each test developed. The values used to construct the maps are drawdown measurements that were determined at the well locations shown in figure 18. Because of its location and continuous record, FR-109 was used to adjust the drawdown data to account for natural ground-water-level declines.

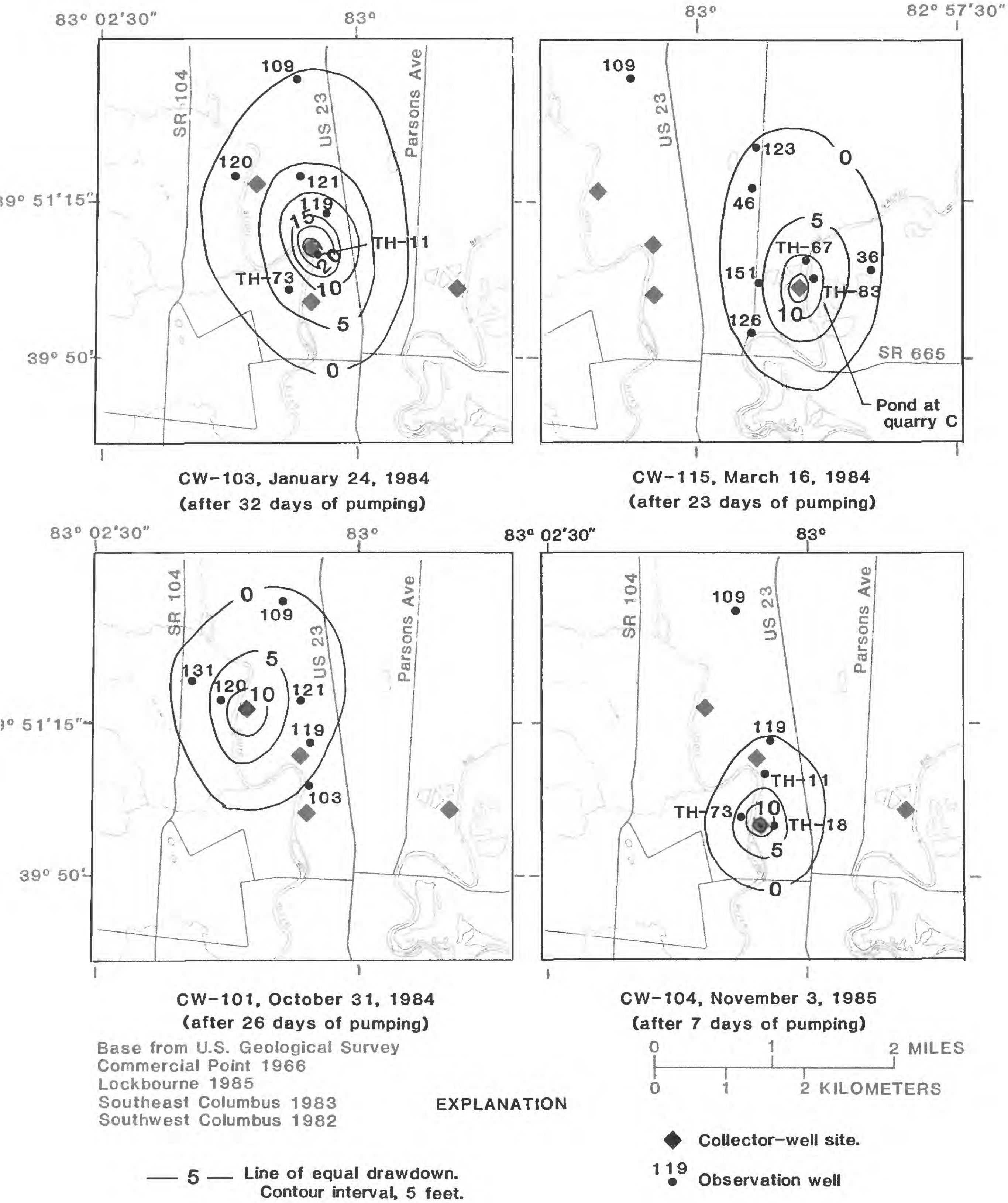


Figure 18.--Estimated maximum cones of depression during collector-well stress tests.

Table 3, which contains data summarizing the collector-well tests, includes results of volume-of-cone analyses. The volume of the dewatered cone is based on a distance-drawdown graph similar to that used by Norris (1979, p. 17). The ratios of the pumped volume to the cone volume are not intended as a true measure of the storage coefficient because in tests of this length, it is unrealistic to assume that the water pumped comes entirely from storage.

In general, the analyses show that, as pumping continued, the ratio of pumped volume to cone volume increased. The higher values are related to increased recharge from precipitation, better stream infiltration, or both. However, the pumped-volume to cone-volume ratio derived for the CW-101 test is unusually high. Some explanation for this is given in discussion of the collector-well tests in the sections that follow.

Collector Well 103

Collector well 103 (CW-103) is located about 75 feet from the river's edge on the east bank of the Scioto River 3.4 miles downstream from Route I-270 (fig. 1). A three-tiered system of sixteen water-collecting laterals radiates from the caisson at depths ranging from 96 to 106 feet below ground level, or about 68 to 78 feet below the average level of the river bed. Average length of the laterals is 77 feet. Only one of the laterals reaches a position below the river. Design capacity of the CW-103 unit is 14.4 Mgal/d.

The CW-103 test, which began December 23, 1983, and ended January 27, 1984, was the first of the four collector-well stress tests planned for the South Well Field. Figure 18 shows the maximum extent estimated for the cone of depression formed during the test. The cone is believed to have reached its maximum size on or about January 24, 1984, some 32 days after the test began. Water levels at FR-109 declined 2.2 feet during the test, but at least 2.0 feet of this probably was due to normal recession.

When the test began, the Scioto River was still receding from periods of peak flow earlier in the month. Records of the Scioto River stage measured daily at CW-104 are not available, and river-level elevations used in figure 19 were extrapolated from data collected at the U.S. Geological Survey's gaging station at the Jackson Pike Sewage Treatment Plant (station 03227500, fig. 2).

For much of the test period, subfreezing to subzero temperatures prevailed, and precipitation, mostly as freezing rain or light snow, was of little consequence as runoff. Because there was no effective recharge from precipitation until after 32 days of pumping, the spread of the cone was greater than in any of the other tests.

Table 3.--*Summary of data from collector-well stress tests*

[ft, feet; est, estimated; ft^3, cubic feet; mi^2, square miles]

Test data	Well number			
	CW-103	CW-115	CW-101	CW-104
Test period	12/23/83 to 1/27/84	2/22/84 to 4/2/84	10/4/84 to 11/15/84	10/22/85 to 12/30/85
Date cone of depression was at maximum size	1/24/84	3/16/84	10/31/84	11/3/85
Number of days after test began	32	23	26	12
Average pumping rate (millions of gallons per day)	14	7	14	7
Volume pumped (millions of gallons)	448	161	364	84
Volume pumped (ft^3)	5.99 x 107	2.15 x 107	4.87 x 107	1.12 x 107
Area of cone of depression (mi^2)	3.40	2.43	2.11	1.01
Area of cone of depression (ft^2)	9.47 x 107	6.78 x 107	5.88 x 107	2.81 x 107
Maximum drawdown (ft) at pumping well	35 (est)	18.7 (est)	16.3	19.1
Volume of cone[1] (ft^3)	3.1 x 108	2.5 x 108	1.37 x 108	1.04 x 108
Ratio of volume pumped to volume of dewatered cone	0.193	0.105	0.355	0.107

1

$V = (\pi/4.6)\Delta s r_0^2 (ft^3)$

where V is volume in ft^3;

Δs is line slope in ft/log cycle; and

r_0 is intercept of line with zero drawdown in distance (ft)

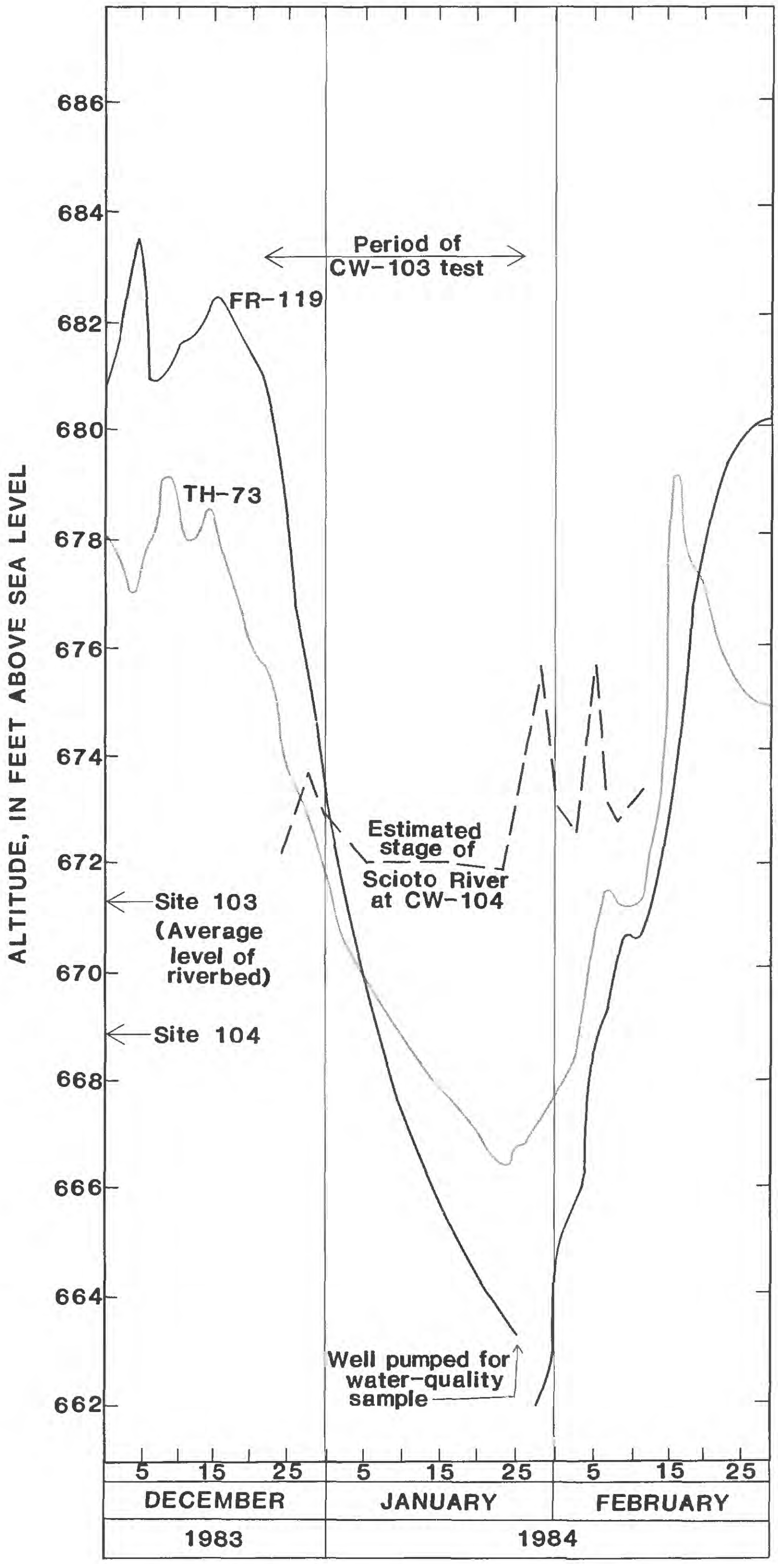


Figure 19.--Hydrographs relative to CW-103 stress test.

The depth to water recorded at TH-73 (fig. 19) suggests that the water table was losing contact with the river near site 104 after January 10. Similar relations between the aquifer and streambed near CW-103 are not known because there were no wells nearby that were equipped with recorders.

Water levels in FR-120 and TH-73 were at their lowest points in the early hours of January 24, 1984, which suggests that the cone was probably at its maximum size at this time. During a warming trend at that time, about one-half inch of rain fell, which was followed by an increase in Scioto River flow. Detailed examination of records reveals that water levels in the wells rose during the rise in streamflow after the rains had stopped. The only response noted at wells FR-109 and FR-119 is a very slight flattening of the hydrograph for both wells.

At well TH-73, the water table was still below the bed of the Scioto River when the rain stopped falling early on January 24. As at FR-120, the rise of ground-water levels coincided with the rise of the Scioto River. Thus, it would seem that the recharge in TH-73 came more from increased stream infiltration than from the rain.

FR-119, which had about 15.2 feet of net drawdown by January 24, was still declining on January 25 when the well was pumped in order to get a sample for water-quality analysis. However, the sampling interfered with further response of FR-119 to pumping and the first few days of recovery of CW-103. Interestingly, periodic measurements made at well FR-121, located about 3,600 feet north of CW-103 (fig. 18), show that water levels were still going down in that area on February 1. The distance of FR-121 from CW-103 and the river may account for what appears to be a lag effect of the pumping at CW-103. Had the record at FR-119 been left intact, the same type of lag response might have been recorded there also.

Collector Well 115

Collector well 115 (CW-115), on the west side of Big Walnut Creek (fig. 1), has a design capacity of 8.4 Mgal/d. Seven water-collecting laterals, averaging 152 feet in length are about 65 feet below ground level or about 46 feet below the bottom of the stream. Of the three laterals that extend toward Big Walnut Creek, only one actually reaches a position below the stream.

East of Big Walnut Creek are several ponds formed as a result of sand and gravel extraction, mainly at quarry C (fig. 1). To help evaluate any drawdown effects in this area caused by pumping at CW-115, a water-stage recorder was operated on the pond nearest CW-115 from June 1982 until late February 1985, when the recorder was lost either because of ice heave or vandalism.

Composited hydrographs made of stream and pond stages and ground-water levels for the CW-115 area reveal some significant characteristics (figs. 20 and 21). First, Big Walnut Creek is a losing stream along its reach at site 115. Second, the level of the pond is for much (and probably all) of the year below the level of Big Walnut Creek (fig. 20). Finally, there is evidence that sustained pumping during the CW-115 stress test had an effect on the level of the pond (fig. 21).

Evidence that Big Walnut Creek is a losing stream near CW-115 was mentioned earlier. Comparison of hydrographs for the stage of Big Walnut Creek at site 115 (fig. 21) shows that whenever there is a nonpumping period lasting for several days, the recovery curve at well TH-83, which rises steeply for the first few days, tends to flatten out at a level lower than the surface of Big Walnut Creek. Three such periods are summarized as follows:

Dates	Elevation of Big Walnut Creek at CW-115 (in feet above sea level)	Elevation of water level at TH-83 (in feet above sea level)
Nov. 10-14, 1984-------------	694.2-696.7	689.7-690.2
June 30-July 14, 1985-------	693.8-695.7	691.3-691.8
June 15-29, 1986-------------	693.8-694.8	691.9-692.1

The altitude of the stream bottom during a test at site 115 in 1976 was as low as 688.5 feet above sea level but averaged 690.0 feet (Stilson and Associates, 1977). Thus, there are times, such as November 1984, when water levels in TH-83 are at or even below the base of the stream after recovering fully.

Figure 20 shows that during periods of major recharge, pond levels have a subdued relation to the peak stages of Big Walnut Creek. The trend also shows the effect of seasonal withdrawals from the pond by the quarrying company. The water pumped is used for gravel-washing operations, and, at times, the pond is pumped to lower the pond to levels required for other plant operations. The company shuts down its gravel-washing operations during freezing weather, and for several months the pond is not pumped. During the summer the pond is pumped at 1,500 gallons per minute for about 8 hours three to five nights per week. The pond, which covers about 22 acres, if pumped for 20 nights at this rate, could be lowered about 2 feet if recharge from rainfall or ground-water seepage did not occur. The year 1983 was chosen to illustrate the relation between Big Walnut Creek,

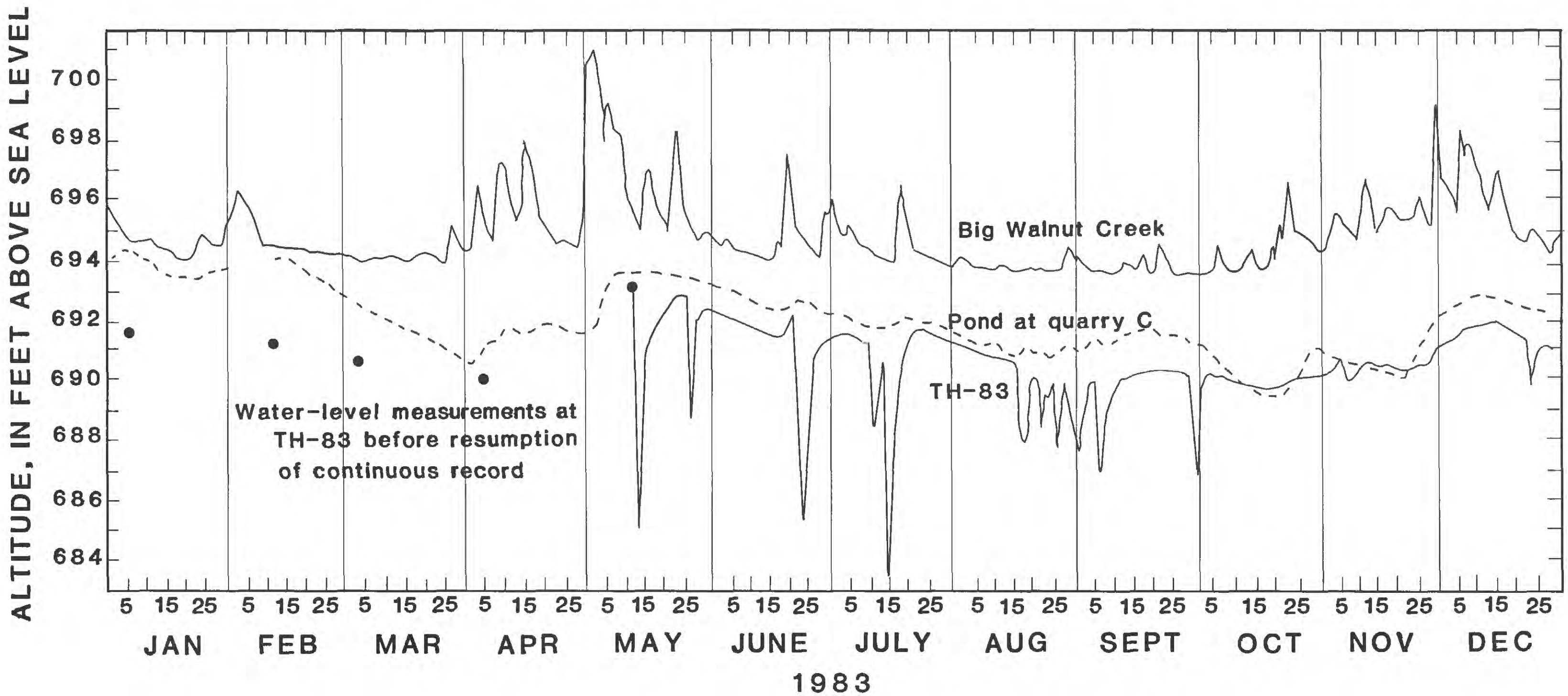


Figure 20.--Stage of Big Walnut Creek at site 115 in relation to surface of pond at quarry C and water level at TH-83.

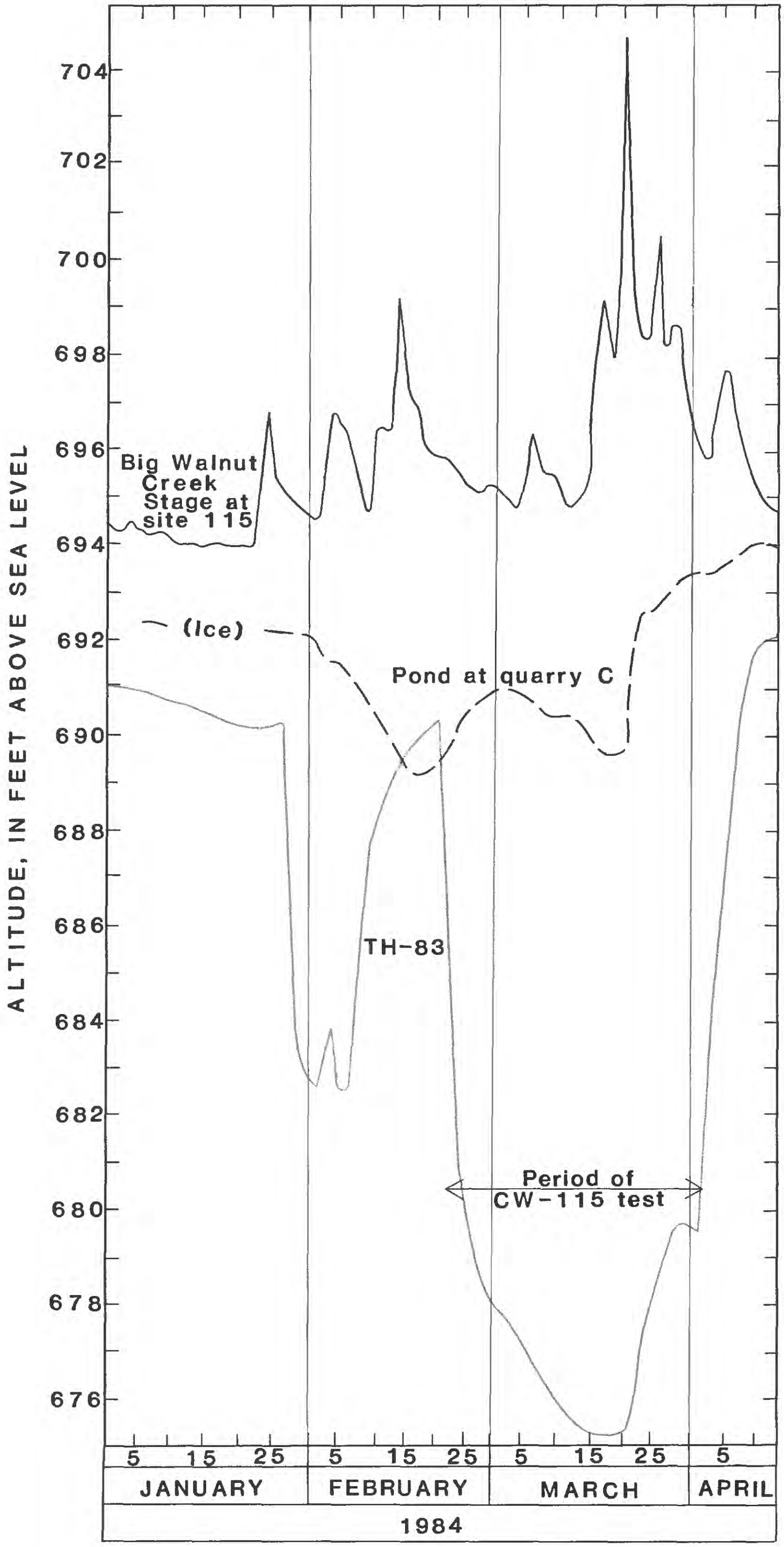


Figure 21.--Hydrographs relative to CW-115 stress test.

well TH-83, and the pond because pumping at CW-115 was intermittent and had no effect on the pond. Instead, static levels at TH-83 may have been controlled to some extent by fluctuations of the pond.

The CW-115 long-term stress test started February 22, 1984, and ended April 2, 1984. Hydrographs of TH-83, the pond, and the stage of Big Walnut Creek show the effect of the test (fig. 21). Records from wells TH-67 and TH-83 indicate that CW-115 was pumped continuously, prior to the stress test, from January 29 to February 7, 1984. These are the only periods in which an effect on the pond can be attributed to pumping at CW-115. Of significance is the fact that declines and recovery periods of the pond seem to be several days out of phase with TH-83, which shows that the pond-level changes lagged in response to pumping at CW-115.

After the first pumping period was terminated on February 7, moderating weather with rain and increased streamflow helped boost recovery. As figure 21 shows, the recovery curve at TH-83 is starting to flatten before the stress test was started on February 22. During the same period, the level of the pond at quarry C, which had been going down since February 1, continued to decline, reached a low point, and began rising shortly before the stress test started on February 22. The pond level rose until March 1, after which it again declined for about 2 weeks. A 2-foot drop of the pond, which covers approximately 22 acres, amounts to 14.3 million gallons, which is equivalent to nearly 9 percent of the water pumped during the CW-115 test.

A heavy snow cover accumulating since February 27 and having a moisture content equivalent to 2 inches of rainfall, contributed nothing to recharge until a general thaw began about March 15. Water levels in TH-67 and TH-83 began rising after March 17, and by March 21 water levels everywhere were rising sharply. After water levels were again declining (about March 30), the test was terminated on April 2.

It is apparent from figure 21 that the response of the pond at quarry C to continuous pumping at CW-115 lags by several days. No pumping was going on at quarry C during this time to interfere with the pond's response to the pumping at CW-115. After heavy rains moved into the area on March 20, the rise of the pond was rapid and showed no further response to the CW-115 test.

From the hydrographs and data gathered, it appears that the maximum stress of the aquifer was reached on or about March 16. Figure 18 shows the estimated extent of the cone of depression that had developed by that date. The drawdowns computed for the CW-115 test are based on the difference between measured levels and the normal recessional curve postulated for the aquifer using the hydrograph for well FR-109. In general, the adjusted values are 0.6 foot less than the differences actually measured.

Collector Well 101

Collector well 101 (CW-101) is about 100 feet from the river on the east bank of the Scioto River 2.2 miles downstream from Route I-270 (fig. 1). A two-tiered system of ten water-collecting laterals radiate outward from the caisson and range in depth from 68 to 71 feet below ground level, or 55 to 58 feet below the average level of the riverbed. Average length of the laterals is 202 feet. Of four laterals directed toward the river, three extend to positions below the west bank of the river.

The CW-101 stress test was conducted from October 4 through November 15, 1984. Figure 18 shows the extent of the cone of depression estimated at the end of the test. Unfortunately, fewer data could be obtained for determining the cone size than in the other tests, partly because of malfunctions of the recorder at FR-120 (fig. 2).

By comparing hydrographs, it was possible to construct an antecedent trend of water levels at the start of the test. Well FR-109 is within the area influenced by the test, and of the 1.57-foot decline in that well during the test period, about 0.6 foot can be attributed to a normal recession of the aquifer based on analysis of several years of record for FR-109.

During the test period, the Scioto River was relatively stable through November 5, 1984. After that, stream discharge increased and peaked on November 13. Rainfall during the period (October 5 to November 15) amounted to 5.22 inches at the Parsons Avenue Water Treatment Facility (fig. 1). More than half the rain fell in November. All of these factors would suggest that the maximum size of the cone may have occurred sometime in early November, but a lack of suitable data prior to November 13 makes it difficult to determine when.

Although CW-101 was pumped at about the same rate for approximately the same length of time as CW-103, the CW-101 cone of depression was smaller than the cone in the CW-103 test. Compared with the other collector-well stress tests, the ratio of water pumped to cone size at CW-101 was much greater, which implies that river infiltration and (or) recharge from precipitation was greater during the CW-101 test. The lowest pumping level in CW-101 during the test was on October 31, when the cone was probably at its largest size (fig. 18). The ratio of the volume pumped to the volume of the cone was about 35.5 percent through October 31. Inasmuch as similar ratios at the other sites were between 10 and 20 percent, the figure for CW-101 is unusually high.

The CW-101 test was made during a warmer period of the year than the CW-103 test, and there was considerably more rainfall. Streambed leakage through induced infiltration could have been enhanced by the warmer weather during the CW-101 test because the viscosity of water decreases with increasing temperature.

Such an increase in induced infiltration coupled with the increase in rainfall probably deterred spreading of the cone.

Collector Well 104

Collector well 104 (CW-104) is located about 100 feet from the river on the east bank of the Scioto River 3.9 miles downstream from I-270 (fig. 1). Two tiers of water-collecting laterals, fifteen in all, radiate outward from the caisson at depths from 78 to 83 feet below ground surface, or 62 to 67 feet below the average level of river bottom. Average length of the laterals is 91 feet. Of several laterals oriented toward the river, three extend to positions below the river.

The CW-104 test began October 22, 1985, and ended December 30, 1985, the longest of any of the collector-well tests. Nearly record rainfall for November in Franklin County, which caused several periods of high water, made for less than ideal conditions for most of the test.

Several days of pumping with both pumps at CW-104 ended October 10 and was followed by 11 days of recovery (fig. 22) before the test. During this period, Scioto River discharge was in the 75-percent flow range (flow that is equaled or exceeded 75 percent of the time), and gage heights, read daily at CW-104, were close to an elevation of 672 feet. After October 1, CW-103 was idled in order to avoid interference from its pumping effects on pre-test collection of data.

Two recorder-equipped wells, TH-73 and FR-119 provided good records of the unusual events during the test. The hydrographs of both wells (fig. 22) show that recovery from the previous period of pumping was not yet complete when the test began. At FR-119, located 3,400 feet to the north of CW-104, the water level continued rising for nearly 3 days after the test started, which indicates a lag in aquifer response to the pumping at CW-104.

Figure 18 shows the estimated extent of the cone of depression at CW-104 developed after 12 days of pumping (October 22 to November 3) at a sustained rate of 7 Mgal/d. This was the smallest cone developed in any of the tests. After November 3, the cone probably became smaller because of increased recharge that resulted from the abundant rainfall.

Figure 22 shows an abrupt flattening of the drawdown curve for TH-73 after November 2, followed by a very steep rise after November 10, when streamflow increased sharply. For the same period the drawdown curve for FR-119 shows a flattening followed by an abrupt rise after November 11 because of local flooding by the Scioto River.

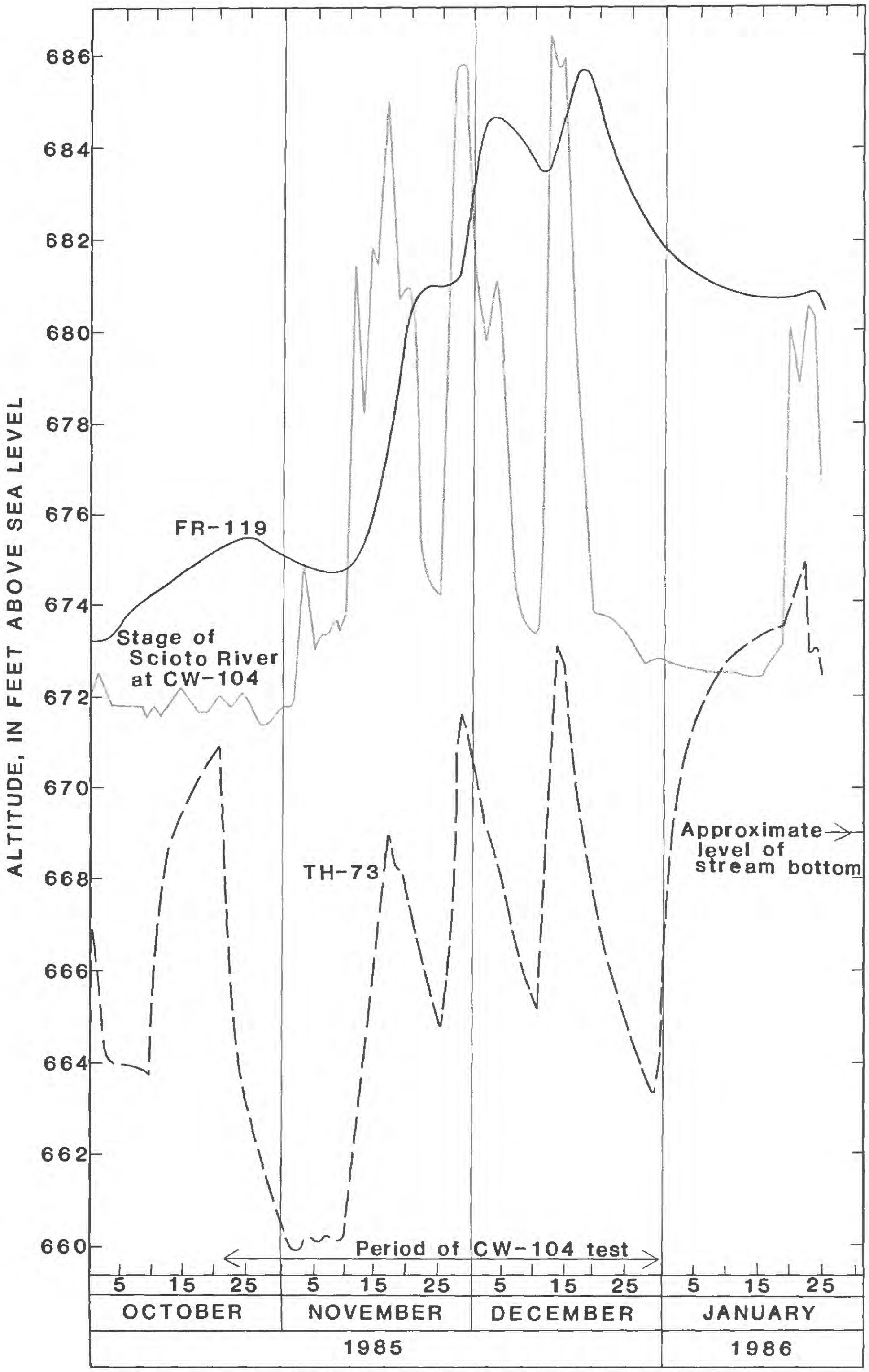


Figure 22.--Hydrographs relative to CW-104 stress test.

The sharp peaks shown in figure 22 for TH-73, which is located along the river, closely correspond to three peak-flow periods of the Scioto River during the test. Each of the water-level peaks is succeeded by a sharp drawdown curve as pumping continued in CW-104. For FR-119, which is located 1,200 feet from the river, the hydrograph is similar except that peaks are more subdued and lag several days behind those of TH-73.

A third drawdown period lasted about 16 days, until the test was completed on December 30. The extent of the cone at this time could not be determined because of the abundant rainfall and river flooding. Because the water level in TH-73 was higher at the end of the test than at the beginning, it follows that the cone probably also was smaller at the end than at the beginning.

Comparison of the recovery curves for TH-73 and FR-119 (fig. 22) shows that after December 30 water levels recovered quickly at TH-73 and were higher than the river surface within a week. This was an effect of increased ground-water storage resulting from earlier periods of peak flow. At FR-119, however, water levels continued to decline, but at a lesser rate, after the test was ended until falling sharply in response to a resumption of pumping at CW-103 on January 20. The hydrograph supports the suggestion that a ground-water mound resulting from flooding in mid-December near FR-119 was diminishing naturally. That the hydrograph for FR-119 shows no upward flexing when the test ended December 30 also suggests that effects of pumping at CW-104 were not reaching as far as earlier in the test.

On the opposite side of the river from CW-104 at TH-73, the water level, which at the start of the test had risen to within 1 foot of the river surface, dropped below the bottom of the stream within the first 24 hours of pumping, and by November 2 was about 9 feet below stream bottom. As the cone of depression grew, connection of the river bed to the aquifer was probably broken in the vicinity of CW-104 and probably remained so until an increase in recharge began refilling the cone.

The size of the cone during the CW-104 test was smaller than that for the CW-103 test because (1) CW-104 was pumped at half the rate, (2) the CW-103 test was essentially uninterrupted by recharge events, and (3) much warmer weather prevailed during the CW-104 test, which provided conditions more favorable for stream infiltration.

WATER QUALITY

Baseline Determination of Organic Chemical and Metal Constituents

Table 7 (at back of report) is presented primarily to document current background levels of organic and metal constituents in the ground water, surface water, streambed sediments, and soil within the study area. The constituents selected for analysis are listed in table 1; most are included in the U.S. Environmental Protection Agency (USEPA) list of priority pollutants (Keith and Telliard, 1979).

The organic constituents listed in table 1 are grouped according to analytical strategies and detection limits that were used at the U.S. Geological Survey National Water-Quality Laboratory. Only those organic constituents which were above detection limits for the respective groups in table 1 are reported in table 7.

For the baseline determination of organic constituents the water samples were all analyzed by the gas-chromatograph flame ionization detection (GC/FID scan) and volatile organic (VOC scan) methods. Methylene chloride was the only organic constituent listed in table 1 that was reported in amounts above the detection limit in the water samples, and is presumably an artifact of the analytical method used. The other organic constituents reported in table 7 were detected only in the stream-bottom and soil-core samples. Except for phenol, an acid-extractable compound, the organic materials were all of the base/neutral-extractable group.

To analyze for the metals and cyanide, listed in table 1, different detection levels were used for the various constituents. All of the metals (table 1) were reported at least once. Cyanide at all 16 baseline-sampling sites was below the detection limit. Although not on the USEPA priority pollutant list of toxic metals, the concentrations of dissolved aluminum, barium, iron, manganese, and strontium also were determined because these constituents were on the same analytical schedule that was used to determine the toxic metals.

The amount of dissolved strontium ranged widely among the baseline ground-water samples. Two wells with the greatest amounts, FR-209 and FR-246, respectively, tap glacial sediments and limestone. Both wells are located along the west side of the Scioto Valley where glacial sediments are underlain by limestone. In western Ohio, Feulner and Hubble (1960, p. 185) reported similar ranges for the occurrence of strontium in water samples collected from wells and streams which were also located in an area of glacial sediments underlain by limestone. The high strontium levels at FR-209 and FR-246 are thus believed to be of natural rather than anthropogenic origin.

Several of the baseline sampling sites also were used for the first (June 1984) periodic collection of water samples. Therefore, the same field measurements, specific conductance, pH, temperature, and dissolved oxygen appear in both tables 7 and 8 (at back of report).

Periodic Sampling

Results of the periodic sampling (June 1984 to April 1986) are given in table 8. Analyses of several miscellaneous samples collected between August 1983 and March 1984 are given in table 9 (at back of report). The objectives of the periodic and miscellaneous sampling were to monitor any changes in ground-water quality that might occur during the period of study and to compare constituent levels with similar data collected in earlier investigations.

In the southern half of the study area, which includes the South Well Field, 39 water samples were collected from 16 wells. Of this group, the following wells or collector-well sites were sampled previously.

Well or site	Data source
CW-115	de Roche and Razem, 1984
CW-103	do.
FR-36	do.
FR-145	do.
FR-73	do.
FR-121	U.S. Geological Survey, 1981
FR-120	do.

Based on the relative amounts of common constituents present, ground water in the southern half of the study area is characterized as a hard, calcium bicarbonate type (de Roche and Razem, 1984). With respect to time, the greatest variations in ground-water quality noted were in amounts of total organic carbon, phenol, and dissolved iron. Variations in concentrations of the common ions with time and between the various wells were minor.

Results of analyses listed in tables 8 and 9 were compared with maximum levels listed for National Drinking Water Regulations being promulgated by the USEPA (U.S. Geological Survey, 1985, p. 465). Nearly all ground-water samples collected in the southern half of the study area contained excessive amounts of iron. Concentrations of dissolved solids and manganese in most of the samples were at or below recommended levels. In general, concentrations of sulfate and chloride were well below the USEPA limits.

Water from one well, FR-73, was anomalously low in dissolved iron compared with other wells in the South Well Field area. In May 1980, the iron concentration was 1,600 µg/L (de Roche and Razem, 1984, p. 39). In June 1984, the concentration was 450 µg/L, and when last sampled in June 1985, the concentration was only 9 µg/L (table 8).

The reasons for this trend are speculative, although an important factor was probably the amount of dissolved oxygen in the water. Dissolved oxygen may oxidize dissolved iron; the oxidized iron may then combine with water to form hydroxides, which are lost as chemical precipitates or are removed during sample filtration through 0.45-micrometer membranes. Therefore, lower concentrations of dissolved iron generally are associated with greater concentrations of dissolved oxygen. Only one dissolved-oxygen measurement (June 1984) was made, however. The measurement showed 1.8 mg/L of dissolved oxygen in the water. The well is equipped with a turbine pump which could cause oxygen-enrichment during use. The well is completed in an unconfined section of sand and gravel and located near a kame terrace where recharge from oxygen-enriched rainfall is favorable.

Nearly all sites were tested for fecal-coliform bacteria. Minor occurrences found in two wells did not exceed the limits specified in the USEPA primary drinking-water regulations (U.S. Environmental Protection Agency, 1982), but amounts in the surface-water samples were many times higher.

Part of the miscellaneous sampling was a result of concern that was raised in 1982 about the possible migration of contaminants toward the recharge area of CW-115 from horse pens at a nearby racetrack (fig. 1). Well FR-151 (fig. 3) was installed in order to monitor water levels and collect samples to determine whether degraded water existed downgradient from the racetrack area. Because of their proximity to potentially degraded water moving toward CW-115, well FR-150 (a domestic well) and FR-115 P3 (near CW-115) also were selected for sampling.

In addition to the potential threat from the racetrack area, it was also learned that a burial site for the incinerated remains of 300 diseased hogs lay between wells FR-150 and FR-115 P3. Samples collected at FR-151, FR-150, and FR-115 P3 on September 3, 1983, however, did not reveal anything unusual in the way of organic constituents at these sites. A sewage system that had been recently installed at the racetrack presumably has served to reduce the threat of contaminated surface runoff entering the aquifer. Continued sampling at FR-151 through April 1986 showed no evidence of severely degraded water at that site.

In the northern half of the study area, 31 ground-water samples from nine wells were collected in the periodic sampling. In an earlier study, de Roche (1985) evaluated the effects of several landfills on local ground-water quality on the basis of samples collected from wells located in areas upgradient and downgradient to the landfills and within the refuse itself. Six of the same wells were sampled in the current study to detect any important changes in water quality that might affect the ground-water system. Wells FR-202 and FR-262, which are upgradient of the landfills, and FR-246 and FR-260, which are downgradient wells, showed little change from the earlier investigation. Wells FR-202 and FR-246 both tap limestone, and the composition of the water in both wells was similar except that iron and manganese were much higher at FR-246.

During the current study, water samples were collected several times at well FR-256 and once at FR-258. Although both wells penetrate areas underlain with refuse, the wells differ greatly in water quality with respect to some constituents, especially iron and manganese. A comparison of the analytical results with those obtained in an earlier study for the same wells (de Roche, 1985) indicates that changes in water quality were somewhat greater within the landfills than in adjacent areas. However, the changes were variable. At FR-256, for example, the amount of calcium and sulfate increased, whereas sodium and chloride decreased.

With respect to USEPA drinking-water regulations (U.S. Geological Survey, 1985, p. 465), the ground-water quality in the northern half of the study area is worse than that in the southern half, even excluding the two refuse-penetrating wells, FR-256 and FR-258. Nearly all of the wells sampled in the current study contained excessive amounts of dissolved solids, iron, and manganese. Excessive amounts of sulfate were noted in two domestic wells, FR-224-R and FR-217. FR-224-R, which taps limestone, was drilled as a replacement for FR-224 on the same property. During the current study, FR-224, which is finished in the sand and gravel aquifer, was mostly dry. Water from well FR-217, which is in the same area and taps sand and gravel, contained the highest concentration of dissolved solids of any of the wells sampled in the current study.

Two surface-water sites, B and C (fig. 3), were sampled eight times each, under a variety of weather conditions, to evaluate the effects of surface leaching and drainage at landfill 5 (fig. 1). Site C was located on an unnamed tributary that carries surface drainage from landfill 5 to Scioto Big Run. Site B, which served as a control, was located on Scioto Big Run just upstream from the unnamed tributary.

Comparison of water-quality records for the two stream sites near landfill 5 shows that there was a general diminution of constituent levels at both sites during periods of high streamflows. Important exceptions, however, were high counts of fecal coliforms and increased levels of total organic carbon at site B. This is a situation that may be expected during periods of storms due to the greater incidence of sewage overflow. The correlation at site C was not as obvious.

High runoff was observed when samples were collected in December 1984 and April 1985, but the highest was observed during the sampling of November 1985 when rainfall was much above normal. The diminution of constituent concentrations was even more pronounced at this time. However, at both sites, dissolved aluminum was at its highest level and, to a lesser extent, the level of dissolved silica was high. This is evidently a function of considerably increased surficial runoff carrying greater loads of suspended clay minerals to streams.

Increases in the amount of dissolved sodium and chloride in December 1984 at site B are significant exceptions to the diminution of concentrations mentioned earlier. Several inches of snow fell on Columbus in early December, and it can be assumed that the increased levels of these constituents were caused by deicing salts used on roads in areas that were drained by Scioto Big Run and its tributaries.

In contrast to site B, levels of sodium and chloride were markedly higher at site C during periods of low runoff. Also, the concentrations of dissolved solids, nitrogen-cycle species, total organic carbon, phosphorus, sodium, and chloride were usually greater at site C than at B. In contrast, concentrations of calcium, magnesium, and sulfate were always greater at site B, and resembled the composition of ground water. This is not surprising because, as suggested earlier (p. 33), a large part of the flow of Scioto Big Run at site B, when local runoff is low, is derived from ground water pumped at quarry B (fig. 1). Conversely, concentrations of the same constituents were lower during periods of high flow because the effluent from quarry B was being diluted by increased runoff.

The analytical results for site C show that, to some extent at least, surface leaching is occurring at landfill 5. Leachate is entering the local drainage system, which eventually enters the Scioto River. The analyses also show that higher runoff reduces the concentration of most of the constituents. Because of the diluting effect, the materials being carried by surface drainage at landfill 5 are not considered to be a threat to the ground-water system in the well-field area.

POTENTIAL EFFECTS OF TOXIC-SUBSTANCE SPILLS OR CESSATION OF QUARRY DEWATERING

Digital Model of the Ground-Water Flow System

A steady-state ground-water flow model was constructed using the McDonald and Harbaugh (1984) ground-water flow program. The model was used to address concerns regarding the location of the municipal ground-water supply with respect to highways, surface drainage, and local landfills. Specifically, ground-water flow directions and average ground-water velocities, based on the calibrated flow model, were used to assess the potential effects of toxic-substance spills along the major highways and directly into the Scioto River.

In addition, the ground-water flow model was used to predict how high water levels would rise near the landfills if quarry dewatering stopped. Changes in directions of ground-water flow corresponding to various scenarios for cessation of quarry dewatering also were determined.

Finally, the ground-water flow model was used to describe three-dimensional flow within the glacial-bedrock aquifer system. Previous steady-state (Weiss and Razem, 1980) and transient (Razem, 1983) models of the study area were two-dimensional simulations of the glacial outwash aquifer. It was necessary to consider the underlying bedrock aquifer during construction of the current model because one objective was to simulate the cessation of dewatering at a local limestone quarry (quarry A).

Assumptions

The following simplifications and assumptions were made to simulate the complex aquifer system:

(1) Flow within each aquifer is horizontal, and flow between aquifers is vertical.

(2) There is no significant horizontal flow in the shale that overlies the carbonate bedrock east of the Scioto River.

(3) There is no flow across the bottom of the bedrock aquifer.

(4) Glacial deposits compose a single, unconfined aquifer throughout the study area.

(5) The hydraulic conductivity of the glacial aquifer is uniform with depth at any point, but differs areally.

(6) The hydraulic conductivity of the bedrock aquifer is uniform with depth at any point. Transmissivity of the bedrock differs areally.

(7) All streambeds have a thickness of 1 foot.

(8) All wells fully penetrate the aquifer in which they are completed.

(9) At the scale of the model, the ground-water system is near steady-state; that is, ground-water levels and velocity at any point are constant with time.

Boundaries

The finite-difference grid used to simulate the study area is illustrated in figure 23. It is oriented north-south, parallel with the Scioto River. The grid consists of 1,344 (32 x 42) grid blocks and covers approximately 48 square miles. Grid spacing is uniform; each grid block is 1,000 feet on a side.

The ground-water flow system was simulated with two layers. Layer 1, the top layer, represents the unconfined glacial aquifer. Layer 2, the bottom layer, represents a composite confined aquifer consisting, from top down, of the Devonian Delaware Limestone and Columbus Limestone, and the upper part of the Silurian Bass Islands Group. (These carbonate rocks constitute a single aquifer within the depths commonly reached in drilling.) The Devonian Ohio Shale and (or) Olentangy Shale overlie the carbonate rocks east of the Scioto River and also are considered part of layer 2. Vertical hydraulic conductivity between layers 1 and 2 and transmissivity in layer 2 are reduced in this area to reflect the presence and hydraulic characteristics of the shales.

The upper boundary of layer 1 is the water table. The lower boundary of layer 1 is the top of bedrock. A top-of-bedrock map was constructed from available driller's logs (fig. 24). This map suggests that the bedrock surface is characterized by moderate relief in the form of subdued hills and intervening valleys. The dashed line depicts the approximate shale/limestone contact used in the model.

The lower boundary of layer 2 was set at 250 feet above sea level. This boundary is not at the base of the Silurian carbonate-rock sequence. Rather, it coincides with the top of the Tymochtee Formation, the most shaley formation of the Bass Islands Group, which isolates the upper part of the Bass Islands Group from the highly permeable Newburg zone at the base of the Bass Islands Group.

The regional potentiometric surface in the consolidated rocks presented in Norris and Fidler (1973) indicates that ground water in the carbonate-rock sequence discharges into the Scioto River; however, it was noted that the wells used in the construction of this potentiometric-surface map range in depth from 80 to 250 feet below land surface and do not penetrate the Newburg zone. In west-central Franklin County, water in the Newburg zone was found to have a dissolved-solids content as high as 2,230 mg/L (Norris and Fidler, 1973), whereas deRoche (1985) noted a dissolved-solids content less than 1,000 mg/L in the overlying shallow carbonates. This information suggests that flow in the upper part of the carbonate-rock sequence is part of a local flow cell that discharges into the Scioto River, whereas flow in the Newburg zone is part of a deeper, regional flow cell that does not.

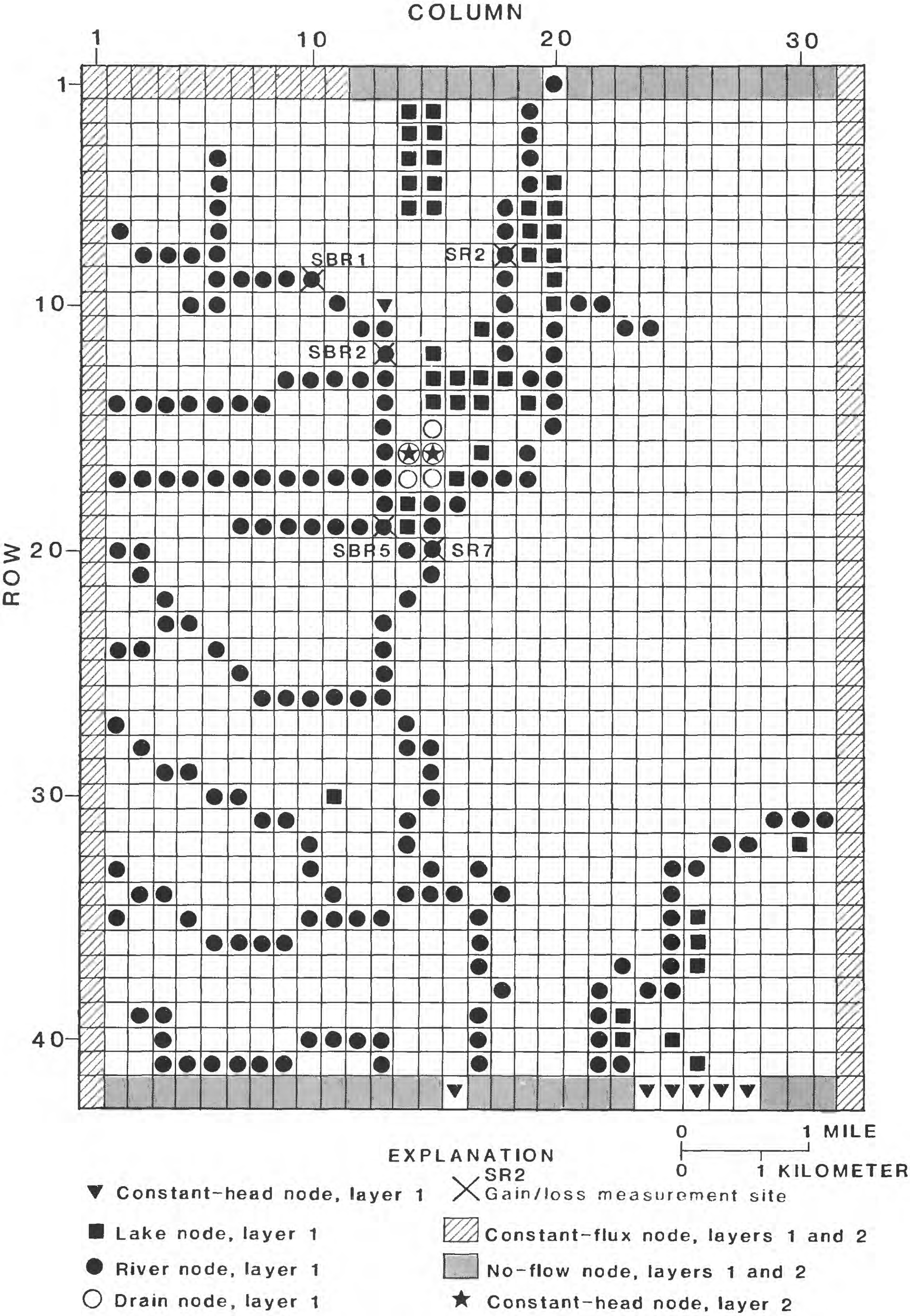
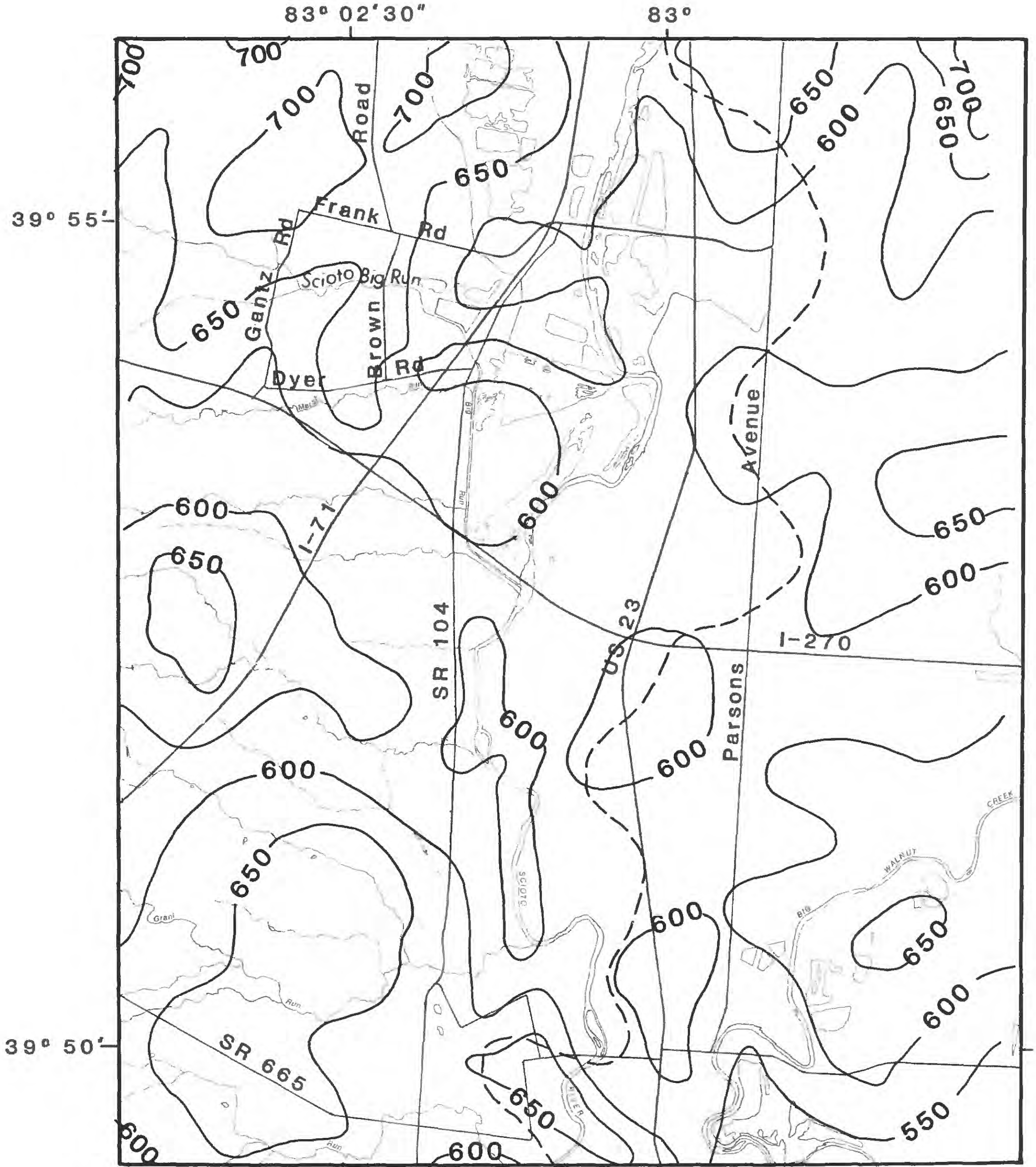


Figure 23.--Finite-difference grid, model boundaries, and location of gain/loss measurement sites.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

——650—— Line of equal altitude of bedrock surface. Contour interval 50 feet. Datum is sea level.

— — — — Line east of which bedrock surface is shale.

Figure 24.--Altitude of bedrock surface.

Data presented in Norris and Fidler (1973) suggest that the top of the Tymochtee Formation in central Franklin County is approximately 250 feet above sea level. By assigning an elevation of 250 feet above sea level to the bottom of layer 2, the bottom of layer 2 coincides with this approximate flow-cell boundary. It is assumed that flow does not occur across this boundary; therefore, the bottom of layer 2 was simulated as a no-flow boundary.

For both layer 1 and layer 2, constant-flux boundary conditions were assigned at each node along the west, east, and western end of the north periphery of the model (fig. 23). Constant-flux values were calculated using Darcy's Law. Hydraulic conductivities were estimated from driller's logs and analyses of pumping tests, and hydraulic gradients were determined from the March 1986 potentiometric-surface maps of the aquifers. Total flow across the west boundary and the western end of the north boundary was estimated at 20 Mgal/d. Boundary flow across the east boundary was estimated to be 18 Mgal/d.

The potentiometric-surface maps (figs. 14 and 15) show that the equipotential lines are approximately perpendicular to the south boundary and the eastern side of the north boundary of the modeled area in both the glacial and bedrock aquifers. Flow is therefore parallel to and not across the south boundary and the eastern side of the north boundary of the model in both layers. Consequently, these boundaries were simulated as no-flow boundaries.

Although the western end of the north boundary was simulated as a constant-flux boundary, as previously discussed, the lack of well control in the northwestern corner of the study area allows for speculation that the western end of the north boundary should be simulated as a no-flow boundary. This was tried, and it was determined that the model is not sensitive to the different methods of simulating the 10 nodes along this northwestern boundary (fig. 23).

The Scioto River, Big Walnut Creek, their tributaries, and numerous lakes constitute the internal boundaries of the simulated flow system (fig. 23). Streambed elevations were taken from U.S. Geological Survey topographic maps. A stream depth of 4 feet was used in all simulations for the Scioto River, whereas a stream depth of 3 feet was used for Big Walnut Creek. All other streams were assigned a depth of 0.5 feet. Lake levels also were derived from U.S. Geological Survey topographic maps.

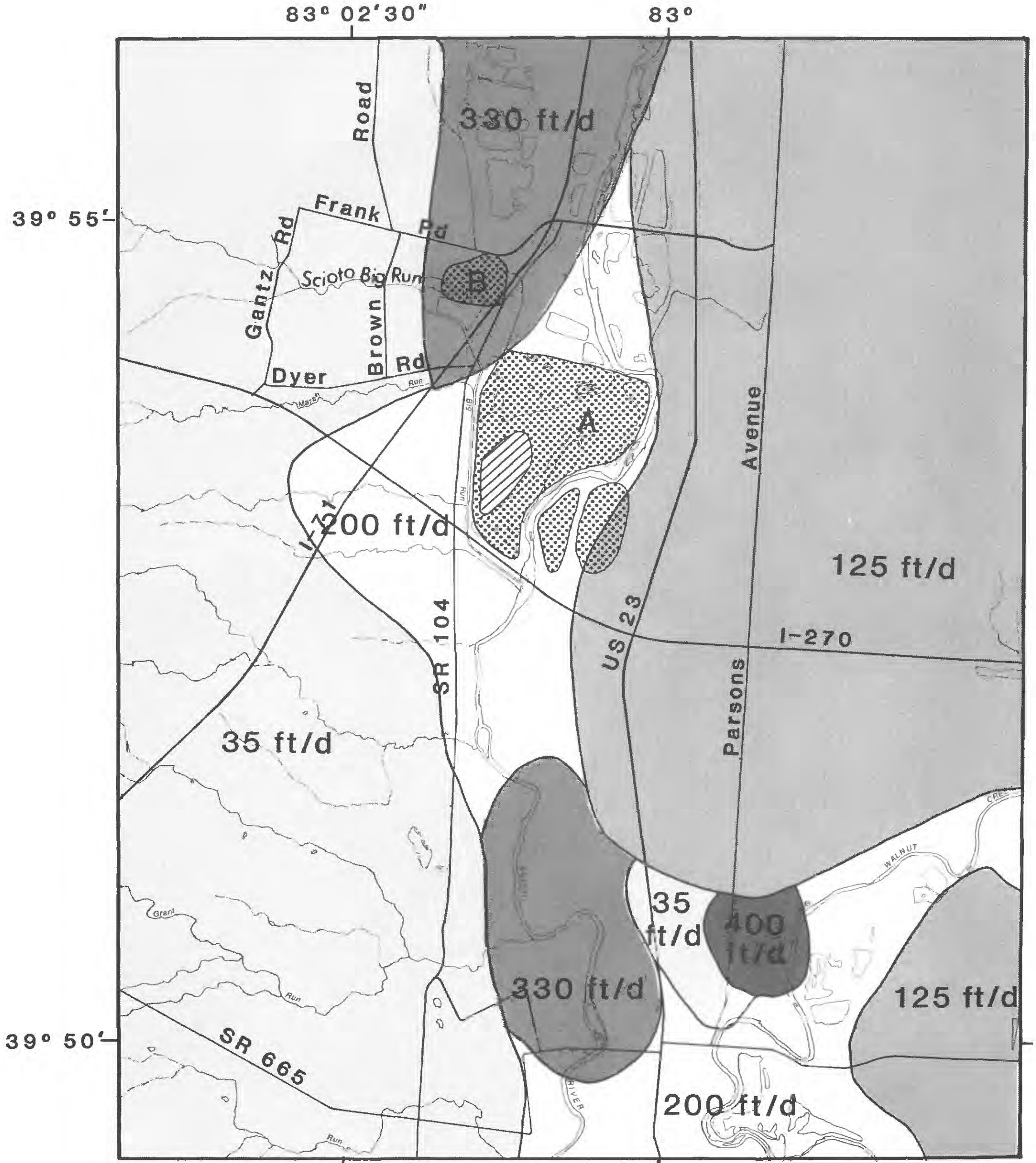
Model Parameters and Sources of Data

Parameters necessary to simulate the ground-water flow system include hydraulic conductivity of the glacial aquifer, transmissivity of the bedrock aquifer, vertical hydraulic conductivity of both aquifers, hydraulic conductivity of the riverbeds, recharge to the aquifers, and pumpage. Initial values for these parameters were derived from a number of sources.

The distribution of horizontal hydraulic conductivity that provided the best match between measured and simulated water levels in the glacial aquifer is illustrated in figure 25. Values for hydraulic conductivity range from 35 ft/d to 400 ft/d and are the result of trial-and-error adjustments during model calibration. The areal distribution of hydraulic conductivity generally mimics the areal distribution of surficial glacial deposits as presented by Schmidt and Goldthwait (1958) and Stowe (1979). Areas that have a hydraulic conductivity of 35 ft/d generally correspond to areas Stowe describes as till containing some outwash. These areas are primarily west of the Scioto River. A small wedge of this low-permeability material was identified between the Scioto River and Big Walnut Creek near the South Well Field during construction of the geologic sections (fig. 7). Weiss and Razem (1980) also identified this area of low-hydraulic conductivity. Areas that were assigned a hydraulic conductivity of 125 ft/d correspond to those areas described by Stowe (1979) as outwash and till. Areas described by Goldthwait (Schmidt and Goldthwait, 1958) as alluvial deposits underlain by valley-train deposits were simulated with a hydraulic conductivity of 200 ft/d. A hydraulic conductivity of 200 ft/d also was assigned to some of the sand and gravel deposits west of the quarry dewatering operations. Deposits described by Goldthwait (Schmidt and Goldthwait, 1958) as valley-train deposits or kames and eskers were simulated with a hydraulic conductivity of 330 ft/d and 400 ft/d.

The principal source of data for hydraulic conductivity of the glacial aquifer was a reevaluation of all aquifer-test data known to have been collected in the study area (S. E. Norris, written commun., 1986). This reevaluation resulted in more conservative estimates for hydraulic conductivity than were originally reported by consultants who have worked in the area (Ranney Water Systems, Inc., 1970; Stilson and Associates, 1976, 1977). The aquifer tests conducted in the study area tend to focus on the South Well Field area. The most representative hydraulic-conductivity value for the well-field area after Norris's reevaluation is 330 ft/d. Values are near 200 ft/d for other areas along the Scioto River and Big Walnut Creek. For areas in which no aquifer-test data were available, hydraulic conductivities were assigned by extrapolating values from known areas on the basis of driller's logs and geologic setting. Previous modeling reports also were consulted.

The values for horizontal hydraulic conductivity that were multiplied by saturated thickness to determine transmissivity of the bedrock aquifer are illustrated in figure 26. A value of 10 ft/d was assigned to the carbonate bedrock aquifer east of the Scioto River where it is overlain by shale. A value of 15 ft/d was assigned to the bedrock aquifer west of the limestone/shale contact, except in the area west of quarry A where the limestone surface is generally low (fig. 24).



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

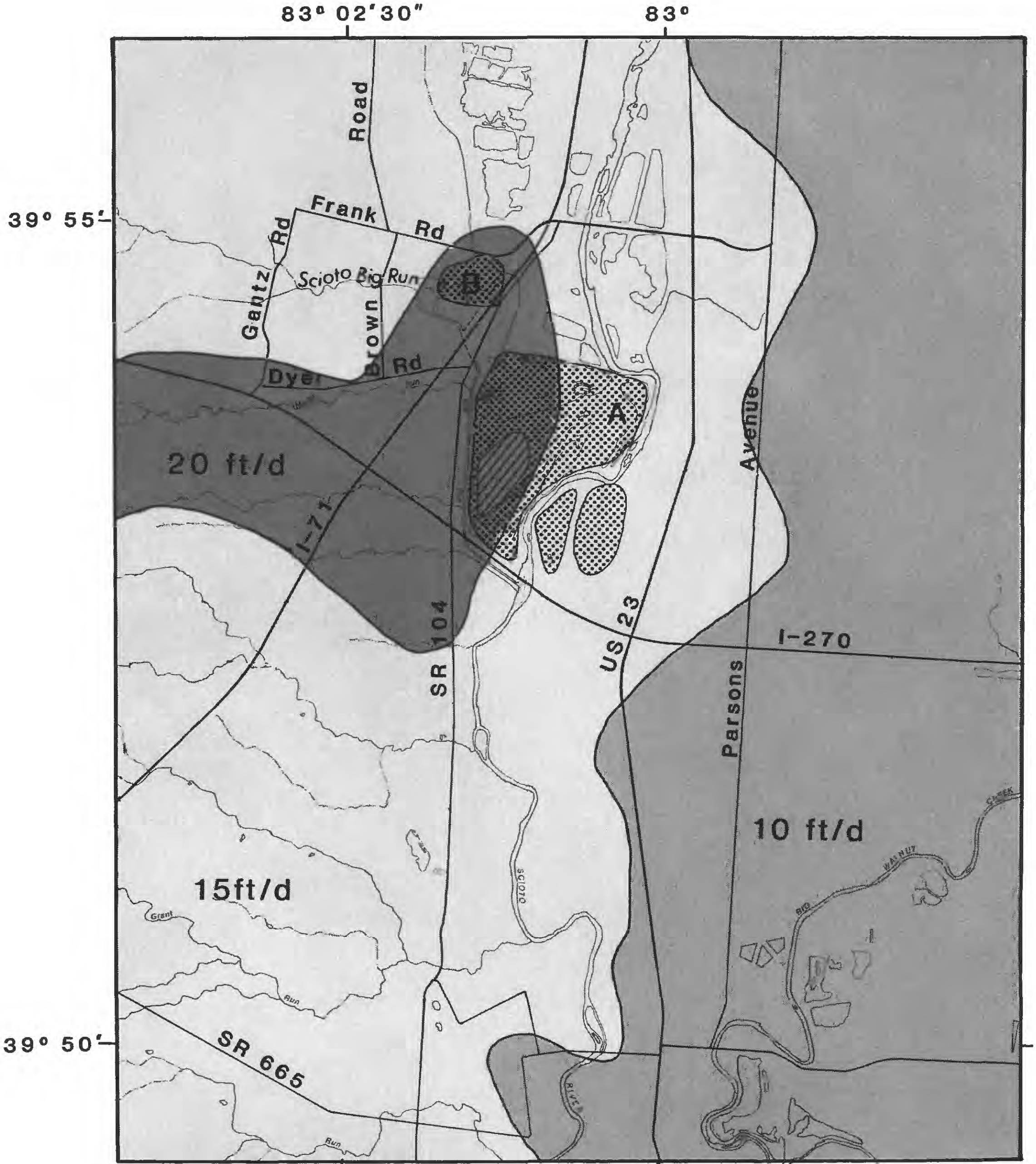
EXPLANATION

A Sand and gravel quarry

Limestone quarry

125 ft/d Hydraulic conductivity, in feet per day

Figure 25.--Areal distribution of horizontal hydraulic conductivity used to simulate the glacial aquifer.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

A Sand and gravel quarry

Limestone quarry

20 ft/d Hydraulic conductivity, in feet per day

Figure 26.—Areal distribution of horizontal hydraulic conductivity used to calculate transmissivity of the bedrock aquifer.

These rocks were assigned a horizontal hydraulic conductivity of 20 ft/d.

Few data on transmissivity or hydraulic conductivity of the carbonate bedrock aquifer were available. Garner (1983) reports a value of 4 ft/d for hydraulic conductivity. The hydraulic conductivity distribution presented herein resulted from a trial-and-error adjustment of the value reported by Garner during calibration of the model. Hydraulic conductivity of a carbonate aquifer can differ significantly both vertically and laterally as a result of the development of secondary porosity and lithologic variations. Permeability in the carbonate rocks in southern Franklin County is predominantly a result of solution by water moving through joints along bedding planes and in other openings. Most permeability developed in association with erosional processes as the upper beds were progressively removed from the top of the rising Cincinnati Arch (Norris and Fidler, 1973). This may be the reason that a lower hydraulic conductivity value was necessary to simulate the carbonate aquifer east of the Scioto River where the Ohio Shale and (or) Olentangy Shale have not been eroded from the top of the carbonate-rock sequence.

Preglacial geomorphology reflects differences in the resistance of the rocks into which the preglacial streams cut their channels (Norris, 1959). The low area in the limestone surface west of quarry A may have resulted from erosion of an area in the carbonate bedrock that had more joints than the surrounding rocks. To obtain agreement between simulated and measured hydraulic heads, the carbonate aquifer was assigned a higher hydraulic conductivity in this low area than in the surrounding rocks.

Vertical hydraulic conductivity in unconsolidated sediments and sedimentary rocks is commonly less than horizontal hydraulic conductivity in the same units. Vertical hydraulic conductivities used in the current model were determined through trial-and-error adjustments during calibration. A value of 5.0×10^{-3} ft/d was used for clay (till) and shale deposits. Assigned values for vertical hydraulic conductivity in the valley train, kames and eskers, and limestone were one order of magnitude less than their respective horizontal hydraulic conductivities.

Riverbed conductance was used to simulate leakage from river nodes. Conductances were calculated by means of the equation:

$$C = KA/b,$$

where C is the riverbed conductance (L^2t^{-1}),
K is hydraulic conductivity of the riverbed (Lt^{-1}),
A is the area of the riverbed within the node (L^2), and
b is the riverbed thickness (L).

Three areas of differing riverbed conductance resulted from trial-and-error adjustments during calibration. The three values presented herein provided the best match between measured and simulated gains and losses along the rivers. The Scioto River above the Jackson Pike sewage-treatment plant was simulated with a riverbed conductance of 1.0×10^5 ft^2/d (feet squared per day). The Scioto River south of the sewage-treatment plant was simulated with a riverbed conductance of 3.3×10^4 ft^2/d. (The riverbed conductance below the sewage-treatment plant is lower than it is above the plant because of the particulate matter contained in the sewage effluent discharged into the river.) A riverbed conductance of 3.3×10^4 ft^2/d also was used to simulate Big Walnut Creek. Infiltration conditions are poor along Big Walnut Creek because of deposition of silt during times of low flow, resulting from a flattening of the stream gradient. This flattening of the gradient may relate to the fact that the lower part of Big Walnut Creek valley is several feet higher than the nearby Scioto River, which causes the Scioto to act as an underdrain (S. E. Norris, Consulting Ground-Water Hydrologist, written commun., 1986). Finally, a riverbed conductance value of 5.0×10^3 ft^2/d was used to simulate tributary streams.

The riverbed conductance, 3.3×10^4 ft^2/d, used to simulate the rivers near the South Well Field corresponds to a river width of 150 feet and a riverbed hydraulic conductivity of 0.22 ft/d. Weiss and Razem (1980) achieved best results simulating aquifer tests and nonpumping steady-state conditions at collector-well site 101 with a value of 0.26 ft/d. The value for riverbed hydraulic conductivity used in the current model is a 15-percent reduction of this earlier value.

Recharge from precipitation was applied to the highest active cell in each vertical column of the model. Values of recharge determined through trial-and-error adjustment range from 4 in./yr (inches per year) to 9 in./yr (fig. 27). This range is similar to that presented by Stowe (1979). The area west of the Scioto River was assigned the lowest estimate of annual recharge, 4 in./yr. These deposits are the most clay-rich in the modeled area and are drained by numerous tributaries to the Scioto River. A recharge rate of 7 in./yr was assigned to the deposits east of the Scioto River, which consist predominantly of outwash and till. The lack of tributary development in this area indicates more infiltration and recharge and less surface drainage than for the area west of the Scioto River. The valley-train deposits, alluvium, kames, and eskers along the Scioto River and Big Walnut Creek were assigned a recharge rate of 9 in./yr.

The minimum amount of pumpage considered for use in the model was 750 ft^3/d (5,600 gal/d), which included municipal, commercial, and industrial wells but excluded domestic wells. March 1986 pumpage data were used for all but one simulation of the South Well Field. Combined pumpage from the four collector wells averaged approximately 8.2 Mgal/d during March 1986.

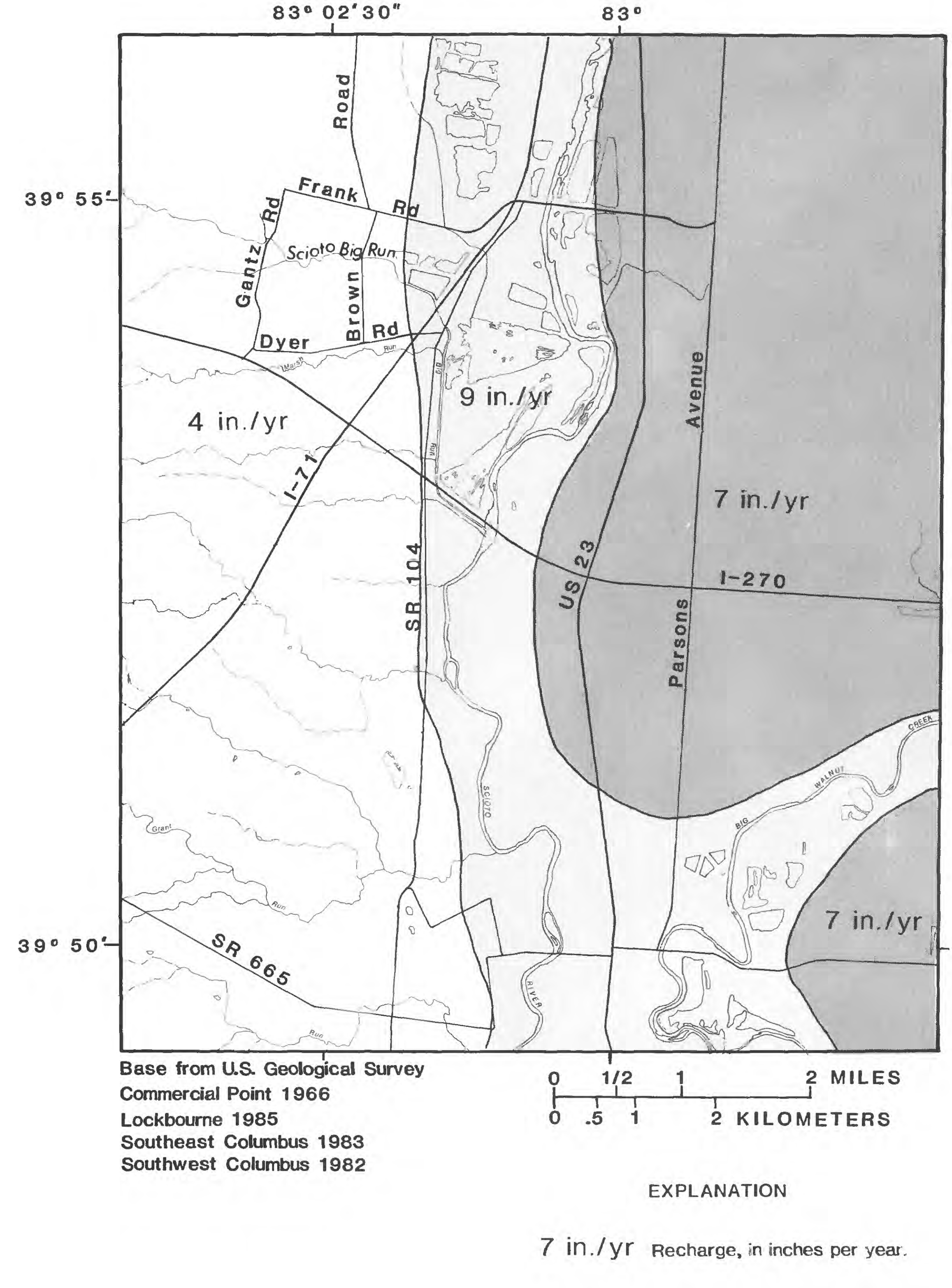


Figure 27.--Areal distribution of recharge used to simulate the glacial-bedrock aquifer system.

Dewatering operations at quarries A and B were simulated with drains and (or) constant-head nodes. Pumpage at the quarries was calculated from model results by summing the amount of water removed at the drain and constant-head nodes.

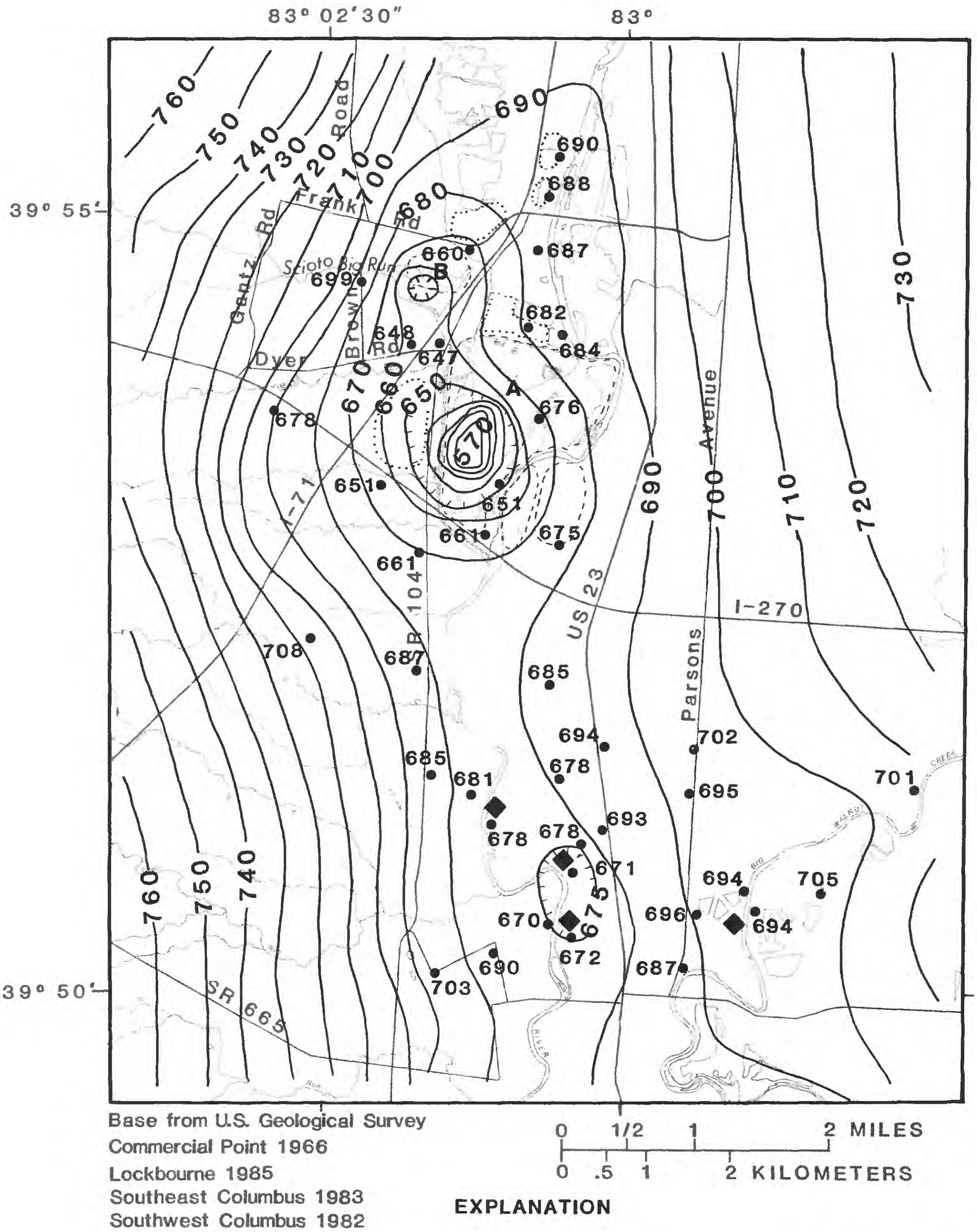
Calibration

The ground-water flow model was calibrated to two different steady-state conditions to increase the uniqueness of the solution. The model was first calibrated to water levels measured in March 1986. March 1986 pumpage data for the South Well Field also were used during this calibration. Once a satisfactory calibration was achieved with the March 1986 water-level and pumpage data, the model was rerun without the municipal, commercial, and industrial pumping centers and simulated water levels were compared with historic water levels taken from driller's logs of wells drilled before bedrock excavation and dewatering began in 1967. The historic water levels do not reflect water levels measured at any one time; rather, they were used to estimate potentiometric surfaces for the glacial and bedrock aquifers before dewatering. Model parameters were adjusted slightly until a best fit for both steady-state conditions resulted.

March 1986 simulated contours compared with measured water levels for the glacial aquifer (layer 1) are illustrated in figure 28. The simulated contours and measured water levels for the carbonate bedrock aquifer (layer 2) are illustrated in figure 29.

Data developed during a gain/loss study of Scioto Big Run and the Scioto River in October 1982 (de Roche, 1985) were used during model calibration. Figure 23 shows locations of the stream measurement sites. The study showed that Scioto Big Run flow originates between stations SBR1 and SBR2 (fig. 23). An analysis of error applied to the measurements for the reach between SBR2 and SBR5 indicated the loss between these stations could vary from a minimum of 0.40 ft^3/s to a maximum of 1.11 ft^3/s. The calibrated model showed a 0.40-ft^3/s loss for this reach.

The analysis of gain/loss between stations SR2 and SR7 on the Scioto River was reported to be difficult because inflow from the sewage-treatment plant varied during the study (de Roche, 1985). Additionally, long time of travel made predictions of the downstream advancement of flow from the treatment plant difficult. On the basis of traveltime data and the variation in treatment-plant outflow, the minimum net loss from the Scioto River to the aquifer in segment SR2/SR7 was reported at 6 ft^3/s. A maximum net loss for this reach was calculated at 61 ft^3/s (J. T. de Roche, U.S. Geological Survey, written commun., 1986). The calibrated model constructed for this study showed a 16-ft^3/s loss for this reach.



EXPLANATION

Quarry

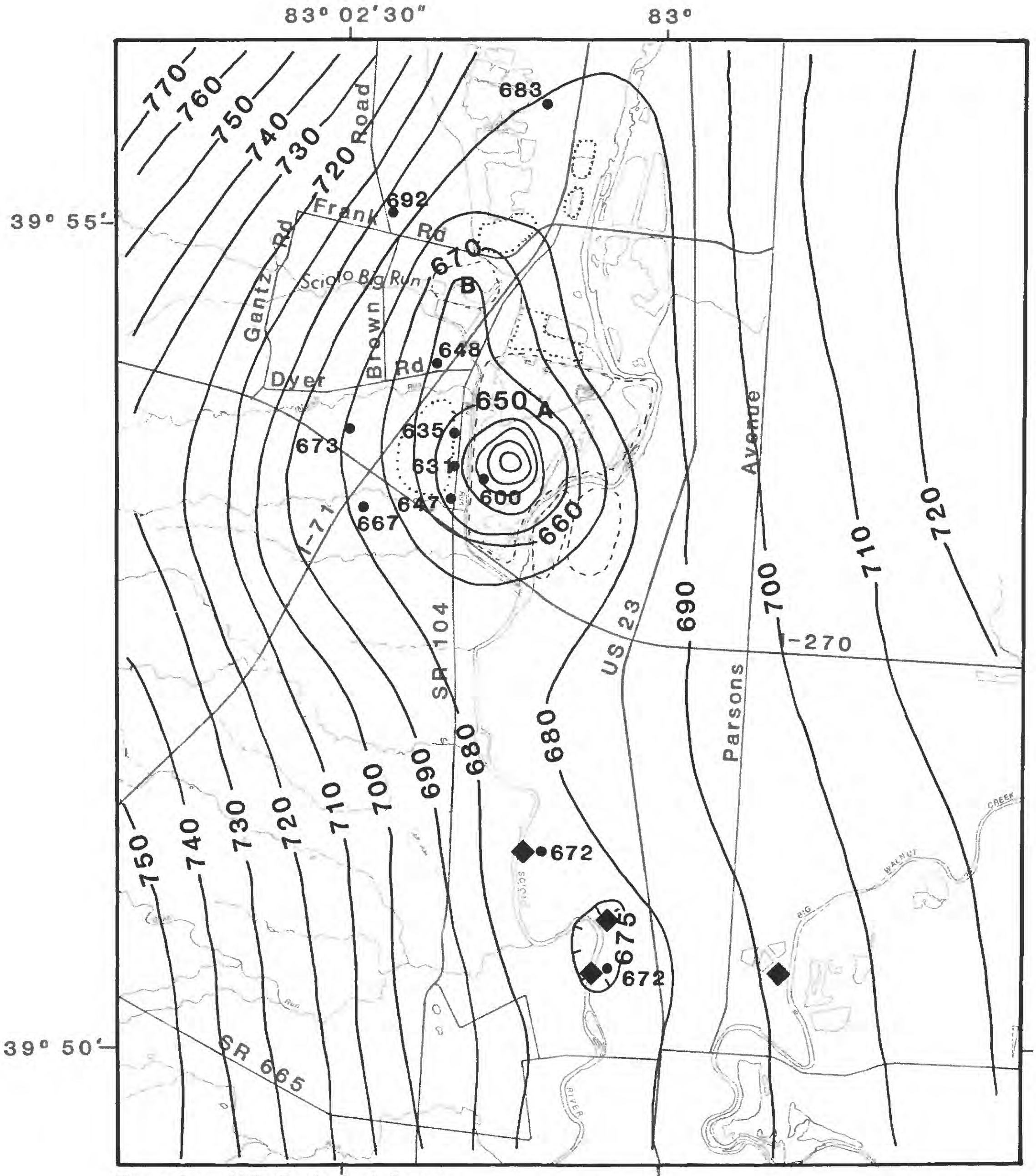
Landfill

◆ Collector well

• 672 Point of measured water level, in feet.

—680— Simulated water-level contour. Interval 10 feet except near large water-level depression and collector wells. Datum is sea level.

Figure 28.--Relation of simulated water levels in the glacial aquifer to water levels measured in March 1986.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

Quarry

Landfill

◆ Collector well

—640— Simulated water-level contour, Interval 10 feet except near large water-level depression and collector wells. Datum is sea level.

672
● Point of measured water-level, in feet.

Figure 29.--Relation of simulated water levels in the bedrock aquifer to measured water levels.

Dewatering at quarry A was simulated with five drain nodes in layer 1 and two constant-head nodes in layer 2. The drain nodes correspond to the deepest part of the excavation, where all glacial material has been removed and bedrock is being excavated. Drain nodes were allowed to dry up during simulations to approximate the absence of these glacial deposits. The constant heads in layer 2 were set at 570 feet above sea level, the altitude of the quarry sump based on field inspection. The amount of water removed at quarry A during simulations was approximately 44 Mgal/d. This amount does not exceed the maximum pump capacity reported for the quarry in 1979 (J. T. de Roche, U.S. Geological Survey, written commun., 1987).

Dewatering at quarry B was simulated with a single constant-head node. The constant-head node was set at 640 feet above sea level, the altitude of the quarry sump based on field inspection. Discharge from the quarry into the adjacent lake was estimated during a site visit to be approximately 11 Mgal/d. The amount of water removed at quarry B during simulations was approximately 11 Mgal/d.

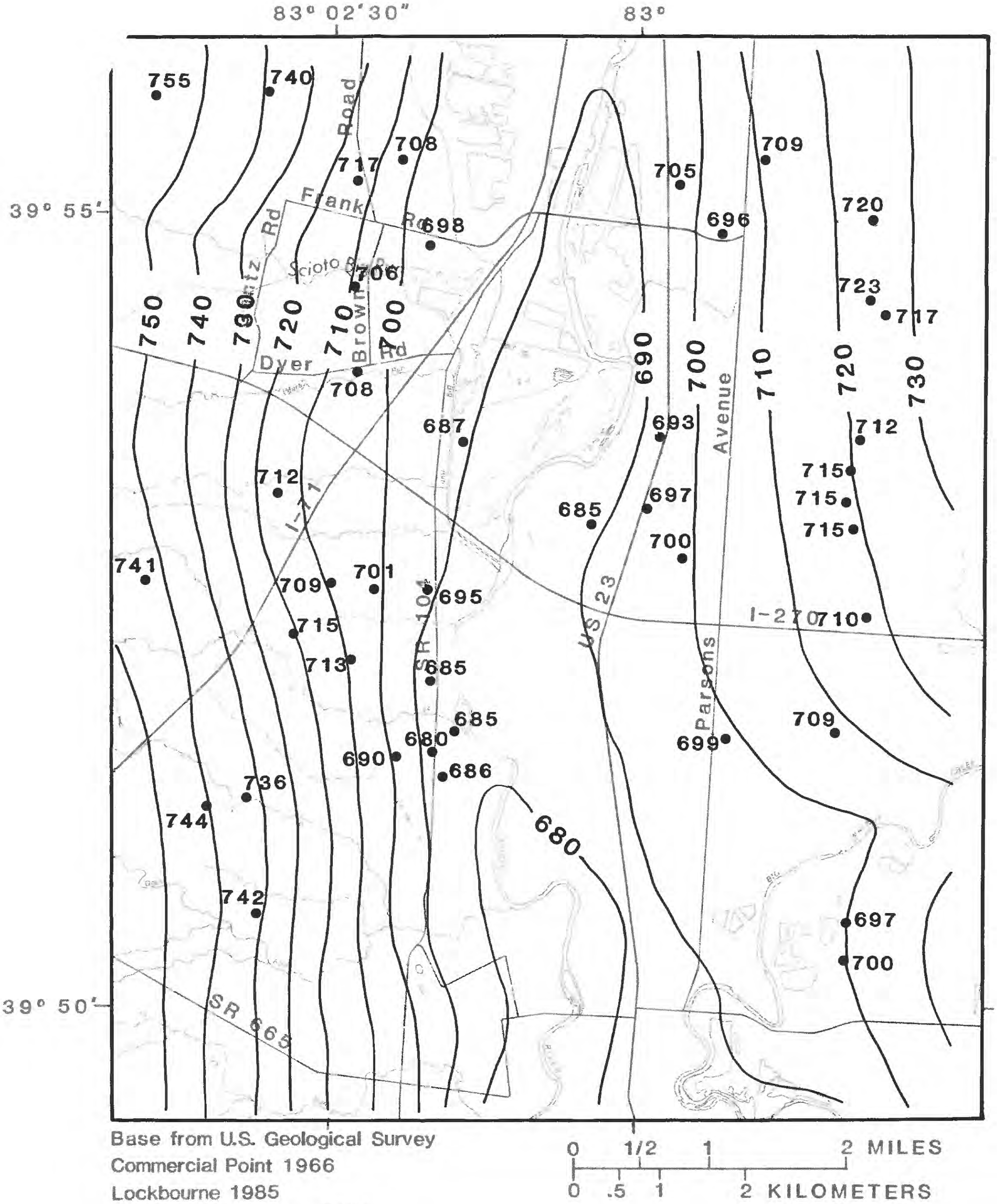
A steady-state ground-water budget was calculated using the calibrated model. A summary of this simulated water budget is presented in table 4. The water budget indicates that in March 1986, approximately 59 percent of the ground water discharged within the study area was from quarry dewatering, whereas approximately 9 percent of the ground water discharged was from the South Well Field. The 55 Mgal/d pumped at the quarries was not completely sustained by the aquifers and includes water induced from the Scioto River and Scioto Big Run, recharge from precipitation, and leakage from lakes within the quarries used to relay water to the rivers.

Historic aquifer conditions were simulated by removing current pumping centers. The drain nodes and constant-head nodes used to simulate the quarry operations were replaced by aquifer parameters thought to represent preexcavation and dewatering conditions. Figures 30 and 31 illustrate simulated contours and historic water levels for the glacial (layer 1) and bedrock (layer 2) aquifers, respectively.

Riverbed conductance was adjusted during calibration to historic water levels because ground-water levels along the Scioto River were too high during the initial historic simulation. Riverbed conductance was increased until it could no longer be increased without causing too much water to flow into quarry A during steady-state calibration to March 1986 conditions. The resulting riverbed conductance produced reasonable water levels for both pre-1967 and March 1986 conditions. Due to the transient nature of stream deposition and bedload transport, it is likely that riverbed conditions have not remained the same throughout time; however, the Jackson Pike Sewage Treatment Plant, which probably has the greatest effect on riverbed conditions, was in operation both in March 1986 and prior to 1967.

Table 4.--*Simulated steady-state ground-water budget of the glacial-bedrock aquifer system, calibrated to March 1986 conditions*

Sources and discharges	Flow (million gallons per day)	Percentage of total
Sources:		
Leakage from stream and lake beds---	42	45
Boundary flux-----------------------	37	40
Recharge from precipitation---------	14	15
Total-------------------------	93	100
Discharges:		
Quarry dewatering------------------	55	59
Ground-water seepage to streams and lakes------------------------	22	23
South Well Field--------------------	8	9
Commercial and industrial wells-----	8	9
Total-------------------------	93	100

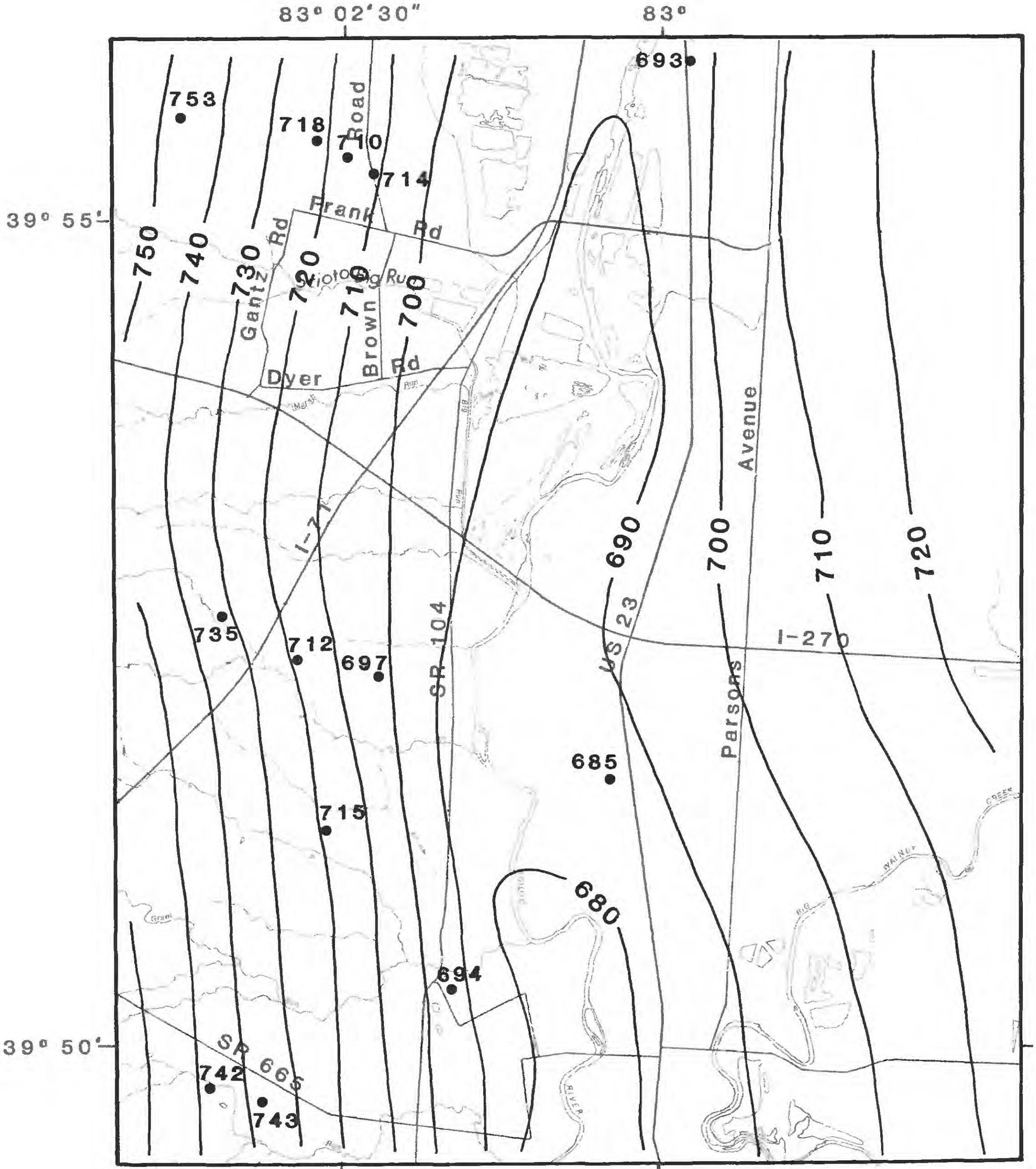


EXPLANATION

693 ● Point of historic water level, in feet.

——680—— Simulated water-level contour. Interval 10 feet. Datum is sea level.

Figure 30.--Relation of simulated water levels in the glacial aquifer to water levels measured prior to 1967.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

685 ● Point of historic water level, in feet.

—680— Simulated water-level contour. Interval 10 feet. Datum is sea level.

Figure 31.--Relation of simulated water levels in the bedrock aquifer to water levels measured prior to 1967.

Toxic-Substance Spills

Contaminants resulting from human activities can enter the ground-water system in three ways: (1) Placement or the spreading of liquids or water-soluble products on the land surface, (2) burial of substances in the ground above the water table, or (3) emplacement or injection of materials in the ground below the water table (Lehr and others, 1976). Potential sources of ground-water contamination and modes of emplacement are listed in table 5. Because of the relation between highways, surface drainage, and the South Well Field, one potential source of ground-water contamination of particular concern in southern Franklin County is accidental spills of toxic substances.

The National Academy of Sciences estimated that approximately 16,000 accidental spills of hazardous materials occur within the United States every year (U.S. Office of Technology Assessment, 1984). When a chemical spill occurs, the contaminant may infiltrate through the soil and unsaturated (vadose) zone and finally reach the aquifer. Once within the aquifer, the contaminant may (1) travel at the velocity of and in the direction of ground water, (2) travel slower than the ground water, (3) float on the surface of the water, (4) "sink" through the aquifer to the bottom, or (5) under some conditions, actually move in a direction against the flow of the ground water (Aller and others, 1985).

Generally, most contaminants travel in the predominant direction of ground-water flow at a velocity somewhat less than that of the ground water (Aller and others, 1985). Longitudinal dispersion, however, may cause a contaminant to arrive at a discharge point prior to the arrival time calculated from the average ground-water velocity, and transverse dispersion may cause a contaminant to spread normal to the direction of ground-water flow and occupy an increasingly large part of the flow region.

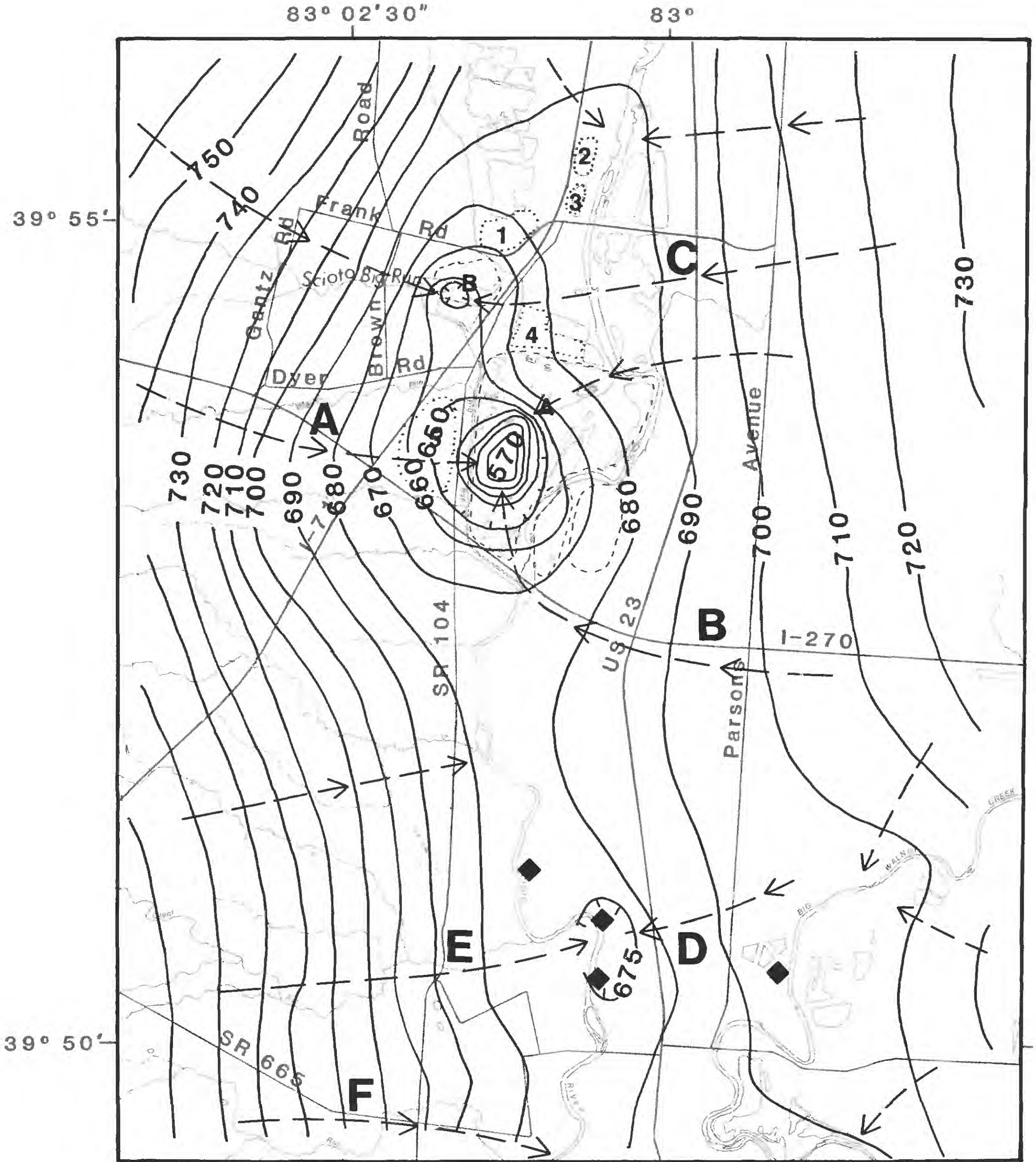
Unless a contaminant is attenuated, it will eventually make its way to a discharge point within the ground-water flow system. In southern Franklin County, discharge points include wells, streams, and quarries. To understand the relation between the South Well Field and a potential toxic-substance spill along one of the major highways, directions of ground-water flow and approximate traveltimes need to be determined.

General directions of ground-water flow superimposed on the March 1986 simulated equipotential surface of the glacial aquifer are illustrated in figure 32. Near the north-central border of the study area, ground water discharges into the Scioto River. Aside from this small area, ground water in the northern half of the study area discharges into either one of the two quarries.

Table 5.--*Potential sources of ground-water contamination and modes of emplacement*

[From Lehr and others (1976); modified by Aller and others (1985)]

On the land surface	In the ground above the water table	In the ground below the water table
1. Land disposal of either solid or liquid waste materials	1. Leaching tile fields, cesspools and privies	1. Waste disposal in wet excavations
2. Stockpiles	2. Holding ponds and lagoons	2. Drainage wells and canals
3. Disposal of sewage and water-treatment plant sludge	3. Sanitary landfills	3. Abandoned/improperly constructed wells
4. Salt spreading on roads, airport runways and parking lots	4. Waste disposal in excavations	4. Exploratory wells
5. Animal feedlots	5. Leakage from underground tanks	5. Water-supply wells
6. Fertilizers and pesticides	6. Leakage from underground pipelines	6. Waste-disposal wells
7. Accidental spills of hazardous materials	7. Artificial recharge	7. Mines
8. Particulate matter from airborne sources	8. Sumps and dry wells	8. Saltwater intrusion
	9. Graveyards	



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

0 1/2 1 2 MILES

0 .5 1 2 KILOMETERS

EXPLANATION

B Quarry

4 Landfill

◆ Collector well

E Approximate flow direction

—680— Simulated water-level contour. Interval 10 feet except near large water-level depression and collector wells. Datum is sea level.

Figure 32.--Generalized directions of ground-water flow in the glacial aquifer, March 1986.

Water removed by the sump at quarry B ultimately is discharged into Scioto Big Run. Scioto Big Run is a losing stream over much of its reach; therefore, some of the water removed by quarry B finds its way into quarry A. The Scioto River loses water to the aquifer in the northern half of the study area along a reach that begins south of landfill 3 and ends just south of the confluence of Scioto Big Run and the Scioto River. The aquifer and the Scioto River actually break hydraulic connection east of quarry A. Ground water removed from the glacial and carbonate bedrock aquifers at the quarry A sump ultimately is discharged into the Scioto River. Ground water in the central part of the study area discharges directly into the Scioto River.

Farther south, ground water discharges into the municipal water-supply wells. The Scioto River is a losing stream in the vicinity of the wells. Model results indicate that approximately 13 percent of the water pumped by the four collector wells is from riverbed infiltration for March 1986 pumping conditions (combined pumpage of 8.2 Mgal/d). Ground water in the glacial aquifer discharges into Big Walnut Creek along the southeastern border of the study area and into the Scioto River at the south-central border.

A toxic-substance spill on any of the major highways within the study area would enter the ground by way of open drainage ditches along the highways. On the basis of March 1986 aquifer conditions, a spill along most of I-270 and I-71 within the study area eventually could discharge into one of the two quarries and ultimately be pumped into the Scioto River. A spill on I-71 near the northern border of the study area could discharge into the Scioto River. A spill on SR 104 and US 23 in the northern two-thirds of the study area also could discharge into the quarries or into the Scioto River. Any spill along SR 104 and US 23 in the vicinity of the collector wells could discharge ultimately into the wells. A toxic-substance spill on SR 665 may ultimately discharge into the Scioto River, Big Walnut Creek, or possibly into the collector wells. A spill directly into the Scioto River upstream of the well field has the potential to reach the collector wells through riverbed infiltration; however, a spill directly into the river would undergo dilution as it moved downstream and would probably undergo attenuation as it filtered through the riverbed and moved through the aquifer. It would also be diluted by the greater percentage of water derived from the aquifer than from the river.

An infinite number of flow lines and associated traveltimes may be used to describe ground-water flow within the study area. As examples of the approximate time it may take spilled materials to reach local discharge points, approximate contaminant traveltimes were calculated for the six flow lines labeled in figure 32. These calculated traveltimes are listed in table 6.

Table 6.--*Examples of approximate contaminant traveltimes calculated for the six flow lines labeled in figure 32*

Flow-line description	Distance along flow line (miles)	Approximate traveltime (days)
A - From junction of I-270 and I-71 to the sump in quarry A	0.9	190
B - 690-foot equipotential at I-270 to the sump in quarry A	2.0	1,480
C - US 23 to the sump in quarry B	1.7	1,140
D - US 23 to the 675-foot equipotential line	0.2	100
E - SR 104 to the 675-foot equipotential line	1.0	1,540
F - 720-foot equipotential line at SR 665 to the Scioto River	1.5	1,640

The following assumptions apply to the contaminant traveltime calculations: (1) The contaminant immediately enters the ground-water flow system (traveltime within the unsaturated zone is not considered); (2) the contaminant is conservative in character and travels with the average linear velocity of the ground water (that is, no chemical or biochemical retardation occurs); and (3) hydraulic gradients can be represented by the simulated steady-state potentiometric surface (no seasonal variations in hydraulic gradients are considered).

Time-of-travel calculations were based on the following equation,

$$Tot = x \Big/ \left[\frac{K}{n}\frac{dh}{dl}\right] \qquad (4)$$

where

Tot is time of travel (t),

x is the distance traveled within the aquifer (L),

K is the horizontal hydraulic conductivity of the aquifer (Lt^{-1}),

n is the effective porosity, and

$\frac{dh}{dl}$ is the hydraulic gradient along the flow line (L/L).

If more than one value for horizontal hydraulic conductivity, effective porosity, and (or) hydraulic gradient is encountered along the flow line, the time-of-travel equation has the following form:

$$Tot = a \Big/ \left[\frac{K_a}{n_a}\frac{dh_a}{dl_a}\right] + b \Big/ \left[\frac{K_b}{n_b}\frac{dh_b}{dl_b}\right] + c \Big/ \left[\frac{K_c}{n_c}\frac{dh_c}{dl_c}\right] + \; . \; . \; . \qquad (5)$$

Distance of travel used in each calculation was taken from figure 32. Values for horizontal hydraulic conductivity in the glacial aquifer were derived from figure 25, whereas hydraulic gradients were derived from figure 32.

In an unconfined aquifer, specific yield approximates effective porosity. Because few specific-yield or effective-porosity values have been determined for the aquifer materials within the study area, generic specific-yield values for similar lithologies (Walton, 1970) were used in conjunction with specific-yield values obtained from pumping tests performed in the vicinity of the collector wells (S. E. Norris, Consulting Ground-Water Hydrologist, written commun., 1986). The following specific-yield values were associated with the hydraulic conductivity values shown on figure 25.

Specific yield	Hydraulic conductivity
0.05	35 ft/d
.10	125 ft/d
.10	200 ft/d
.15	330 ft/d

It should be noted that approximate traveltimes along flow lines D and E were calculated from the highways to the 675-foot equipotential line, rather than to the collector wells, because the ground-water flow model constructed for this study does not compute drawdown at the radius of the wells. The hydraulic head calculated for a node represents the average hydraulic head for the area of the entire cell, which is much larger than the area of a well. As a result, changes in hydraulic gradient near the wells cannot be determined directly from the model. In addition, the model assumes wells fully penetrate the layer in which they are located, whereas most wells only partially penetrate the aquifer.

Actual contaminant traveltimes to the collector wells would be slightly greater than the traveltimes presented for flow paths D and E in table 6 because the distance between the 675-foot equipotential line and the radial-collector wells is not considered in the calculations.

A toxic-substance spill has the greatest potential to contaminate the carbonate bedrock aquifer where a downward hydraulic gradient exists. The bedrock aquifer in the northwestern corner of the study area may be particularly susceptible to contamination because of the presence of a downward hydraulic gradient and the shallow depth to bedrock. Although a downward hydraulic gradient exists east of the Scioto River, the shale that overlies the carbonate sequence in this area probably would significantly retard a toxic-substance spill. Therefore, the carbonate bedrock aquifer is less vulnerable to contamination east of the river than west of the river. An upward hydraulic gradient exists along the Scioto River; as a result, a toxic-substance spill in this area probably would not contaminate the bedrock aquifer.

It is important to note that the above scenarios correspond to March 1986 aquifer conditions. If the collector wells were pumped at a greater rate, their cone of influence would increase, and ground water and surface water from a larger part of the study area would discharge into the wells. This could include ground water from areas along I-71 and I-270. In addition, an increase in pumpage at the collector wells would steepen the hydraulic gradient near the wells. Such an increase in hydraulic gradient would lessen the amount of time necessary for spilled materials to reach the collector wells.

Cessation of Quarry Dewatering

In past years, quarry dewatering has had a locally positive effect on ground-water quality in parts of the aquifer system in southern Franklin County due to the lowering of water levels beneath adjacent landfills. The five landfills in the vicinity of the quarry dewatering operations were all constructed in abandoned sand and gravel pits (de Roche and Razem, 1981). A thick unsaturated zone under landfill 5 is a result of quarry dewatering. Ground-water levels are near the bottom of landfill 1, and landfills 2, 3, and 4 currently are saturated because of higher ground-water levels. As the quarries are phased out and dewatering ends, water levels will start to rise and could saturate landfill 1 and hydraulically connect landfill 5 with the glacial aquifer. It is important to note that the northern part of landfill 5 is partially insulated by a manmade clay liner.

Landfills located in abandoned sand and gravel pits are susceptible to ground-water contamination problems because of the generation of leachate caused by water percolating through the refuse. Leachate formation and subsequent ground-water contamination are the result of simple solution of wastes and decomposition of refuse and are dependent upon the amount of water that passes through the refuse. Decomposition is affected by microbial activity, which, in turn, depends upon refuse composition, temperature, moisture content, and the availability of free oxygen (Miller, 1980).

Aerobic decay produces stable end products such as carbon dioxide, nitrate, sulfate, water, and a relatively inert residue. In contrast, anaerobic decay produces carbon dioxide, methane, ammonia, hydrogen gas, alcohols and organic acids, and other partially oxidized organic species that exert a high biochemical oxygen demand. Refuse cells usually become anaerobic shortly after emplacement. However, within refuse cells unsaturated by water, traces of oxygen may be present, resulting in both aerobic and anaerobic decay at any depth. Burial of refuse in direct or intermittent contact with the zone of saturation has repeatedly been shown to cause contamination of ground water (Apgar and Langmuir, 1971).

De Roche (1985) noted that concentrations of most chemical constituents were higher in wells in and downgradient from the landfills within southern Franklin County than in wells upgradient from the landfills. Increases in concentrations of the common ionic species were the most noticeable effect of the landfills on ground-water quality. The increase in sodium, chloride, potassium, and magnesium concentrations was related to the decomposition of refuse and the subsequent attenuation processes. Elevated concentrations of dissolved organic carbon were related to the decomposition of refuse. Concentrations of carbon dioxide and ammonia and chemical oxygen demand were reported to be highest in water from wells penetrating landfills, intermediate for downgradient wells, and lowest for upgradient wells. The results of this 1985 study indicated that ground water beneath landfill 4 was the most degraded, and ground water near landfills 2 and 3 was significantly affected. Degradation in ground-water quality beneath landfill 5 was noted to be less than at landfills 2, 3, and 4. This was attributed to increased attenuation resulting from the presence of a thick unsaturated zone beneath landfill 5. De Roche also noted that modification of the relation between the aquifers and the landfills would affect the production and ultimate destination of leachate being produced by the landfills.

The ground-water flow model described previously was used to assess the effects of cessation of quarry dewatering on ground-water levels and directions of ground-water flow within the study area. Model results were evaluated with respect to the local landfills and the South Well Field. Three scenarios were simulated: (1) Cessation of dewatering at quarry A, (2) cessation of dewatering at quarry B, and (3) cessation of dewatering at quarries A and B. All predictive simulations were steady-state because the modeling objective was simply to estimate maximum changes in water levels that could occur if quarry dewatering were to cease.

Cessation of Dewatering at Quarry A

Sand, gravel, and limestone are mined at quarry A. The limestone excavation is the deepest excavation within quarry A. The sump used to dewater the aquifers has an altitude of 570 feet above sea level and is the lowest point of ground-water withdrawal within the study area. Ground water removed from the aquifers at the sump is used for aggregate processing and pumped into the lake at the north periphery of quarry A; most of the water ultimately discharges into the Scioto River.

Dewatering at quarry A was simulated with five drain nodes and two constant-head nodes. The five drain nodes were used to represent areal seepage in the sand and gravel, whereas the two constant-head nodes were used to represent the sump. Cessation of dewatering at quarry A was simulated by removing the drain nodes and the constant-head nodes from the model and allowing the aquifer system to reach new steady-state conditions.

The simulated potentiometric surfaces for the glacial and bedrock aquifers that correspond to a cessation of dewatering at quarry A are shown in figures 33 and 34. Simulated ground-water levels within the vicinity of landfills 2 and 3 are nearly the same as those measured in March 1986. Ground-water levels near landfills 1 and 4 are approximately 5 feet higher, and model results indicate that, if quarry dewatering ceased at quarry A, ground-water levels could rise nearly 40 feet in the vicinity of landfill 5 and reach an altitude near the base of the landfill. The base of landfill 5 is approximately 690 feet above sea level.

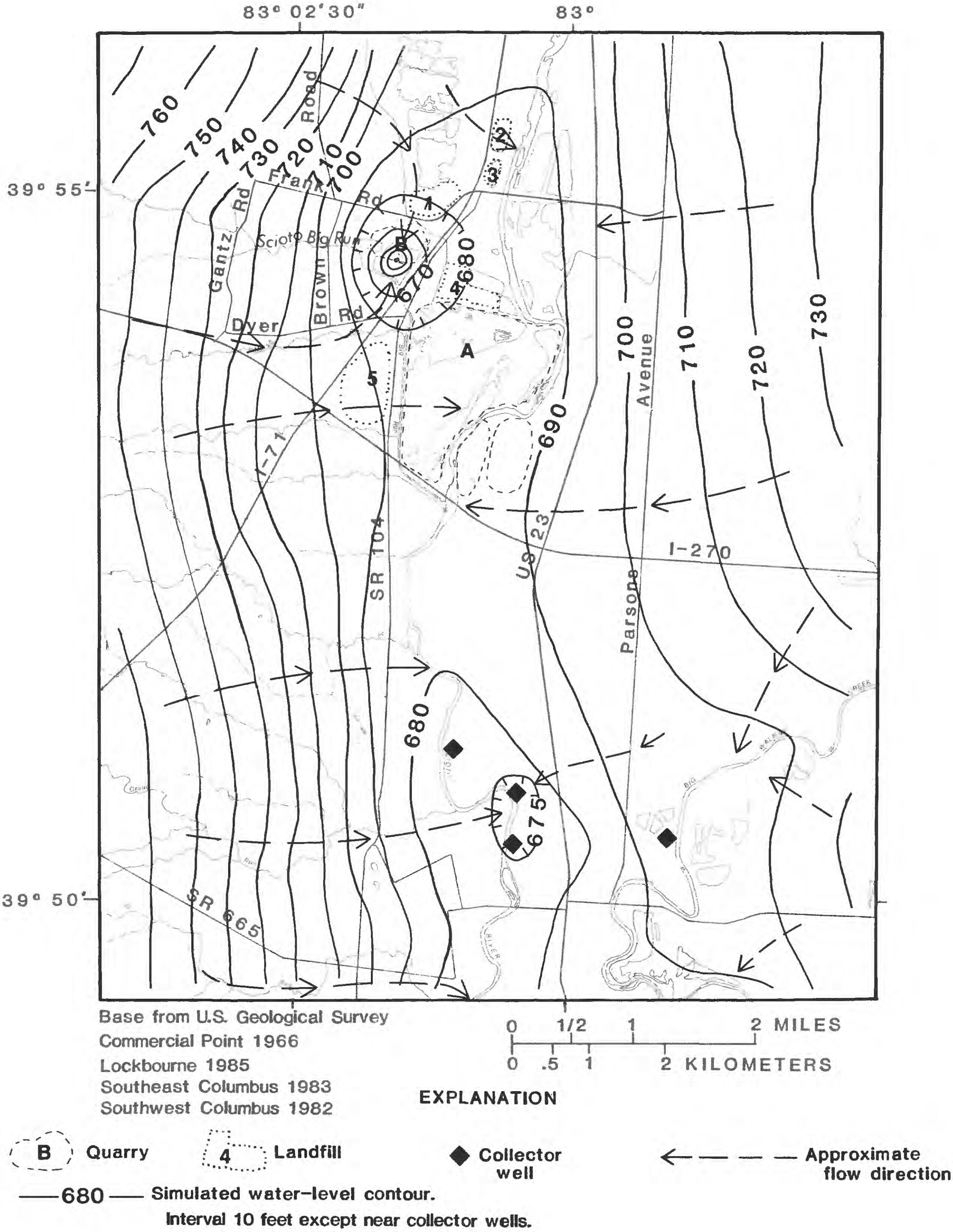


Figure 33.--Potentiometric surface and generalized ground-water flow directions in the glacial aquifer that could result from the cessation of dewatering at quarry A.

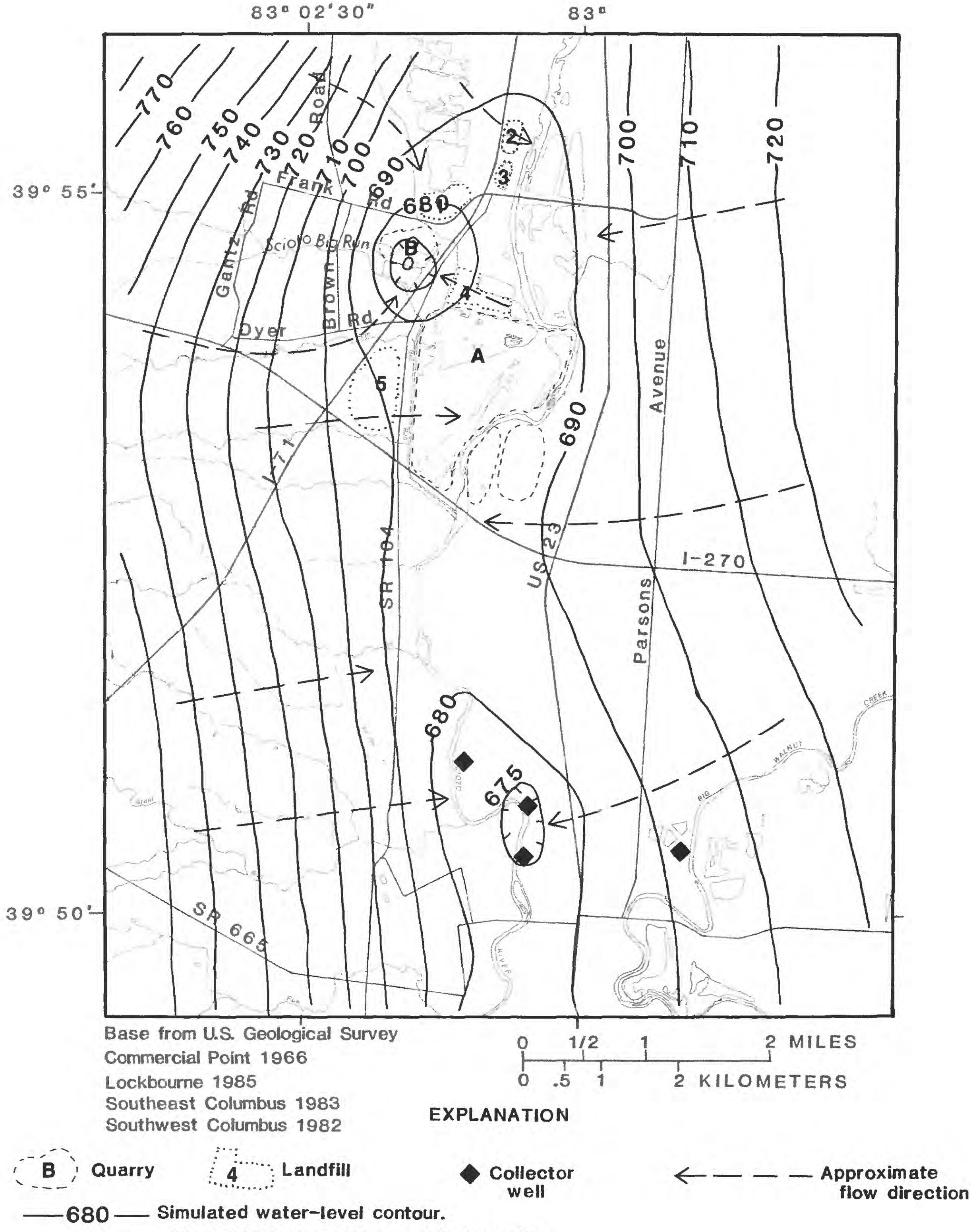


Figure 34.--Potentiometric surface and generalized ground-water flow directions in the bedrock aquifer that could result from the cessation of dewatering at quarry A.

Therefore, the landfill potentially could become hydraulically connected to the aquifers. If hydraulic connection did not occur, the thick unsaturated zone beneath landfill 5 nevertheless would be greatly reduced, which would result in decreased attenuation of leachate produced by the refuse.

Simulated changes in ground-water flow directions that could result from the cessation of dewatering at quarry A also are illustrated in figures 33 and 34. Leachate produced by landfills 2 and 3 probably would discharge into the Scioto River. Leachates produced by landfills 1 and 4 probably would discharge into quarry B. Leachate from landfill 4 discharged into both quarries A and B under March 1986 conditions. Landfill 5 has an operating leachate collection system. However, any leachate entering the ground water from landfill 5 would probably discharge into the Scioto River if dewatering ceased at quarry A, rather than into quarry A as it would under March 1986 conditions.

These simulated ground-water levels and directions of ground-water flow are based on the assumption that quarry B would continue to maintain a pumping elevation of 640 feet above sea level. Model results indicate that, if dewatering were to cease at quarry A, quarry B would need to increase pumpage nearly 40 percent to maintain a water-level elevation of 640 feet.

Cessation of Dewatering at Quarry B

Sand and gravel aggregate is mined at quarry B. Ground water removed from the aquifers at the sump in quarry B ultimately is discharged into Scioto Big Run. Pumping is maintained at 640 feet above sea level. Dewatering at quarry B was simulated with a single constant-head node in the glacial aquifer centered on the deepest part of the excavation within the quarry. Steady-state conditions that could result from cessation of dewatering at quarry B were simulated by removing this constant-head node from the model.

The simulated potentiometric surfaces for the glacial and bedrock aquifers that correspond to a cessation of dewatering at quarry B are illustrated in figures 35 and 36. Water levels in the vicinity of landfills 2, 3, and 4 could rise nearly 5 feet as compared with March 1986 ground-water levels. The results of the model also suggest ground-water levels could rise between 10 and 15 feet in the vicinity of landfill 1 if dewatering were to cease at quarry B. This would further saturate the landfill. Even with the cessation of dewatering at quarry B, the unsaturated zone beneath landfill 5 would still be nearly 40 feet thick. Consequently, leachate generation at landfill 5 would probably not be affected by a cessation of dewatering at quarry B.

Ground-water flow directions that could result from a cessation of dewatering at quarry B also are illustrated in figures 35 and 36. Leachate produced by landfills 2 and 3 probably would discharge into the Scioto River. Leachate entering the ground water from landfills 1, 4, and 5 ultimately may discharge into quarry A.

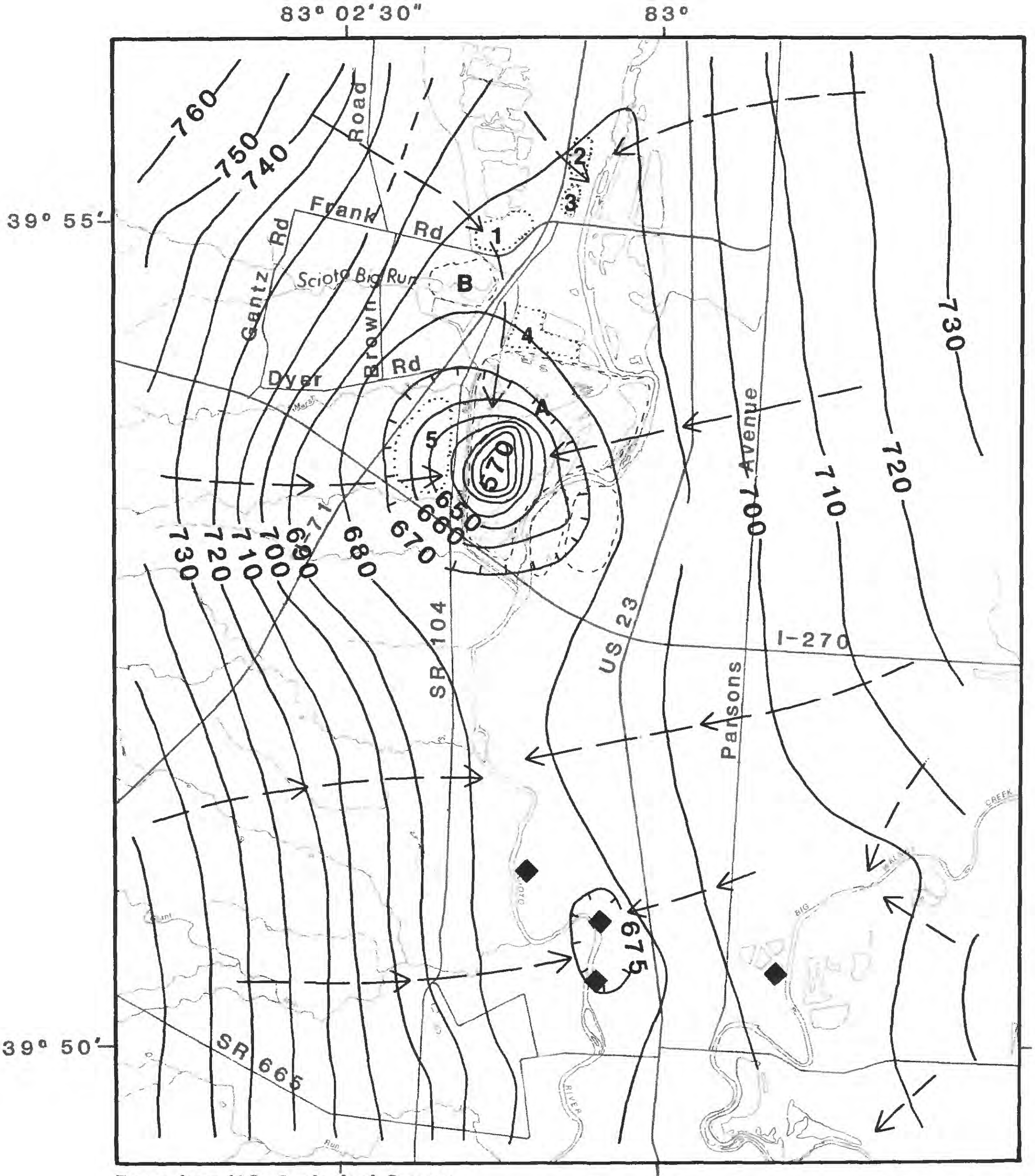
These simulated ground-water levels and directions of ground-water flow were based on the assumption that quarry A would continue to maintain a pumping elevation of 570 feet above sea level. Model results indicate that, if dewatering were to cease at quarry B, quarry A would need to increase pumpage approximately 5 percent to maintain a water-level elevation of 570 feet. This estimate does not take into account any decrease in streambed leakage from Scioto Big Run into quarry A which may result if quarry B stopped discharging into Scioto Big Run.

Cessation of Dewatering at Quarries A and B

Steady-state conditions that may result from the simultaneous cessation of dewatering at quarries A and B were simulated by removing the five drain nodes and the three constant-head nodes used to simulate their dewatering. The steady-state conditions that were generated during simulation of a cessation of dewatering at both quarries are illustrated in figures 37 and 38. These potentiometric maps indicate that water levels could rise nearly 5 feet in the vicinity of landfills 2 and 3 as compared with March 1986 ground-water levels. Ground-water levels could rise nearly 10 feet in the vicinity of landfill 4, between 15 and 20 feet near landfill 1, and just over 40 feet beneath landfill 5 if dewatering at both quarries ceases.

Figures 37 and 38 also illustrate changes in ground-water flow directions that could result from a complete cessation of dewatering at quarries A and B, assuming pumping rates at the South Well Field were similar to that of March 1986. As shown in these figures, any leachate from existing landfills transported by the ground water would discharge into the Scioto River. Ground water in the vicinity of the South Well Field would continue to discharge into the collector wells and would be unaffected by cessation of quarry dewatering.

Steady-state conditions and ground-water flow directions that could result from the cessation of dewatering at both quarries if the well field were pumped at its maximum capacity are illustrated in figures 39 and 40. Although the net cone of depression associated with the South Well Field would increase, and ground water from a larger part of the study area would discharge into the wells, leachate generated by the existing landfills still would discharge into the Scioto River and would not enter the area of influence of the South Well Field except as induced infiltration from the Scioto River.



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

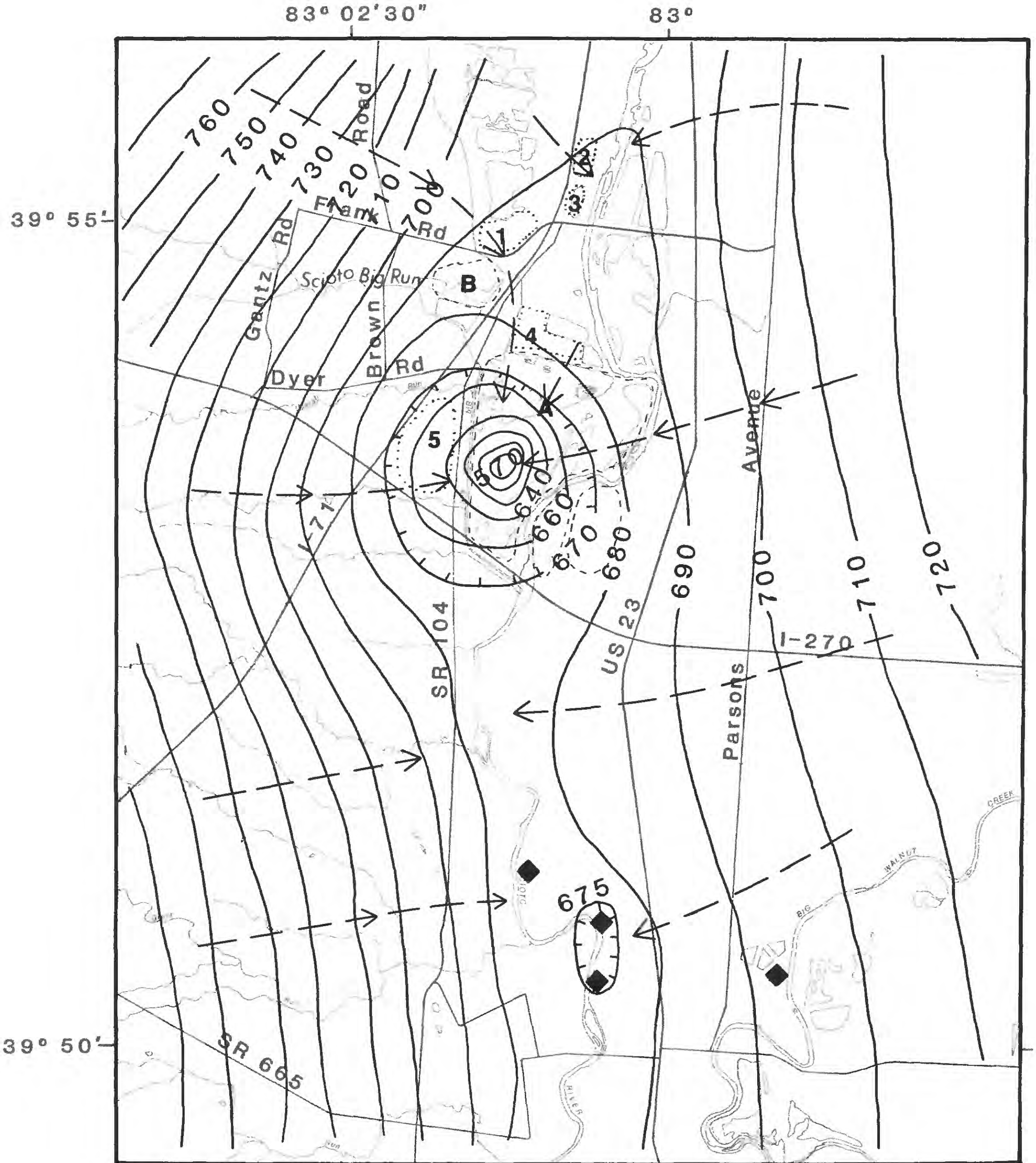
0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

B Quarry   **4** Landfill   ◆ Collector well   ←— — — Approximate flow direction

—680— Simulated water-level contour. Interval 10 feet except near large water-level depression and collector wells. Datum is sea level.

Figure 35.--Potentiometric surface and generalized ground-water flow directions in the glacial aquifer that could result from the cessation of dewatering at quarry B.



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

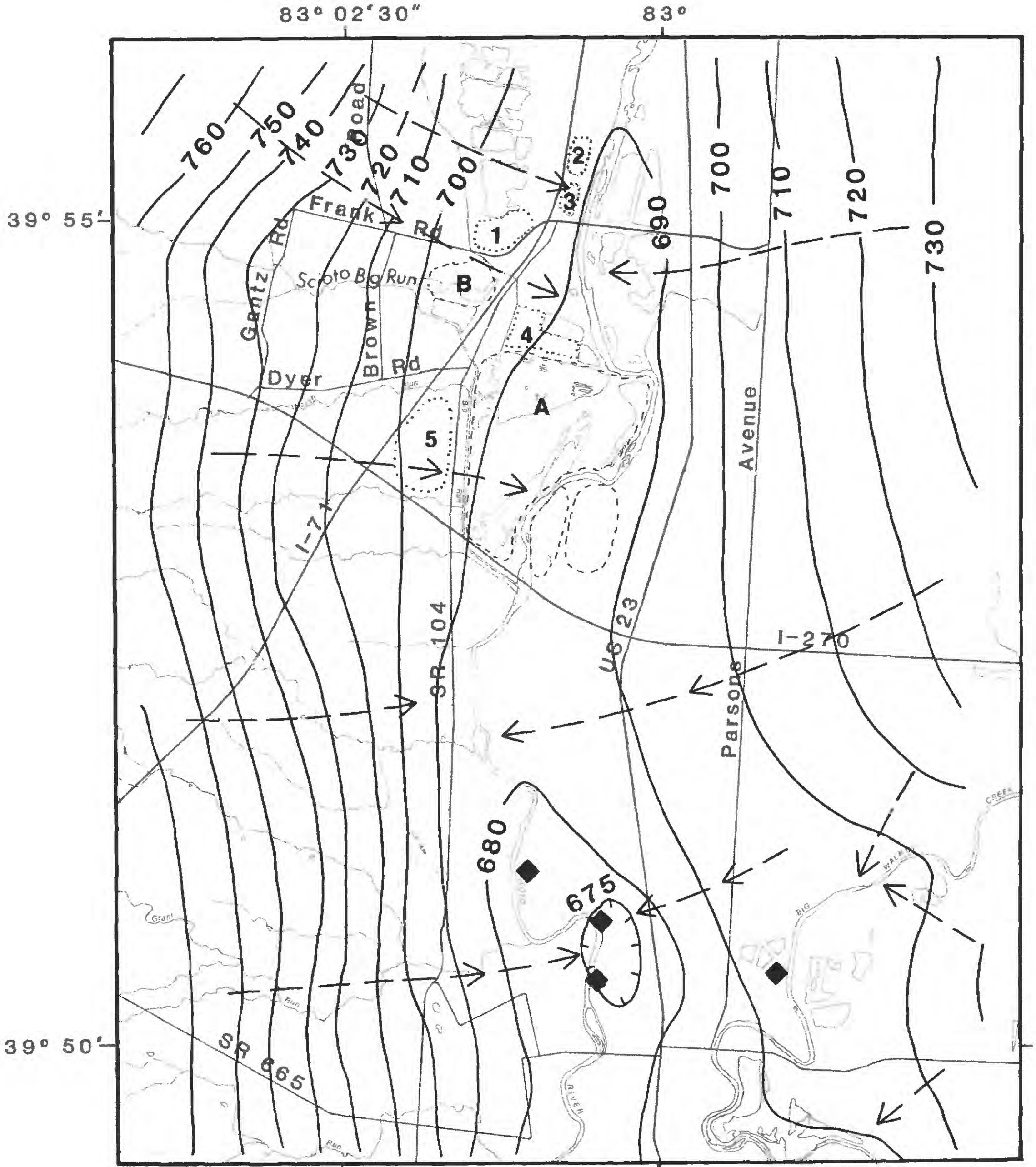
0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

B Quarry — 4 Landfill — ◆ Collector well — ←— — — Approximate flow direction

——680—— **Simulated water-level contour.**
Interval 10 feet except near large water-level depression and collector wells. Datum is sea level.

Figure 36.--Potentiometric surface and generalized ground-water flow directions in the bedrock aquifer that could result from the cessation of dewatering at quarry B.



EXPLANATION

B Quarry

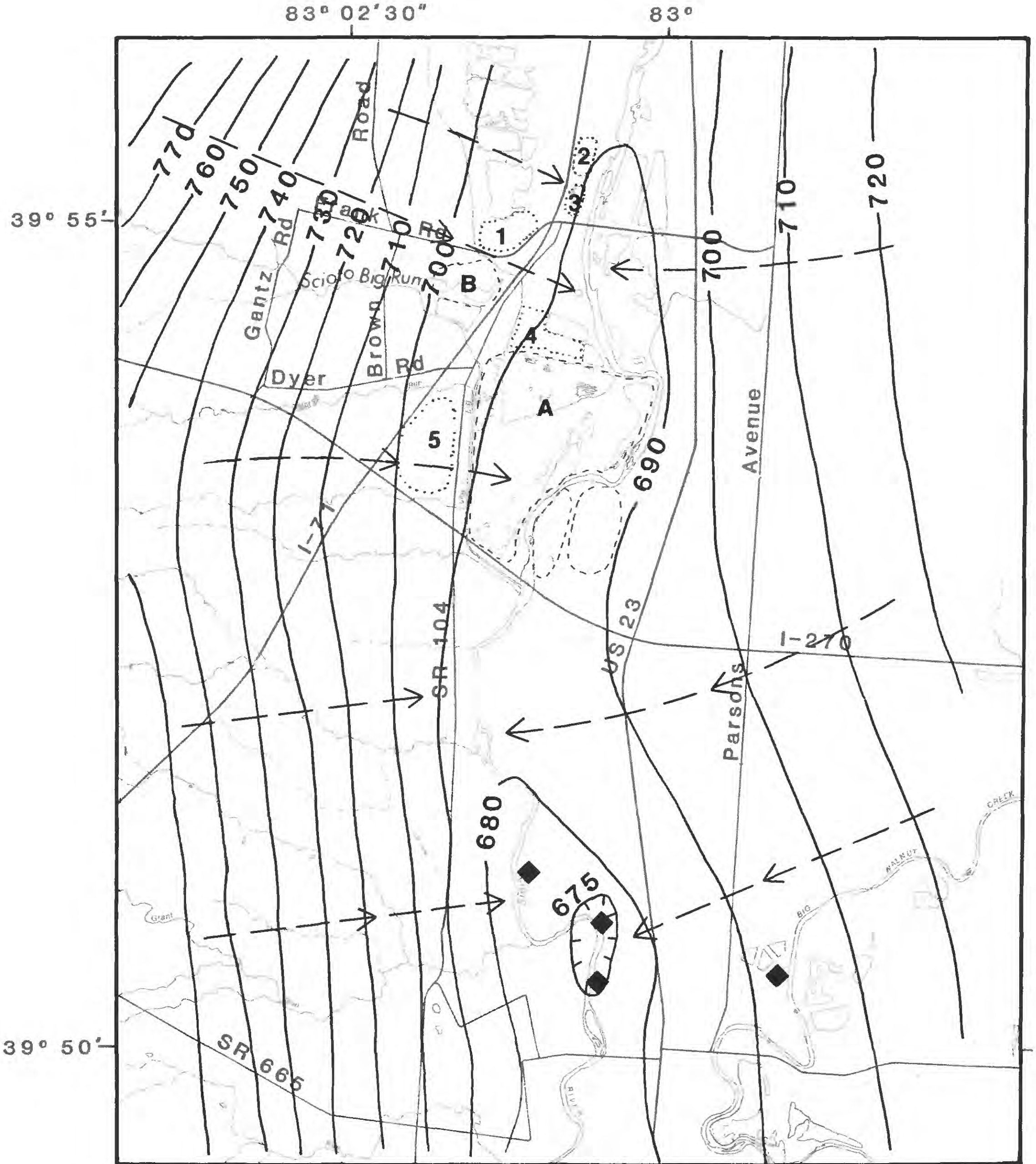
4 Landfill

◆ Collector well

← — — — Approximate flow direction

——680—— Simulated water-level contour.
Interval 10 feet except near collector wells.
Datum is sea level.

Figure 37.---Potentiometric surface and generalized ground-water flow directions in the glacial aquifer that could result from the cessation of dewatering at quarries A and B, based on March 1986 well-field pumping conditions.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

B Quarry

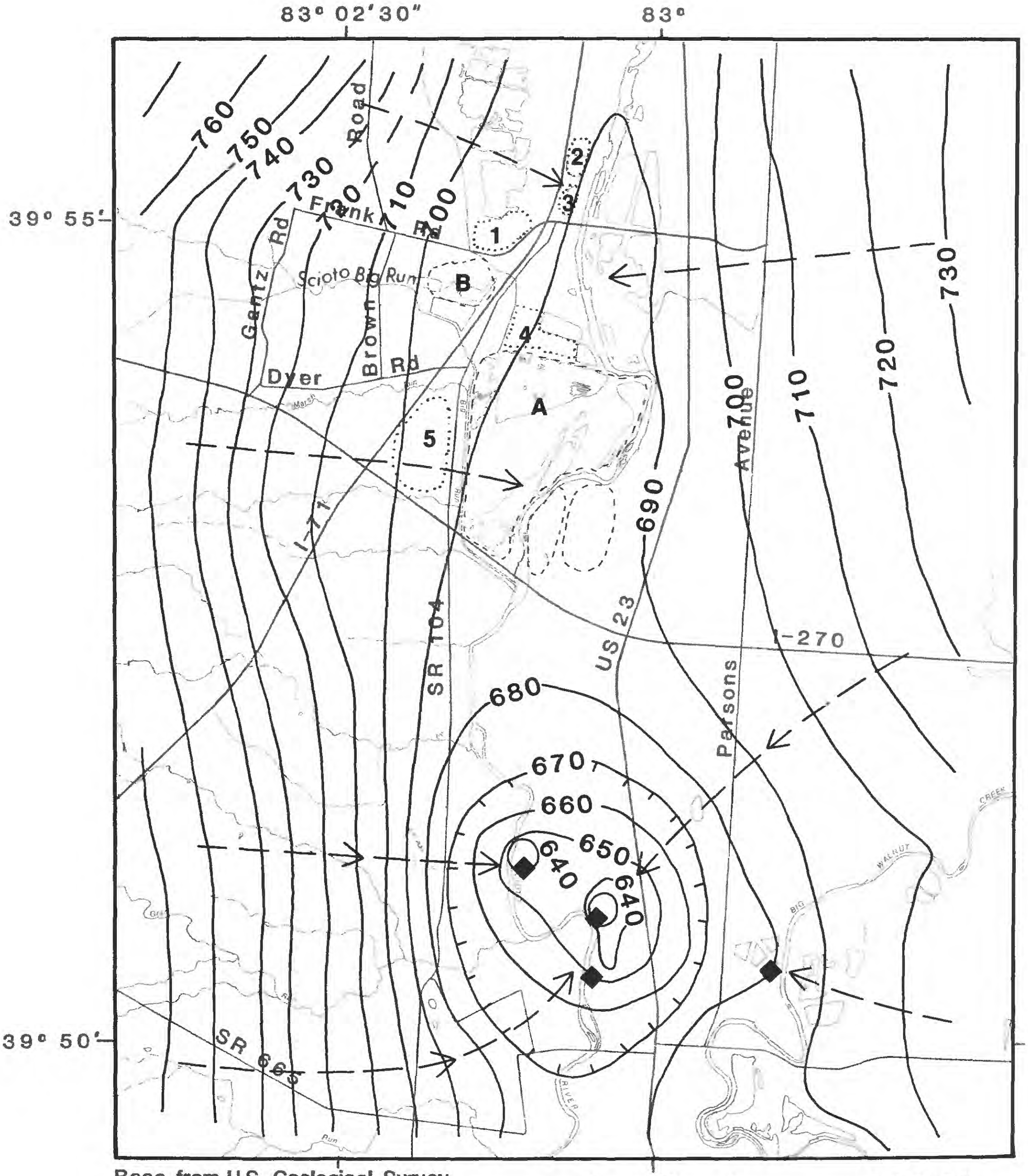
4 Landfill

◆ Collector well

←— — — — Approximate flow direction

——680—— Simulated water-level contour. Interval 10 feet except near collector wells. Datum is sea level.

Figure 38.--Potentiometric surface and generalized ground-water flow directions in the bedrock aquifer that could result from the cessation of dewatering at quarries A and B, based on March 1986 well-field pumping conditions.



EXPLANATION

B Quarry

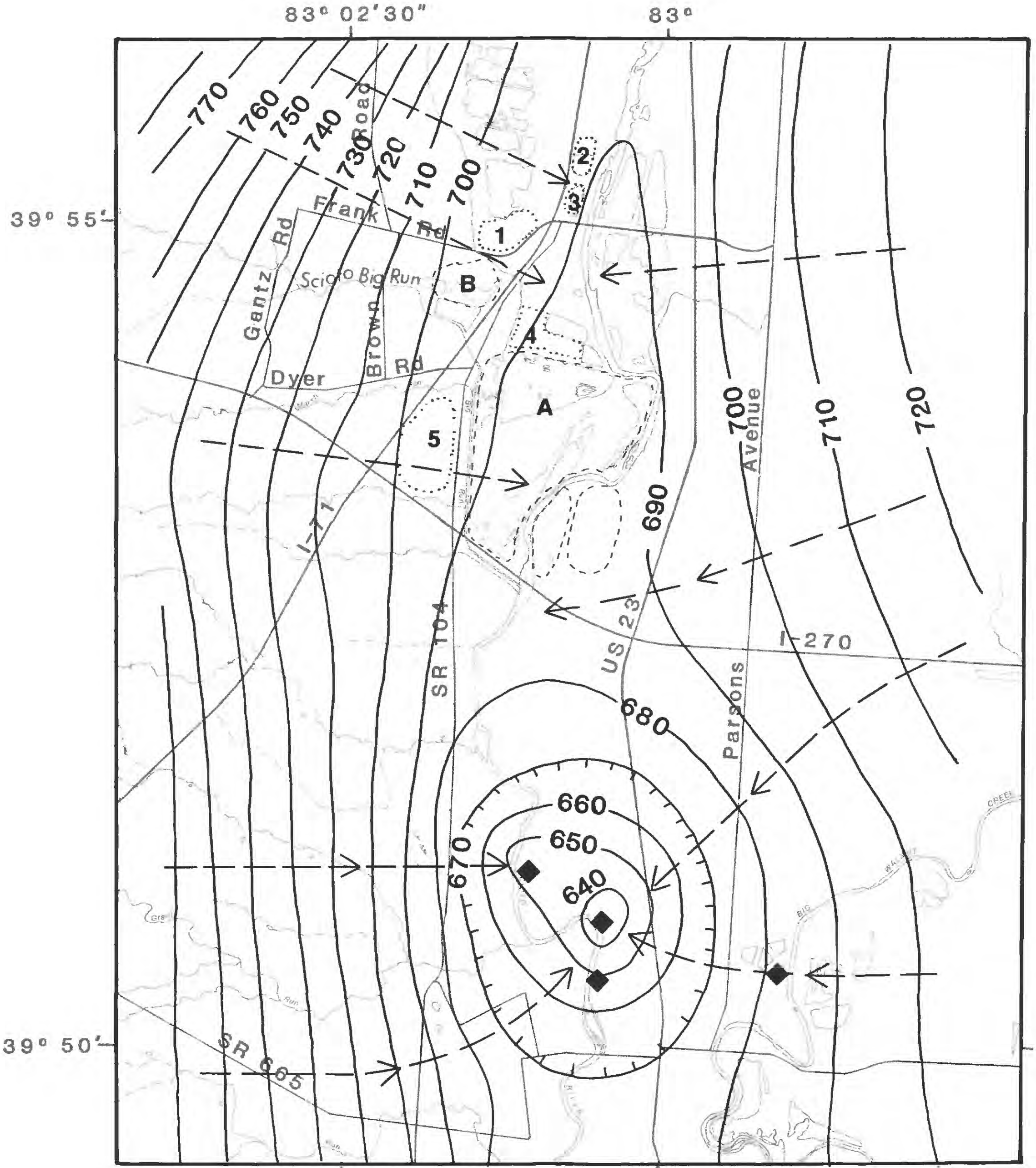
4 Landfill

◆ Collector well

←— — — — Approximate flow direction

——680—— Simulated water-level contour. Interval 10 feet. Datum is sea level

Figure 39.--Potentiometric surface and generalized ground-water flow directions in the glacial aquifer that could result from the cessation of dewatering at quarries A and B, based on maxium well-field pumpage.



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

0 1/2 1 2 MILES
0 .5 1 2 KILOMETERS

EXPLANATION

B Quarry

4 Landfill

◆ Collector well

←— — — Approximate flow direction

—680— Simulated water-level contour. Interval 10 feet. Datum is sea level

Figure 40.—Potentiometric surface and generalized ground-water flow directions in the bedrock aquifer that could result from the cessation of dewatering at quarries A and B, based on maxium well-field pumpage.

SUMMARY AND CONCLUSIONS

The South Well Field of the City of Columbus, Ohio, derives water from a stream-aquifer system that consists of 60 feet or more of saturated sands and gravels of glacial origin. As much as one-fourth of annual precipitation is estimated to contribute directly to aquifer recharge. In addition, regional ground-water flow and infiltration induced from the Scioto River and Big Walnut Creek contribute to recharge within the study area.

Ground water also is available from the underlying bedrock aquifer, which is composed largely of carbonate rock; however, the quantities of ground water available generally are less than for the unconsolidated aquifer.

Historic water-level data indicate that ground-water flow directions in the glacial and bedrock aquifers are toward the Scioto River valley. Potentiometric levels in the bedrock aquifer near the Scioto River are slightly higher than those in the overlying unconsolidated aquifer and are typical of a discharge area.

The study area can be divided into two principal areas of large-scale ground-water withdrawals. In the northern part of the study area, two quarries operate dewatering systems to mine below the natural water table. In the southern part of the study area, four radial-collector wells are operated by the City of Columbus. The quarry dewatering has produced two deep cones of depression. At quarry A, there is nearly 120 feet of persistent drawdown compared with historic water levels, and at quarry B there is approximately 45 feet of drawdown. The ground water pumped is derived mostly from the unconsolidated aquifer. However, at quarry site A, the unconsolidated aquifer has been locally dewatered, and much of the water pumped is from bedrock. In the southern part of the study area, the four collector wells that comprise the City of Columbus's South Well Field together pumped an average of about 8.2 Mgal/d in early 1986. At this pumping rate, no persistent cones of depression have developed.

Ground-water flow directions in the northern half of the study area have been modified since the late 1960's, when quarrying began. At present, flow largely converges on the major dewatering pumping centers. In the southern half of the study area, ground-water flow is mainly toward the Scioto River but locally converges on each of the four collector wells, depending on the amount of pumping at each well. In effect, the ground-water withdrawal regimen in the study area has created a ground-water divide, and there is little or no ground-water flow from the northern to the southern half of the study area.

The South Well Field is susceptible to potential sources of pollution because of the location of the ground-water supply with respect to highways, surface drainage, and local landfills.

Among these sources are potential spills of toxic substances. In addition, ground water of degraded quality is present in the vicinity of the landfills, all of which are located upstream from the municipal supply.

Because of the susceptibility of the stream-aquifer system to damage by accidental spills of toxic substances, a specialized sampling program for metals and organic chemicals was conducted early in the project to determine the baseline level of such materials in the soil and waters of southern Franklin County. In addition, between 1983 and 1986, a surveillance program of water-level measurement and water-quality sampling was conducted to observe conditions in the vicinity of the landfill sites and other sites considered to be critical.

General conclusions drawn from the baseline sampling and surveillance programs were:

(1) No acute problem areas were revealed by the baseline sampling.

(2) Conditions of water levels and water quality as of early 1986 are stable near the collector wells.

(3) Although problems of water-level decline and degraded ground water remain in the northern part of the study area, no unusual developments were revealed in the study.

(4) Chemical constituents removed by surface leaching of landfill 5 may enter surface drainage but, because of dilution by the streams, pose little threat to the South Well Field.

A three-dimensional steady-state ground-water flow model was used to assess potential effects of toxic-substance spills and cessation of quarry dewatering on the glacial aquifer. The simulated steady-state ground-water budget of the glacial-bedrock aquifer system, based on March 1986 conditions, indicates that approximately 59 percent of the ground water discharged within the study area is from quarry dewatering, whereas approximately 9 percent of the ground water discharged within the study area is from the South Well Field. The rest is discharged by seepage to streams and lakes and by commercial and industrial pumpage.

Unless a contaminant is attenuated, it will eventually make its way to a discharge point within the ground-water system. On the basis of March 1986 aquifer conditions, a toxic-substance spill along the major highways in the northern two-thirds of the study area eventually could discharge into one of the two quarries or into the Scioto River. Any spill along SR 104 and US 23 in the vicinity of the collector wells ultimately could discharge into the wells. A toxic-substance spill on SR 665 ultimately may discharge into the Scioto River, Big Walnut Creek, or possibly into the collector wells. A spill directly into the Scioto River upstream of the well field has the potential to reach the wells through induced river infiltration. Results of the model indicate that only 13 percent of the water pumped by the collector wells is from infiltration through the riverbeds.

It is important to note that the above scenarios correspond to March 1986 aquifer conditions. If the collector wells were pumped at a greater rate, their cone of influence would increase, and ground water and surface water from a greater part of the study area would discharge into the wells. This could include ground water from areas along I-71 and I-270.

Results of the ground-water flow model suggest cessation of dewatering at quarry A or simultaneous cessation of dewatering at quarries A and B would result in hydraulic connection between landfill 5 and the aquifers. This could produce pathways for leachate migration away from landfill 5 and would remove the benefits of leachate attenuation within the current (March 1986) unsaturated zone beneath landfill 5. Cessation of dewatering at quarry B would not affect the production and migration of leachate produced by landfill 5. Complete cessation of quarry dewatering within the study area would result in hydraulic gradients that are flatter than those measured in March 1986. Flatter hydraulic gradients would reduce ground-water velocities and slow migration of leachate.

Simulations of cessation of dewatering also indicate that it is unlikely landfill leachate would reach the South Well Field based on either March 1986 pumping rates or maximum well-field pumping rates. Landfill leachate could reach the collector wells only through riverbed infiltration. Any landfill leachate entering the Scioto River will undergo attenuation by the aquifer materials through which the leachate passes, dilution once within the river, and further attenuation as it filters through the riverbed.

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WATER-QUALITY DATA

Table 7.--*Water-quality data from baseline sampling, June 1984*

[mg/L, milligrams per liter; µg/kg, micrograms per kilogram; µg/g, micrograms per gram; µg/l, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; dash indicates no data available.]

Local number	Specific conductance (µS/cm)	pH (standard units)	Temperature water (deg. C)	Oxygen, dissolved (mg/L)	Aluminum, dissolved (µg/L as Al)	Barium, dissolved (µg/L as Ba)	Antimony dissolved (µg/L as Sb)	Antimony, total in bottom material (µg/g)	Arsenic, dissolved (µg/L as As)
Wells									
FR-145	700	6.70	13.5	0	<10	100	<1	--	1
FR-151	700	6.90	14.5	1.6	30	100	<1	--	1
FR-36	872	6.80	12.5	--	<10	74	<1	--	5
FR-120	555	6.90	12.5	0.2	<10	300	<1	--	3
FR-73	650	7.00	12.5	1.8	50	300	<1	--	1
FR-209	830	6.90	12.5	0.1	20	51	<1	--	6
FR-262	810	6.40	14.0	0.1	20	300	<1	--	1
FR-246	1,280	6.60	14.5	0.1	<10	140	<1	--	3
FR-260	790	7.00	18.5	0.6	10	92	<1	--	1
FR-256	1,680	6.50	17.0	0	10	1,200	<1	--	6
Surface-water sites									
03229500	660	7.40	21.5	7.2	20	--	<1	<1	2
Site H	695	7.40	23.5	7.9	30	100	<1	<1	1
Site D	730	7.30	23.0	7.6	20	--	2	2	1
Site A	588	7.90	23.5	12.7	10	--	<1	<1	1
Soil-core sites									
SC-1	--	--	--	--	--	--	<1	<1	--
SC-2	--	--	--	--	--	--	<1	<1	--

Table 7.--*Water-quality data from baseline sampling, June 1984*--Continued

Local number	Arsenic, total in bottom material (µg/g as As)	Beryllium, dissolved (µg/L as Be)	Beryllium, recoverable from bottom material (µg/g)	Cadmium, dissolved (µg/L as Cd)	Cadmium, recoverable from bottom material (µg/g as Cd)	Chromium, dissolved (µg/L as Cr)	Chromium, recoverable from bottom material (µg/g)	Copper, dissolved (µg/L as Cu)	Copper, recoverable from bottom material (µg/g as Cu)	Lead, dissolved (µg/L as Pb)	Lead, recoverable from bottom material (µg/g as Pb)
Wells											
FR-145	--	--	--	<1	--	10	--	<1	--	2	--
FR-151	--	--	--	1	--	10	--	<1	--	3	--
FR-36	--	--	--	1	--	<10	--	3	--	1	--
FR-120	--	--	--	1	--	<10	--	<1	--	3	--
FR-73	--	--	--	1	--	<10	--	6	--	1	--
FR-209	--	--	--	<1	--	10	--	2	--	4	--
FR-262	--	--	--	<1	--	10	--	3	--	3	--
FR-246	--	--	--	<1	--	<10	--	1	--	5	--
FR-260	--	--	--	<1	--	10	--	<1	--	1	--
FR-256	--	--	--	1	--	10	--	<1	--	5	--
Surface-water sites											
03229500	10	<10	<1	<1	3	<10	10	7	80	2	90
Site H	28	--	<1	1	3	<10	20	5	70	2	90
Site D	10	<10	1	<1	6	10	110	8	110	4	470
Site A	20	<10	<1	<1	9	10	90	11	200	3	530
Soil-core sites											
SC-1	10	--	<1	--	2	--	30	--	60	--	120
SC-2	10	--	<1	--	2	--	20	--	70	--	80

Table 7.--*Water-quality data from baseline sampling, June 1984*--Continued

Local number	Mercury, dissolved (µg/L as Hg)	Mercury, recoverable from bottom material (µg/g as Hg)	Nickel, dissolved (µg/L as Ni)	Nickel, recoverable from bottom material (µg/g as Ni)	Selenium, dissolved (µg/L as Se)	Selenium, total in bottom material (µg/g)	Silver, dissolved (µg/L as Ag)	Silver, recoverable from bottom material (µg/g as Ag)	Zinc, dissolved (µg/L as Zn)	Zinc, recoverable from bottom material (µg/g as Zn)	Strontium, dissolved (µg/L as Sr)
Wells											
FR-145	0.3	--	3	--	<1	--	<1	--	75	--	170
FR-151	0.4	--	1	--	<1	--	<1	--	30	--	130
FR-36	0.5	--	3	--	<1	--	3	--	490	--	110
FR-120	0.2	--	2	--	<1	--	1	--	40	--	1,100
FR-73	0.2	--	3	--	<1	--	<1	--	50	--	240
FR-209	0.2	--	2	--	<1	--	<1	--	26	--	12,000
FR-262	0.1	--	<1	--	<1	--	3	--	10	--	380
FR-246	0.3	--	3	--	<1	--	1	--	150	--	15,000
FR-260	0.3	--	2	--	<1	--	<1	--	10	--	1,300
FR-256	0.7	--	13	--	<1	--	3	--	12	--	2,700
Surface-water sites											
03229500	0.3	1.6	2	30	<1	<1	1	0	15	200	470
Site H	0.3	1.2	4	40	<1	<1	3	0	20	210	540
Site D	0.5	2.2	6	60	<1	<1	2	0	27	870	1,500
Site A	0.3	2.8	3	40	<1	2	1	--	45	490	1,500
Soil-core sites											
SC-1	--	0.72	--	20	--	<1	--	--	--	180	--
SC-2	--	0.88	--	30	--	<1	--	0	--	120	--

Table 7.--*Water-quality data from baseline sampling, June 1984--Continued*

Local number	Iron, dis-solved (µg/L as Fe)	Manga-nese, dis-solved (µg/L as Mn)	Cyanide, total (mg/L as Cn)	Cyanide, total in bottom mate-rial (µg/g as Cn)	Ace-naph-thene, bottom mate-rial (µg/kg)	Anthra-cene, bottom mate-rial (µg/kg)	Benzo(b) fluo-ran-thene, bottom mate-rial (µg/kg)	Benzo(k) fluo-ran-thene, bottom mate-rial (µg/kg)	Benzo(a) pyrene, bottom mate-rial (µg/kg)	Chry-sene, bottom mate-rial (µg/kg)	Diethyl phthal-ate, bottom mate-rial (µg/kg)
Wells											
FR-145	2,100	43	<0.010	--	--	--	--	--	--	--	--
FR-151	1,000	40	<0.010	--	--	--	--	--	--	--	--
FR-36	--	--	<0.010	--	--	--	--	--	--	--	--
FR-120	2,200	44	<0.010	--	--	--	--	--	--	--	--
FR-73	450	36	<0.010	--	--	--	--	--	--	--	--
FR-209	2,800	32	<0.010	--	--	--	--	--	--	--	--
FR-262	--	--	<0.010	--	--	--	--	--	--	--	--
FR-246	4,500	610	<0.010	--	--	--	--	--	--	--	--
FR-260	1,300	19	<0.010	--	--	--	--	--	--	--	--
FR-256	10,000	37	<0.010	--	--	--	--	--	--	--	--
Surface-water sites											
03229500	--	--	<0.010	<0.5	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Site H	<3	13	<0.010	<0.5	390	350	<10.0	<10.0	<10.0	410	<10.0
Site D	--	--	<0.010	<0.5	<10.0	<10.0	150	380	190	230	<10.0
Site A	--	--	<0.010	<0.5	<10.0	<10.0	210	280	<10.0	350	<10.0
Soil-core sites											
SC-1	--	--	--	<0.5	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
SC-2	--	--	--	<0.5	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	200

Table 7.--*Water-quality data from baseline sampling, June 1984*--Continued

Local number	Fluoranthene, bottom material (µg/kg)	Fluorene, bottom material (µg/L)	Methylene chloride, total (µg/L)	Naphthalene, bottom material (µg/kg)	Phenanthrene, bottom material (µg/kg)	Pyrene, bottom material (µg/kg)	Benzo(a) anthracene, bottom material (µg/kg)	Di-n-octylphthalate, bottom material (µg/kg)	Phenol (C6H-5OH), bottom material (µg/kg)	Di-n-butyl phthalate, bottom material (µg/kg)
Wells										
FR-145	--	--	<3.0	--	--	--	--	--	--	--
FR-151	--	--	4.2	--	--	--	--	--	--	--
FR-36	--	--	3.1	--	--	--	--	--	--	--
FR-120	--	--	3.8	--	--	--	--	--	--	--
FR-73	--	--	4.1	--	--	--	--	--	--	--
FR-209	--	--	<3.0	--	--	--	--	--	--	--
FR-262	--	--	<3.0	--	--	--	--	--	--	--
FR-246	--	--	<3.0	--	--	--	--	--	--	--
FR-260	--	--	<3.0	--	--	--	--	--	--	--
FR-256	--	--	<3.0	--	--	--	--	--	--	--
Surface-water sites										
03229500	<10.0	570	<3.0	<10.0	420	420	<10.0	1,600	<20.0	<10.0
Site H	1,500	610	<3.0	290	2,200	1,700	330	<10.0	<20.0	1,100
Site D	<10.0	560	<3.0	<10.0	260	570	300	630	180	<10.0
Site A	650	<10.0	<3.0	<10.0	390	750	380	<10.0	<20.0	<10.0
Soil-core sites										
SC-1	180	<10.0	--	<10.0	<10.0	200	<10.0	<10.0	<20.0	450
SC-2	<10.0	<10.0	--	<10.0	<10.0	<10.0	<10.0	<10.0	<20.0	1,300

Table 8.--*Water-quality data from periodic sampling, June 1984 through April 1986*

[cols., colonies; K1, at least 1 colony per 100 milliliters detected for a less-than-ideal sample; mg/L, milligrams per liter; mL, milliliter; µg/l, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; dash, no data available.]

Local identi-fier	Date	Spe-cific conduc-tance (µS/cm)	pH, field	Temper-ature (deg. C)	Oxygen, dis-solved (mg/L)	Coli-form, fecal, 0.7 UM-MF (cols. per (100 mL)	Hard-ness (mg/L as CaCO3)	Hard-ness, noncar-bonated (mg/L as CaCO3)	Cal-cium, dis-solved (mg/L)	Magne-sium, dis-solved (mg/L)	Sodium, dis-solved (mg/L)	Potas-sium, dis-solved (mg/L)
Site H	06/07/84	695	7.4	23.5	7.9	120	300	70	80	25	25	3.0
FR-145	06/14/84	700	6.7	13.5	0	<1	360	85	93	32	2.1	1.4
	08/31/84	655	6.9	13.5	--	<1	370	100	97	31	2.1	1.4
	04/02/85	710	7.3	12.0	--	<1	370	91	95	32	2.1	1.4
	06/21/85	675	7.4	13.0	--	<1	370	88	94	32	2.1	1.7
TH-72	11/20/85	725	7.8	14.5	--	<1	330	0	81	32	18	2.9
TH-73	09/03/85	730	6.9	11.5	--	<1	400	92	99	37	5.3	1.3
	11/20/85	681	7.4	11.0	--	<1	410	90	100	38	5.7	1.4
TH-18	09/03/85	815	7.1	13.5	--	<1	440	97	110	39	12	1.4
	11/20/85	640	7.8	11.5	--	K1	340	19	70	40	12	1.7
Site G	11/20/85	427	8.2	12.0	11.6	8,600	210	83	56	16	13	4.7
FR-151	06/12/84	700	6.9	14.5	1.6	K1	390	77	100	33	8.6	1.4
	12/12/84	765	6.7	11.5	--	<1	410	100	110	34	9.0	1.3
	04/02/85	770	6.7	11.5	--	<1	380	84	100	32	8.0	1.4
	07/05/85	750	7.3	12.5	--	<1	390	94	100	33	7.2	1.6
	09/04/85	730	7.2	14.0	--	<1	390	88	100	33	7.7	1.3
	11/14/85	720	7.1	13.0	0.9	<1	380	100	100	32	8.7	1.5
	04/11/86	737	7.4	11.5	0.3	<1	380	130	100	32	9.3	1.5
FR-36	08-31-84	825	7.0	12.0	1.5	<1	490	100	130	41	4.3	4.3
	12-12-84	940	6.8	12.0	--	<1	530	150	140	44	4.5	4.5
	04-02-85	980	7.1	12.0	--	<1	530	150	140	44	4.7	4.7
Site F	06-06-84	765	7.0	21.5	6.3	180	290	95	77	24	35	4.8
FR-120	06-12-84	555	6.9	12.5	0.2	<1	360	47	93	31	4.1	1.4
	09-04-84	645	7.2	11.5	--	<1	360	43	93	30	3.9	1.3
	12-12-84	685	6.7	11.0	--	<1	370	39	94	32	4.8	1.4
	07-05-85	700	7.3	12.0	--	<1	370	45	94	32	3.8	1.7
	04-09-86	670	7.5	11.0	0.2	<1	360	30	93	31	4.2	1.5
FR-121	09-03-85	795	7.2	14.5	--	<1	470	80	120	42	5.1	1.3
FR-73	06-12-84	650	7.0	12.5	1.8	<1	370	38	96	32	2.8	1.1
	09-04-84	665	7.1	15.0	--	<1	380	59	99	32	2.8	1.0
	06-21-85	685	7.2	12.5	--	<1	370	37	94	32	2.8	1.3
FR-209	06-14-84	830	6.9	12.5	0.1	<1	410	50	96	38	15	1.7
	08-31-84	755	6.8	12.5	--	<1	410	51	98	39	15	1.6
	12-14-84	805	7.2	12.0	--	<1	410	47	100	40	15	1.6
	06-21-85	850	7.3	12.5	--	<1	390	35	95	38	14	1.8

FR-262	09-04-84	825	7.1	11.5	--	<1	450	120	120	37	9.2	1.2
	12-12-84	830	7.1	11.5	--	<1	450	110	120	37	9.9	1.3
	04-01-85	810	7.2	11.0	--	<1	410	93	110	34	7.6	1.2
	11-14-85	830	7.1	13.0	--	<1	460	130	120	38	11	1.6
FR-202	04-10-86	945	7.5	12.5	0.2	<1	460	110	110	44	26	2.3
FR-213	09-04-85	910	7.3	13.5	--	<1	450	97	110	42	22	2.1
Site B	06-06-84	1,140	7.4	24.0	8.8	210	500	160	130	42	48	4.7
	09-04-84	1,200	7.8	18.0	7.5	190	540	210	140	47	47	6.0
	12-13-84	955	7.2	7.5	11.6	3,000	350	120	92	29	60	3.5
	04-03-85	800	7.7	8.5	8.9	7,400	320	100	82	28	39	2.5
	06-24-85	1,100	7.8	21.0	9.0	760	500	200	130	43	50	6.5
	09-03-85	1,050	7.9	25.5	3.7	87	460	190	120	38	42	5.8
	11-13-85	455	8.0	13.0	10.6	4,200	190	61	51	16	20	3.3
	04-10-86	1,180	8.4	11.5	11.0	K13	520	200	140	41	54	5.5
Site C	06-06-84	1,170	7.5	26.0	--	2,300	360	24	88	35	100	3.3
	09-04-84	1,250	7.9	16.5	7.0	4,400	320	75	80	29	150	4.9
	12-13-84	735	7.8	8.5	12.1	1,800	260	86	67	23	44	2.4
	04-03-85	720	7.8	7.5	9.6	1,100	300	88	74	27	34	1.6
	06-24-85	1,350	8.7	20.5	8.9	4,100	330	99	79	32	150	4.2
	09-03-85	1,550	8.8	25.0	3.9	830	390	120	97	36	160	5.5
	11-13-85	373	8.3	13.0	10.6	2,500	170	8	43	14	13	2.9
	04-10-86	1,060	8.8	7.0	18.0	130	350	99	83	34	80	2.2
FR-246	06-14-84	1,280	6.6	14.5	0.1	<1	610	56	160	47	34	2.5
	08-31-84	1,130	6.6	14.5	--	<1	570	73	150	48	36	2.7
	12-12-84	1,200	6.7	11.5	--	K1	600	58	160	49	35	2.6
	04-01-85	1,100	6.9	11.5	--	<1	580	100	150	50	37	2.8
	09-04-85	1,180	6.6	16.5	--	<1	620	98	170	47	29	2.5
FR-217	12-14-84	1,510	7.0	13.0	--	<1	760	530	200	64	43	3.6
	04-01-85	1,450	7.0	12.0	--	<1	760	540	200	63	42	3.2
	06-21-85	1,390	7.2	13.0	--	<1	740	520	190	64	43	4.0
	09-04-85	1,550	7.1	15.5	--	<1	770	550	200	65	44	3.7
	04-10-86	1,600	7.1	13.0	0.2	<1	790	570	210	65	53	4.2
FR-224R	04-10-86	1,100	7.2	11.0	<0.1	K1	590	310	140	58	21	2.9
FR-260	06-13-84	790	7.0	18.5	0.6	<1	260	0	67	22	39	7.7
	09-04-84	710	6.5	14.0	--	<1	250	4	65	22	38	7.7
	04-02-85	770	7.2	13.0	--	<1	250	18	64	22	37	6.8
	07-03-85	830	7.2	15.0	--	<1	250	14	65	22	38	7.2
	11-14-85	780	7.2	15.0	--	<1	270	46	70	23	40	7.6
	04-10-86	750	7.6	14.0	0.6	<1	270	60	70	22	35	6.5
FR-258	04-11-86	985	7.3	15.0	1.6	<1	400	50	110	31	32	11
FR-256	06-13-84	1,680	6.5	17.0	0	<1	630	0	110	85	91	23
	12-13-84	1,520	6.9	15.5	--	<1	600	0	110	79	79	16
	04-01-85	1,420	7.0	14.0	--	<1	580	7	110	75	64	15
	07-03-85	1,290	7.0	15.5	--	<1	590	0	110	77	56	17
	09-04-85	1,400	6.8	16.5	--	<1	620	10	120	78	58	15
	11-13-85	1,400	7.2	16.0	--	<1	670	70	130	84	64	16
	04-11-86	1,560	7.0	15.5	0.5	<1	690	70	140	83	74	16

Table 8.--*Water-quality data from periodic sampling, June 1984 through April 1986*--Continued

Local identi- fier	Date	Alka- linity, field (mg/L as CaCO3)	Carbon dioxide, dis- solved (mg/L)	Sulfide, total (mg/L)	Sulfate, dis- solved (mg/L)	Chlo- ride, dis- solved (mg/L)	Fluo- ride, dis- solved (mg/L)	Silica, dis- solved (mg/L)	Solids, sum of constit- uents, dis- solved (mg/L)	Nitrogen, ammonia, dis- solved (mg/L as N)	Nitrogen, ammonia + organic, dis- solved (mg/L as N)
Site H	06/07/84	233	18	--	83	47	0.20	3.6	410	--	--
FR-145	06/14/84	279	108	--	110	16	0.20	11	440	--	--
	08/31/84	270	66	0	100	16	0.20	11	420	--	--
	04/02/85	278	27	<0.1	99	15	0.20	11	420	--	--
	06/21/85	279	21	<0.1	88	16	0.20	11	410	--	--
TH-72	11/20/85	425	13	0	29	26	0.40	13	460	--	--
TH-73	09/03/85	308	75	<0.1	78	15	0.40	15	440	--	--
	11/20/85	314	24	0.2	86	13	0.40	15	450	--	--
TH-18	09/03/85	338	52	<0.1	72	31	0.40	14	490	--	--
	11/20/85	312	9.8	0	55	32	0.30	5.6	410	--	--
Site G	11/20/85	117	1.5	--	70	29	0.20	9.3	270	--	--
FR-151	06/12/84	309	75	--	85	36	0.20	10	460	--	--
	12/12/84	312	121	<0.1	99	30	0.20	10	480	--	--
	04/02/85	297	115	<0.1	88	32	0.20	10	450	--	--
	07/05/85	292	28	<0.1	79	35	0.20	10	440	--	--
	09/04/85	298	36	<0.1	79	32	0.10	10	440	--	--
	11/14/85	280	44	0	86	33	0.10	10	440	--	--
	04/11/86	253	19	<0.1	85	33	0.20	10	420	0.050	0.30
FR-36	08-31-84	392	76	0	120	28	0.20	12	580	--	--
	12-12-84	384	118	<0.1	150	30	0.20	11	610	--	--
	04-02-85	381	59	<0.1	140	32	0.20	11	600	--	--
Site F	06-06-84	196	38	--	120	55	0.50	4.3	440	--	--
FR-120	06-12-84	314	77	--	70	11	0.30	14	420	--	--
	09-04-84	313	38	0	65	12	0.40	13	410	--	--
	12-12-84	328	127	<0.1	64	14	0.40	13	420	--	--
	07-05-85	322	31	<0.1	61	16	0.40	13	420	--	--
	04-09-86	330	20	0.2	58	16	0.30	13	420	0.220	0.40
FR-121	09-03-85	393	48	<0.1	77	27	0.30	15	530	--	--
FR-73	06-12-84	334	65	--	62	5.0	0.30	14	410	--	--
	09-04-84	320	49	0	73	5.3	0.30	13	420	--	--
	06-21-85	330	40	<0.1	58	4.9	0.40	14	410	--	--
FR-209	06-14-84	360	88	--	100	18	1.3	16	520	--	--
	08-31-84	354	109	0	98	16	1.2	16	500	--	--
	12-14-84	367	45	<0.1	99	16	1.1	16	510	--	--
	06-21-85	359	35	<0.1	93	20	1.3	15	500	--	--

FR-262	09-04-84	333	51	0	110	36	0.20	11	530	--	--
	12-12-84	338	52	<0.1	100	34	0.20	11	520	--	--
	04-01-85	322	39	<0.1	98	28	0.20	11	480	--	--
	11-14-85	321	50	0	110	39	0.10	11	520	--	--
FR-202	04-10-86	349	21	<0.1	190	8.0	1.6	15	610	0.600	0.70
FR-213	09-04-85	351	34	0.1	150	15	1.8	16	570	--	--
Site B	06-06-84	338	26	--	190	90	0.30	10	720	--	--
	09-04-84	329	10	0	250	89	0.30	11	790	--	--
	12-13-84	233	28	<0.1	130	110	0.30	9.2	570	--	--
	04-03-85	218	8.4	<0.1	100	68	0.30	7.7	460	--	--
	06-24-85	302	9.2	--	220	93	0.20	9.6	730	--	--
	09-03-85	270	6.6	--	170	66	0.20	8.1	610	--	--
	11-13-85	135	2.5	--	72	33	0.20	7.3	280	--	--
	04-10-86	315	2.4	--	210	100	0.30	11	750	1.20	1.3
Site C	06-06-84	340	21	--	120	140	0.40	6.3	700	--	--
	09-04-84	244	5.9	--	130	220	0.60	8.8	780	--	--
	12-13-84	176	5.4	--	65	89	0.30	7.8	400	--	--
	04-03-85	208	6.4	--	66	65	0.30	7.6	400	--	--
	06-24-85	230	0.9	--	100	250	0.60	3.3	760	--	--
	09-03-85	270	0.8	--	130	260	0.50	4.9	860	--	--
	11-13-85	159	1.5	--	45	22	0.20	8.5	240	--	--
	04-10-86	248	0.7	--	95	150	0.30	1.8	600	0.060	0.050
FR-246	06-14-84	554	269	--	150	43	0.90	18	810	--	--
	08-31-84	499	243	0	160	40	1.1	17	760	--	--
	12-12-84	543	210	<0.1	150	43	0.90	18	790	--	--
	04-01-85	478	117	<0.1	150	47	0.90	18	750	--	--
	09-04-85	520	253	<0.1	140	45	1.1	18	770	--	--
FR-217	12-14-84	231	45	<0.1	520	78	0.40	11	1,100	--	--
	04-01-85	222	43	<0.1	560	78	0.40	11	1,100	--	--
	06-21-85	219	27	<0.1	460	80	0.30	11	980	--	--
	09-04-85	214	33	<0.1	540	76	0.30	11	1,100	--	--
	04-10-86	218	34	<0.1	600	85	0.30	11	1,200	0.320	0.50
FR-224R	04-10-86	281	34	1.5	350	8.3	1.6	11	760	0.490	0.60
FR-260	06-13-84	260	50	--	87	53	0.80	16	450	--	--
	09-04-84	249	152	0	76	53	0.80	15	430	--	--
	04-02-85	232	28	<0.1	75	56	0.80	15	420	--	--
	07-03-85	239	29	<0.1	74	60	1.0	15	430	--	--
	11-14-85	222	27	0	93	64	0.80	15	450	--	--
	04-10-86	205	10	<1.0	100	58	0.90	14	440	8.40	9.9
FR-258	04-11-86	352	34	<0.1	120	56	0.50	11	590	7.70	9.8
FR-256	06-13-84	728	446	--	69	120	0.20	25	970	--	--
	12-13-84	628	153	0.3	98	120	0.30	25	910	--	--
	04-01-85	577	112	<0.1	130	97	0.30	24	870	--	--
	07-03-85	605	117	<0.1	130	91	0.30	25	880	--	--
	09-04-85	611	188	0.8	110	89	0.30	25	870	--	--
	11-13-85	596	73	0.3	110	100	0.20	26	900	--	--
	04-11-86	621	120	1.2	100	120	0.20	27	950	0.810	9.4

Table 8.--*Water-quality data from periodic sampling, June 1984 through April 1986*--Continued

Local identifier	Date	Nitrogen nitrite, dissolved (mg/L as N)	Nitrogen, NO2+NO3 dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Aluminum, dissolved (µg/L)	Iron, dissolved (µg/L)	Manganese, dissolved (µg/L)	Carbon, organic, total (mg/L)	Phenols, total (µg/L)
Site H	06/07/84	--	0.160	<0.010	30	<3	13	3.8	<1
FR-145	06/14/84	--	<0.100	<0.010	<10	2,100	43	0.4	<1
	08/31/84	--	<0.100	<0.010	<100	2,000	43	0.5	<1
	04/02/85	--	<0.100	<0.010	200	1,700	44	1.3	<1
	06/21/85	--	<0.100	0.020	100	2,400	48	<0.1	4
TH-72	11/20/85	--	<3.90	0.060	300	4,400	140	3.2	<1
TH-73	09/03/85	--	0.180	0.050	100	1,200	65	2.5	9
	11/20/85	--	<0.100	<0.010	<100	2,100	56	1.1	--
TH-18	09/03/85	--	0.100	0.030	100	2,600	95	1.1	5
	11/20/85	--	<0.100	<0.010	<100	1,800	200	1.7	<1
Site G	11/20/85	--	4.40	0.080	600	440	18	9.6	<1
FR-151	06/12/84	--	0.170	0.020	30	1,000	40	0.8	<1
	12/12/84	--	<0.100	<0.010	<100	990	38	2.4	1
	04/02/85	--	<0.100	<0.010	<100	970	36	1.5	<1
	07/05/85	--	<0.100	<0.010	<100	970	37	<0.1	5
	09/04/85	--	<0.100	0.050	100	970	37	1.2	12
	11/14/85	--	<0.100	0.010	100	930	35	0.6	<1
	04/11/86	<0.010	<0.100	<0.010	--	910	36	0.3	3
FR-36	06-07-84	--	--	--	<10	--	--	--	--
	08-31-84	--	<0.100	<0.010	<100	3,300	94	1.0	<1
	12-12-84	--	<0.100	<0.010	<100	3,100	94	2.9	1
	04-02-85	--	<0.100	<0.010	<100	2,800	93	1.7	<1
Site F	06-06-84	--	4.30	0.720	<100	25	26	5.5	<1
FR-120	06-12-84	--	0.180	<0.010	<10	2,200	44	1.2	<1
	09-04-84	--	<0.100	<0.010	<100	2,200	53	0.9	<1
	12-12-84	--	<0.100	<0.010	<100	2,100	44	2.7	3
	07-05-85	--	<0.100	<0.010	<100	2,300	55	3.8	3
	04-09-86	<0.010	<0.100	<0.010	--	2,100	47	1.2	1
FR-121	09-03-85	--	<0.100	0.030	<100	3,800	65	1.7	4
FR-73	06-12-84	--	<0.100	<0.010	50	450	36	1.0	<1
	09-04-84	--	<0.100	<0.010	<100	36	18	1.2	<1
	06-21-85	--	<0.100	<0.010	100	9	34	1.8	8
FR-209	06-14-84	--	<0.100	<0.010	20	2,800	32	--	--
	08-31-84	--	<0.100	<0.010	<100	3,500	37	0.8	<1
	12-14-84	--	0.350	<0.010	200	3,200	35	2.5	1
	06-21-85	--	<0.100	<0.010	<100	2,900	31	1.7	<1

FR-262	09-04-84	--	<0.100	<0.010	200	570	190	1.3	<1
	12-12-84	--	<0.100	<0.010	<100	580	190	2.0	1
	04-01-85	--	<0.100	<0.010	<100	470	170	1.7	<1
	11-14-85	--	<0.100	<0.010	<100	600	210	1.1	<1
FR-202	04-10-86	<0.010	<0.100	<0.010	--	1,100	40	0.3	1
FR-213	09-04-85	--	0.120	<0.010	100	2,300	36	1.0	3
Site B	06-06-84	--	0.760	<0.010	<100	12	66	3.0	<1
	09-04-84	--	2.50	0.070	200	11	37	3.1	<1
	12-13-84	--	2.60	0.030	<100	38	46	6.0	6
	04-03-85	--	2.90	0.070	<100	41	46	5.2	13
	06-24-85	--	0.950	<0.010	<100	84	20	4.0	<1
	09-03-85	--	1.00	0.040	200	36	48	3.8	4
	11-13-85	--	1.30	0.040	300	79	21	7.4	3
	04-10-86	0.030	0.390	<0.010	--	51	130	4.0	1
Site C	06-06-84	--	3.00	0.690	<100	59	59	6.3	<1
	09-04-84	--	5.00	3.00	<100	27	31	8.9	1
	12-13-84	--	5.70	0.040	<100	41	17	6.9	3
	04-03-85	--	5.00	0.080	<100	10	33	4.4	1
	06-24-85	--	1.40	0.860	<100	68	43	6.3	4
	09-03-85	--	6.40	1.40	100	7	6	5.9	3
	11-13-85	--	2.20	0.050	200	110	13	8.2	3
	04-10-86	0.010	0.690	0.150	--	59	37	6.3	3
FR-246	06-14-84	--	<0.100	<0.010	<10	4,500	610	1.8	<1
	08-31-84	--	<0.100	0.020	<100	3,400	310	1.7	<1
	12-12-84	--	<0.100	<0.010	<100	4,500	480	5.7	1
	04-01-85	--	<0.100	<0.010	<100	4,000	340	3.1	1
	09-04-85	--	0.110	0.010	100	7,600	550	1.6	6
FR-217	12-14-84	--	<0.100	<0.010	<100	690	130	2.9	1
	04-01-85	--	<0.100	<0.010	<100	1,100	120	2.2	1
	06-21-85	--	0.160	<0.010	100	1,000	150	3.1	<1
	09-04-85	--	<0.100	<0.010	<100	930	150	1.2	2
	04-10-86	<0.010	<0.100	<0.010	--	1,500	160	1.1	1
FR-224R	04-10-86	<0.010	<0.100	<0.010	--	90	18	0.7	3
FR-260	06-13-84	--	<0.100	<0.010	10	1,300	19	3.9	<1
	09-04-84	--	0.380	<0.010	<100	1,200	17	4.4	<1
	04-02-85	--	<0.100	<0.010	200	1,200	17	4.1	2
	07-03-85	--	0.390	0.050	<100	1,100	17	3.8	<1
	11-14-85	--	<0.100	<0.010	100	1,300	19	4.3	19
	04-10-86	<0.010	<0.100	<0.010	--	1,300	21	3.5	13
FR-258	04-11-86	<0.010	<0.100	<0.010	--	220	560	3.9	3
FR-256	06-13-84	--	<0.100	<0.010	10	10,000	37	18	<1
	12-13-84	--	<0.100	<0.010	<100	9,900	36	17	5
	04-01-85	--	<0.100	<0.010	<100	7,100	44	9.5	5
	07-03-85	--	<0.100	<0.010	<100	10,000	36	10	2
	09-04-85	--	0.280	0.030	100	11,000	39	10	14
	11-13-85	--	<0.100	<0.010	100	9,000	40	12	15
	04-11-86	<0.010	<0.100	<0.010	--	12,000	46	22	4

Table 9.--*Water-quality data from miscellaneous sampling, August 1983 through March 1984*

[cols., colonies; K1, at least 1 colony per 100 milliliters detected for a less-than-ideal sample; mg/L, milligrams per liter; mL, milliliter; µg/l, micrograms per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; dash indicates no data available.]

Local identifier	Date	Specific conductance (µS/cm)	pH	Temperature (deg. C)	Oxygen, dissolved (mg/L)	Coliform, fecal, 0.7 UM-MF (cols. per 100 ml)	Streptococci, fecal, KF agar (cols. per 100 ml)	Hardness (mg/L as CaCO3)	Hardness, noncarbonate (mg/L as CaCO3)	Calcium, dissolved (mg/L)
FR-126	09-01-83	520	7.20	12.5	1.4	<1	42	270	0	65
FR-150	09-01-83	720	7.30	14.5	1.6	<1	<1	420	0	110
FR-151	09-01-83	745	7.20	12.5	1.4	<1	K2	410	0	110
	03-13-84	825	7.00	12.0	2.1	--	--	420	86	110
FR-115 P3	09-01-83	785	7.00	12.5	1.6	<1	<1	450	0	120
CW-115	03-13-84	645	6.90	11.0	0.3	--	--	420	94	110
Site I	03-12-84	790	6.70	3.0	12.8	--	--	270	110	72
CW-103	01-25-84	865	6.90	11.5	0.6	--	--	440	95	110
FR-119	01-27-84	870	6.50	10.0	2.7	--	--	480	81	120
Site E	01-27-84	725	6.70	0.5	13.7	--	--	300	110	78

Table 9.--*Water-quality data from miscellaneous sampling, August 1983 through March 1984*--Continued

Local identifier	Date	Magnesium, dissolved (mg/L)	Sodium, dissolved (mg/L)	Potassium, dissolved (mg/L)	Alkalinity, field (mg/L as CaCO3)	Carbon dioxide, dissolved (mg/L)	Hydrogen sulfide, total (mg/L)	Sulfate, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Silica, dissolved (mg/L)	Solids, sum of constituents, dissolved (mg/L)
FR-126	09-01-83	25	6.1	2.3	--	40	1.0	3.1	3.6	0.60	7.2	320
FR-150	09-01-83	35	4.9	1.2	--	31	0	84	30	0.20	12	470
FR-151	09-01-83	34	9.1	1.4	--	42	0	73	27	0.20	11	470
	03-13-84	35	8.5	1.4	333	64	0	77	36	0.10	11	480
FR-115 P3	09-01-83	37	2.6	1.0	--	70	0	91	19	0.30	14	510
CW-115	03-13-84	35	6.4	1.3	325	79	0	94	25	0.20	13	480
Site I	03-12-84	23	77	2.9	169	65	0	82	130	0.20	3.5	490
CW-103	01-25-84	39	16	1.5	340	83	1.9	110	42	0.60	12	540
FR-119	01-27-84	44	4.2	1.5	400	245	0.2	110	23	0.30	11	570
Site E	01-27-84	25	32	3.9	190	73	0	110	59	0.30	6.8	450

Table 9.--*Water-quality data from miscellaneous sampling, August 1983 through March 1984*--Continued

Local identi- fier	Date	Nitrogen, ammonia, dis- solved (mg/L as N)	Nitrogen, ammonia + organic, dis- solved (mg/L as N)	Nitrogen, nitrite, dis- solved (mg/L as N)	Nitrogen, NO2+NO3, dis- solved (mg/L as N)	Nitrogen, nitrate, dis- solved (mg/L as N)	Phos- phorus, dis- solved (mg/L)	Phos- phorus, ortho, dis- solved (mg/L)	Alu- minum, dis- solved (µg/L)	Iron, dis- solved (µg/L)	Manga- nese, dis- solved (µg/L)	Arsenic dis- solved (µg/L)
FR-126	09-01-83	0.280	0.60	--	<0.100	--	<0.010	--	--	11,000	800	--
FR-150	09-01-83	0.040	0.30	--	<0.100	--	<0.010	--	--	1,800	53	3
FR-151	09-01-83	0.010	0.20	--	<0.100	--	<0.010	--	--	1,100	52	4
	03-13-84	0.140	0.30	<0.010	0.580	--	--	<0.010	100	990	40	--
FR-115 P3	09-01-83	0.040	0.30	--	<0.100	--	0.010	--	--	5,200	72	--
CW-115	03-13-84	0.090	0.40	<0.010	<0.100	--	--	<0.010	100	2,700	67	--
Site I	03-12-84	0.110	0.80	0.020	1.60	1.58	--	0.030	200	29	53	--
CW-103	01-25-84	0.120	0.40	<0.010	<0.100	--	--	<0.010	<100	670	68	--
FR-119	01-27-84	0.180	0.80	<0.010	<0.100	--	--	<0.010	<100	11,000	440	--
Site E	01-27-84	0.610	1.7	0.100	4.40	4.30	--	0.120	<100	39	31	--

Table 9.--*Water-quality data from miscellaneous sampling, August 1983 through March 1984*--Continued

Local identi-fier	Date	Cadmium, dis-solved (µg/L)	Chro-mium, dis-solved (µg/L)	Copper, dis-solved (µg/L)	Lead, dis-solved (µg/L)	Mercury, dis-solved (µg/L)	Sele-nium, dis-solved (µg/L)	Zinc, dis-solved (µg/L)	Carbon, organic, dis-solved (mg/L)	Carbon, organic sus-pended, total (mg/L)	Phenols, total (µg/L)
FR-126	09-01-83	--	--	--	--	--	--	--	3.0	0.6	--
FR-150	09-01-83	<1	<10	3	<1	<0.1	<1	16	0.8	0.2	--
FR-151	09-01-83	<1	<10	3	<1	<0.1	<1	12	0.9	0.3	--
	03-13-84	--	--	--	--	--	--	--	1.0	0.1	<1
FR-115 P3	09-01-83	--	--	--	--	--	--	--	0.8	0.2	--
CW-115	03-13-84	--	--	--	--	--	--	--	1.6	0.1	<1
Site I	03-12-84	--	--	--	--	--	--	--	5.2	0.3	<1
CW-103	01-25-84	--	--	--	--	--	--	--	1.6	0.1	2
FR-119	01-27-84	--	--	--	--	--	--	--	5.2	1.1	<1
Site E	01-27-84	--	--	--	--	--	--	--	6.5	1.0	<1

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