Senior Honors Thesis

Comparison of Analytical and Numerical Flow Models Used to Delineate Capture Zones of Wells at the South Well Field, Columbus, Ohio

by

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1991

Submitted as partial fulfillment of the
requirements for the degree of Bachelor of
Science, with Distinction, in Geological Sciences
at The Ohio State University,
Summer Quarter, 1991

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ACKNOWLEDGMENTS

I would like to express my sincere appreciation to my thesis advisor, Dr. E. Scott Bair, for his suggestion of this project and the unfailing guidance he provided throughout. With sincere gratitude, I acknowledge the invaluable assistance and suggestions given to me by Craig Payne during the learning phase of the computer programs. I especially want to thank my wife for her support and total help in caring for our three children. Funds for this work were provided from an undergraduate research scholarship from the College of Arts and Sciences of The Ohio State University.

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ABSTRACT

An analytical flow model of the ground-water flow system in the Southern Franklin County area was used with a two-dimensional particle-tracking program to delineate traveltime-related capture zones of a municipal well field completed in an unconfined glacial-drift aquifer. The results were compared to the flow model and capture zones already constructed for the area using a numerical model coupled with a three-dimensional particle-tracking program. The analytical flow model uses the Theis equation describing the two-dimensional distribution of drawdown surrounding a well completed in an unconfined aquifer and superposes the results on a generalized historical head distribution that reflects pre-1967 non-pumping conditions. In contrast, the numerical flow model uses a finite-difference solution and incorporates two model layers, specified flux-boundaries conditions, leakage from riverbeds, and spatially variable hydraulic parameters. Additional simulations using the analytical flow model were performed reflecting 1990 pumping rates.

The comparisons show that the inability of the analytical flow model and the two-dimensional particle-tracking program to account for spatial variations in hydraulic conductivity and aquifer thickness cause the size of the capture zones to be overestimated and their shapes to incorrectly simulate the geologic and hydrologic conditions at the study area. However, the head distribution between the analytical and numerical flow models are reasonably similar due to similar simplifying assumptions and the relatively low discharge rates at the well field.

These results suggest that for the optimum location of sentinel wells used in a wellhead-protection program, the numerical flow model coupled with the three-dimensional particle-tracking program is the most appropriate methodology to use in this type of complex hydrogeologic setting. However, in terms of cost and accuracy, the analytical flow model coupled with the two-dimensional particle-tracking program may be more appropriate for communities in less complex hydrogeologic settings.

INTRODUCTION

The 1986 amendments to the Federal Safe Drinking Water Act (SDWA) established voluntary procedures for the protection of municipal ground-water supplies from contamination. The Wellhead Protection Program encourages communities to develop and implement land-use policies that regulate commercial and industrial activities in the areas surrounding their municipal water-supply wells. This "wellhead protection area" would be subject to zoning ordinances to minimize the risk of contamination from potential sources of pollution. The U.S. EPA (1987) has defined wellhead protection area "as the surface and subsurface area surrounding a water well or well field, surrounding a public water system, through which contaminants are likely to move toward and reach such water well or well field" (U.S. EPA, 1987, p. C-20).

In accordance with U.S. EPA guidelines, time-of-travel criteria commonly are used to delineate wellhead protection areas. The areas would be of a sufficient size (sufficient time-of-travel) to allow a reasonable amount of time to implement remedial measures, if necessary, upon detection of contaminants migrating toward the well field. Six methods for delineation of wellhead protection areas are recommended

(U.S. EPA, 1987). These methods vary in level of accuracy, time of investigation and implementation, materials required, and cost. The methods are numerical models, hydrogeologic mapping, analytical models, simplified-variable shapes, and a circle of arbitrary or calculated fixed radius. Generally, time and cost requirements are greatest for numerical models, whereas they are least for circles of arbitrary radius.

In addition to identifying the wellhead protection area for local zoning boards, use of a particle-tracking program to delineate capture zones provides guidance to water-supply authorities for locating "sentinel" wells. These wells may be used in a monitoring scheme that would allow a reasonable length of time to respond to the presence of migrating contaminants. However, determination of "sentinel" well locations is dependent on the type of model used and the parameter values used in the model. Accurate values of site-specific geologic and hydraulic parameters such as permeability, water-level gradients, porosity, and aquifer thickness help ensure accurate location of planned "sentinel" wells.

Purpose and Scope

The purpose of this study is to compare the differences in accuracy between an analytical flow model coupled with a two-dimensional particle-tracking program used to delineate capture zones of wells with the results of a previously constructed numerical flow model coupled with a three-dimensional particle-tracking program used for the same purpose. The study site is the South Well Field at Columbus, Ohio, which supplies about 25 percent of the water to the City and its suburbs (Sedam et al., 1989; Bair et al., 1990). The capture zones based on the numerical flow model incorporated geologic and hydraulic parameters which varied spatially. This study, however, uses a computer program using an analytical, well hydraulic equation that computes the two-dimensional distribution of drawdown surrounding a fully penetrating pumping well. The two-dimensional flow model uses best-estimate, uniform values of geologic and hydraulic parameters and requires many simplifying assumptions. Infiltration from area waterways is incorporated in the analytical flow model using image-well theory.

A large number of communities in Ohio, the Midwest, and New England abstract ground water from geologic settings similar to the South Well Field. This study adds to the body of knowledge which guides scientists, engineers, and policy-makers toward identifying the methods of delineation most appropriate for their community and associated geologic setting.

Location

The study area (fig. 1) is located south of the City of Columbus in southern Franklin County, Ohio, and covers about 21 square miles of relatively flat to gently sloping terrain in the Scioto River valley and the adjacent upland areas. The Scioto River and a tributary, Big Walnut Creek, flow roughly from north-to-south through the study area and merge about two miles south of the study area in northern Pickaway County, about a mile west of the Village of Lockbourne.

GEOLOGIC SETTING

The study area is located near the southern border of terrain glaciated by the Scioto Lobe during the last stages of Wisconsinan glaciation. Surface deposits consisting of alluvium, ground moraine, and glacial outwash comprise an unconfined aquifer that is hydraulically connected to underlying Paleozoic carbonate rocks.

Figure 2 shows regional cross sections of the general geology of Franklin County, Ohio. Figures 3 through 6 are specific cross sections through the study area. The upland areas to the west of the floodplain of the Scioto River consist of clay-rich tills with small amounts of glacial outwash. Deposits of alluvial silt, clay and sand (Schmidt

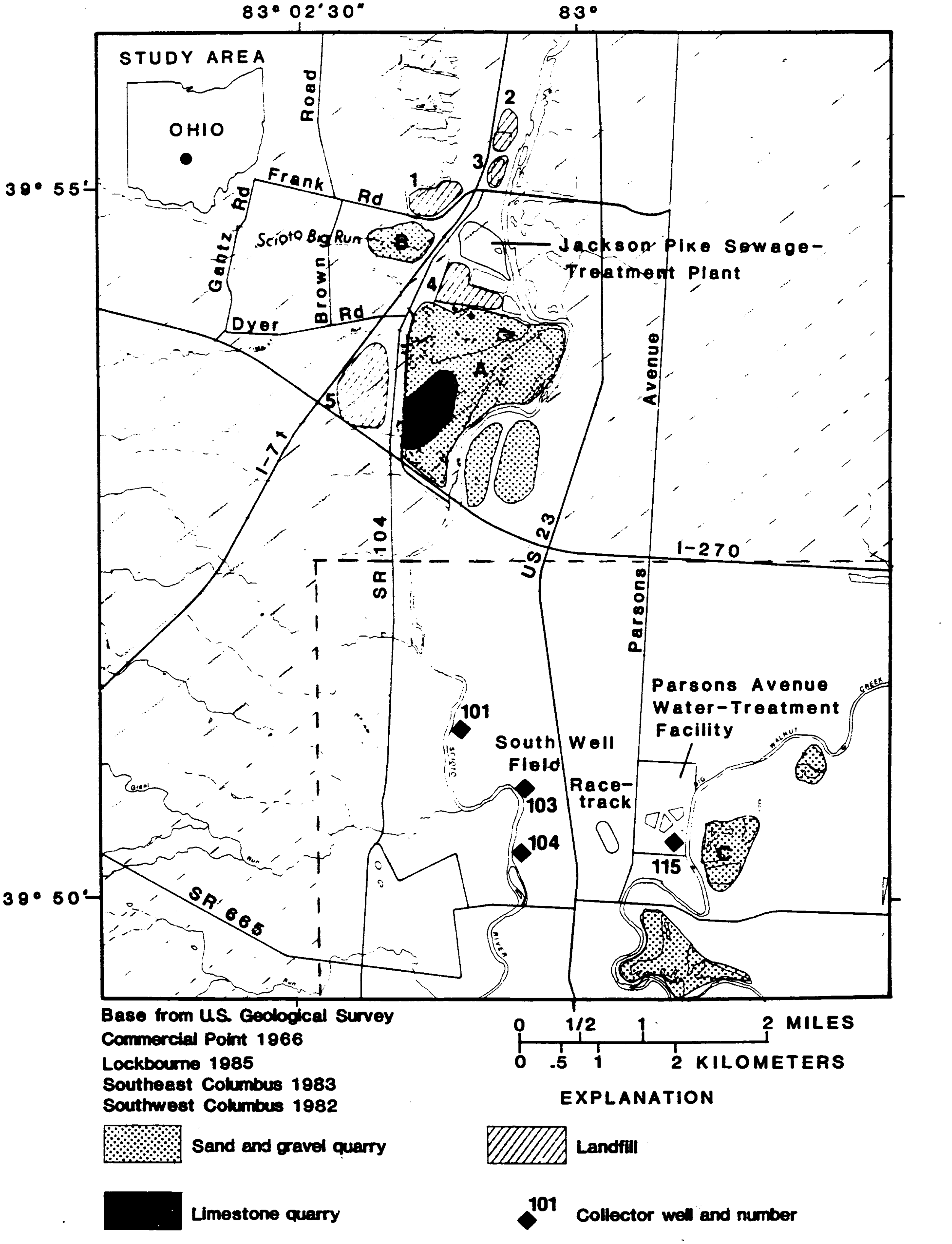


Figure 1. Location of study area, principal quarries and landfills, and the South Well Field (modified from Sedam et al., 1989).

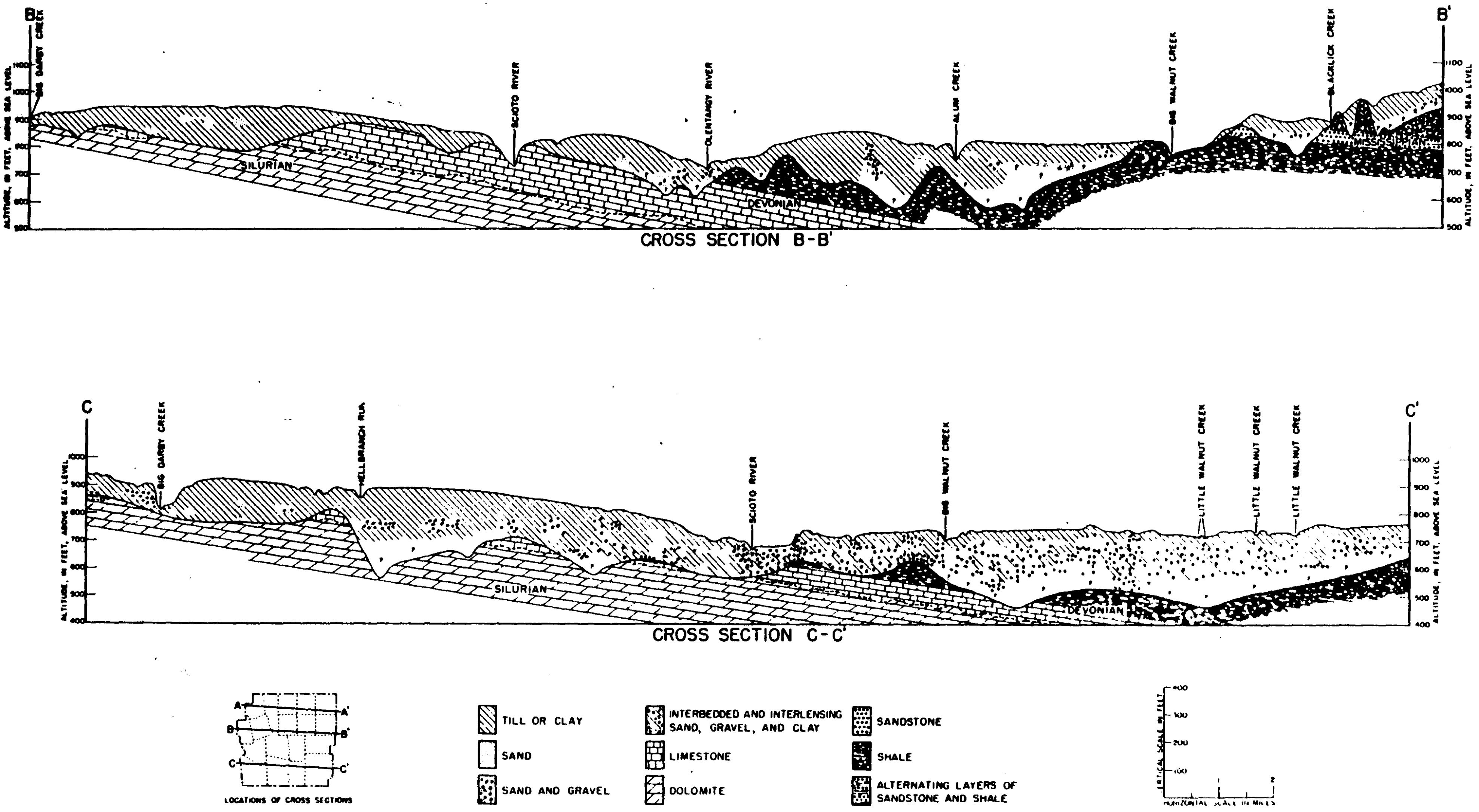
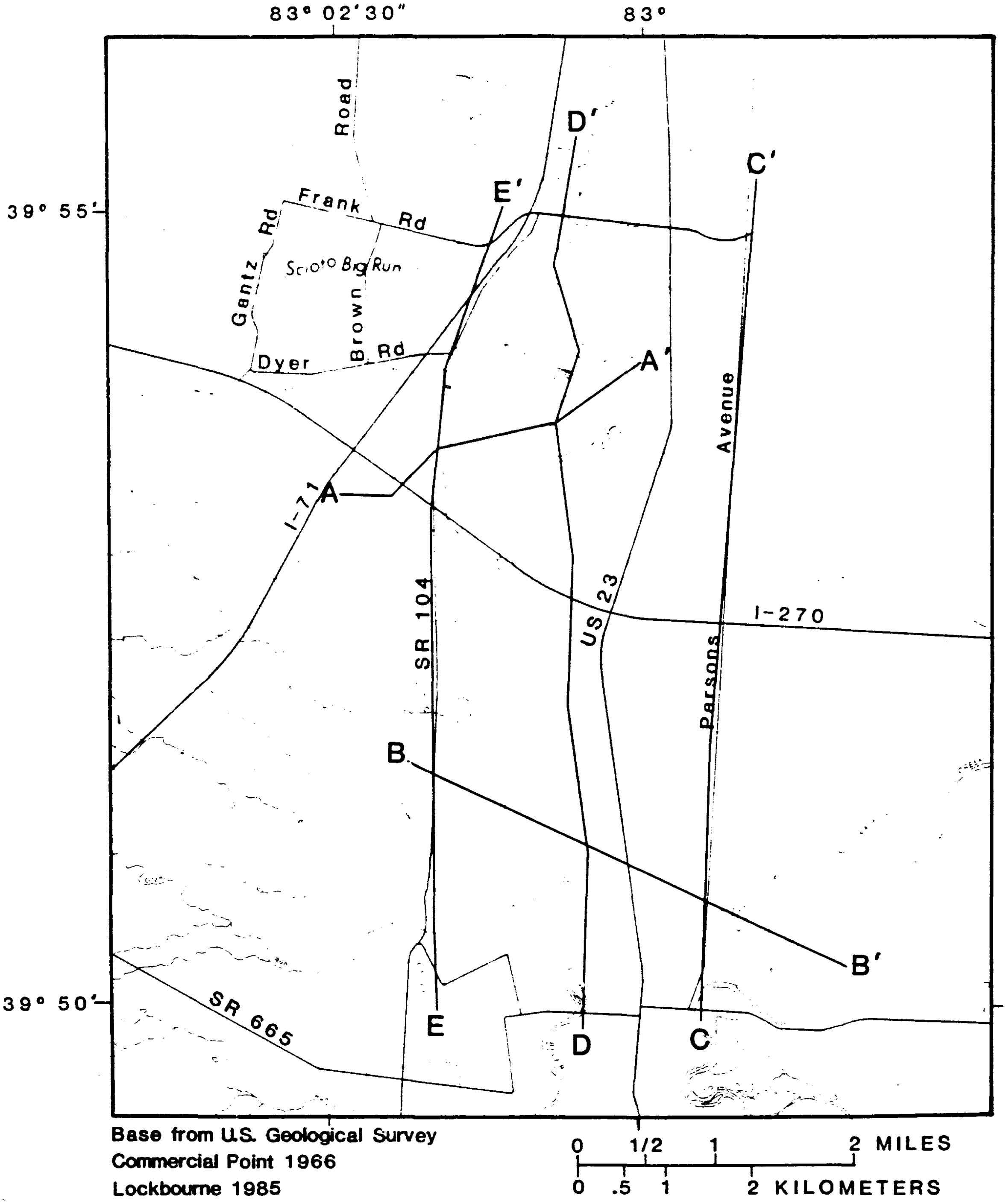


Figure 2. Generalized cross-sections of the study area (modified from Schmidt an Goldthwait, 1958).



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

Figure 3. Locations of applicable geologic cross-sections shown in figures 4 through 6 (Sedam et al., 1989).

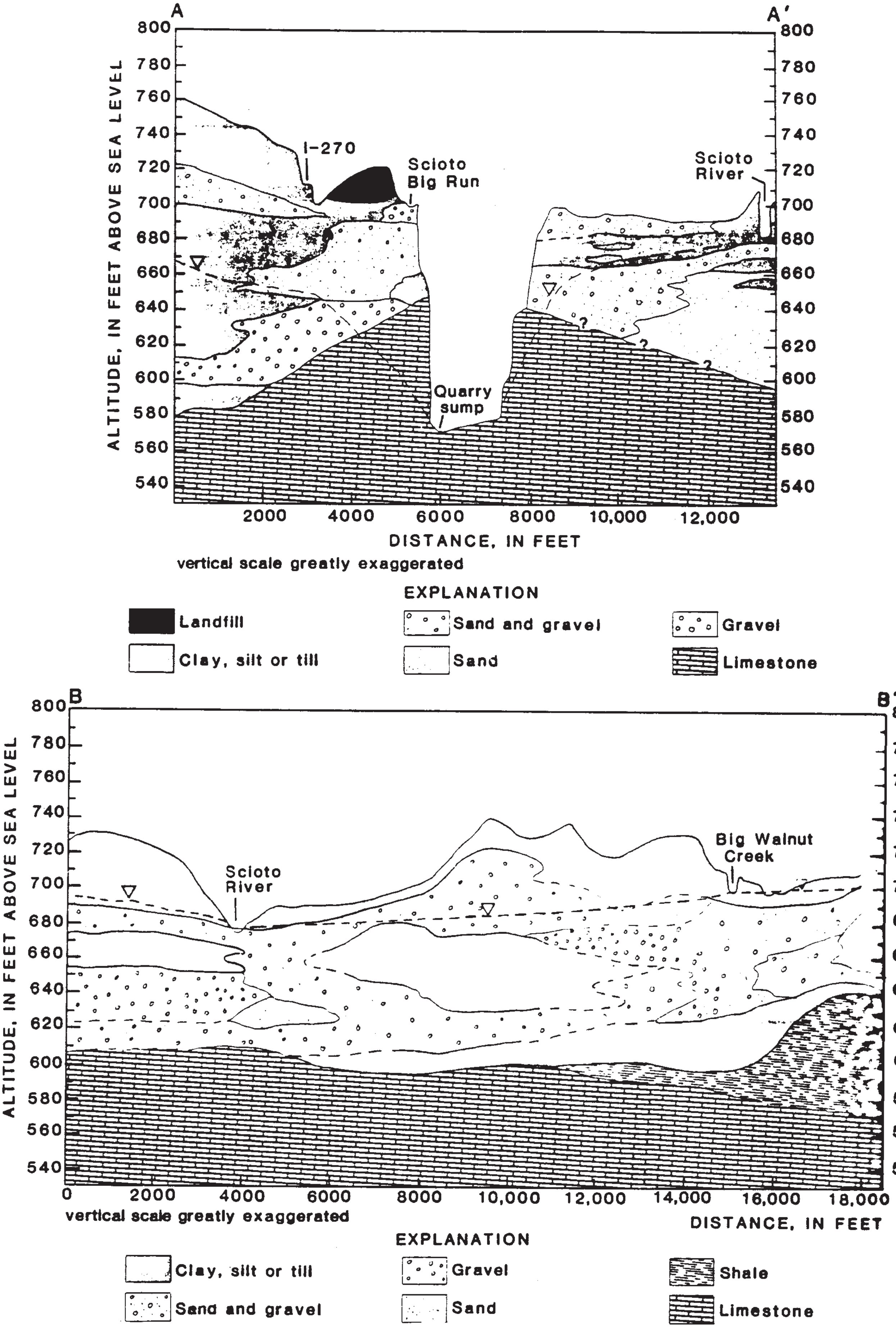


Figure 4. Geologic sections A-A' and B-B' (Sedam et al., 1989).

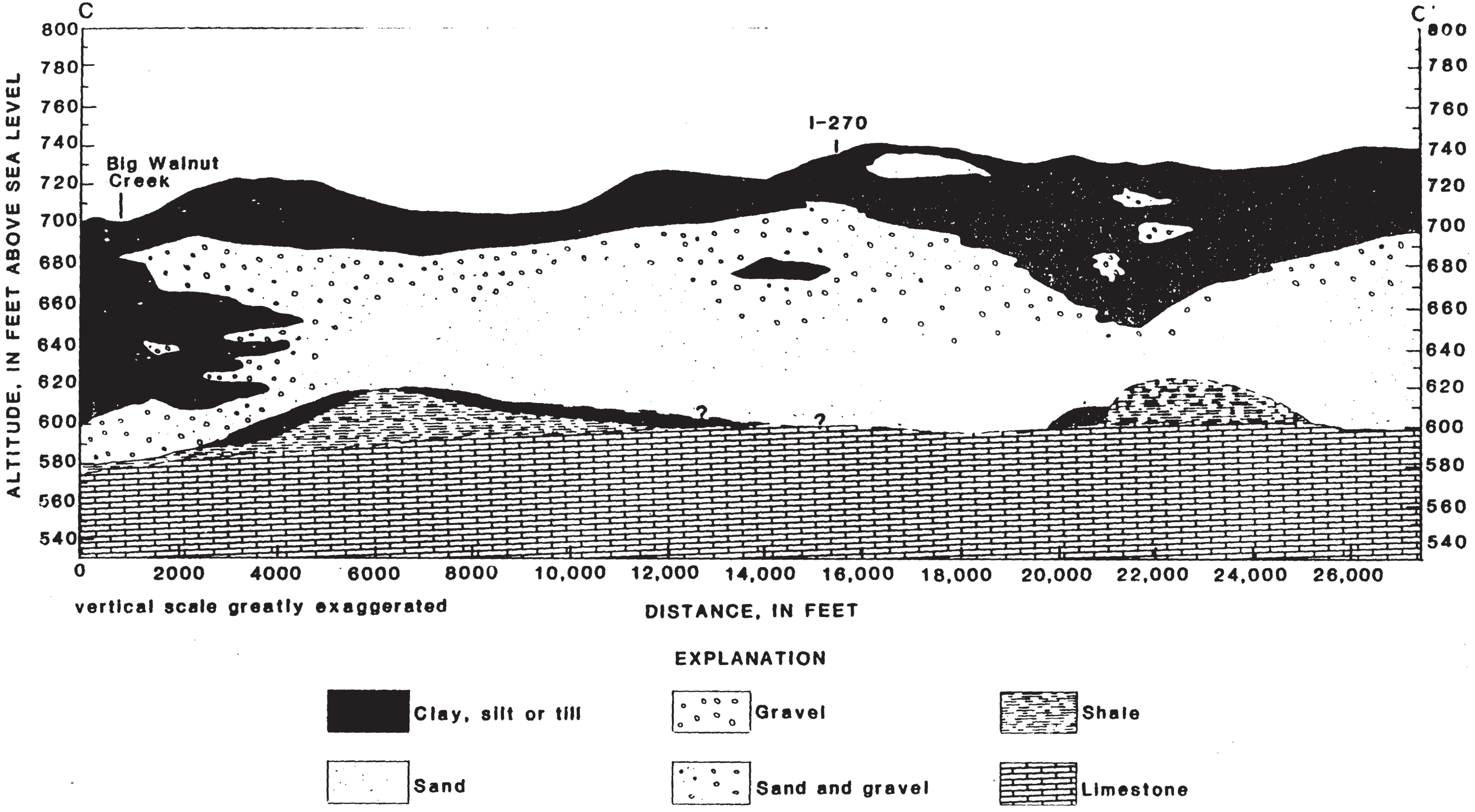


Figure 5. Geologic section C-C′ (Sedam et al., 1989).

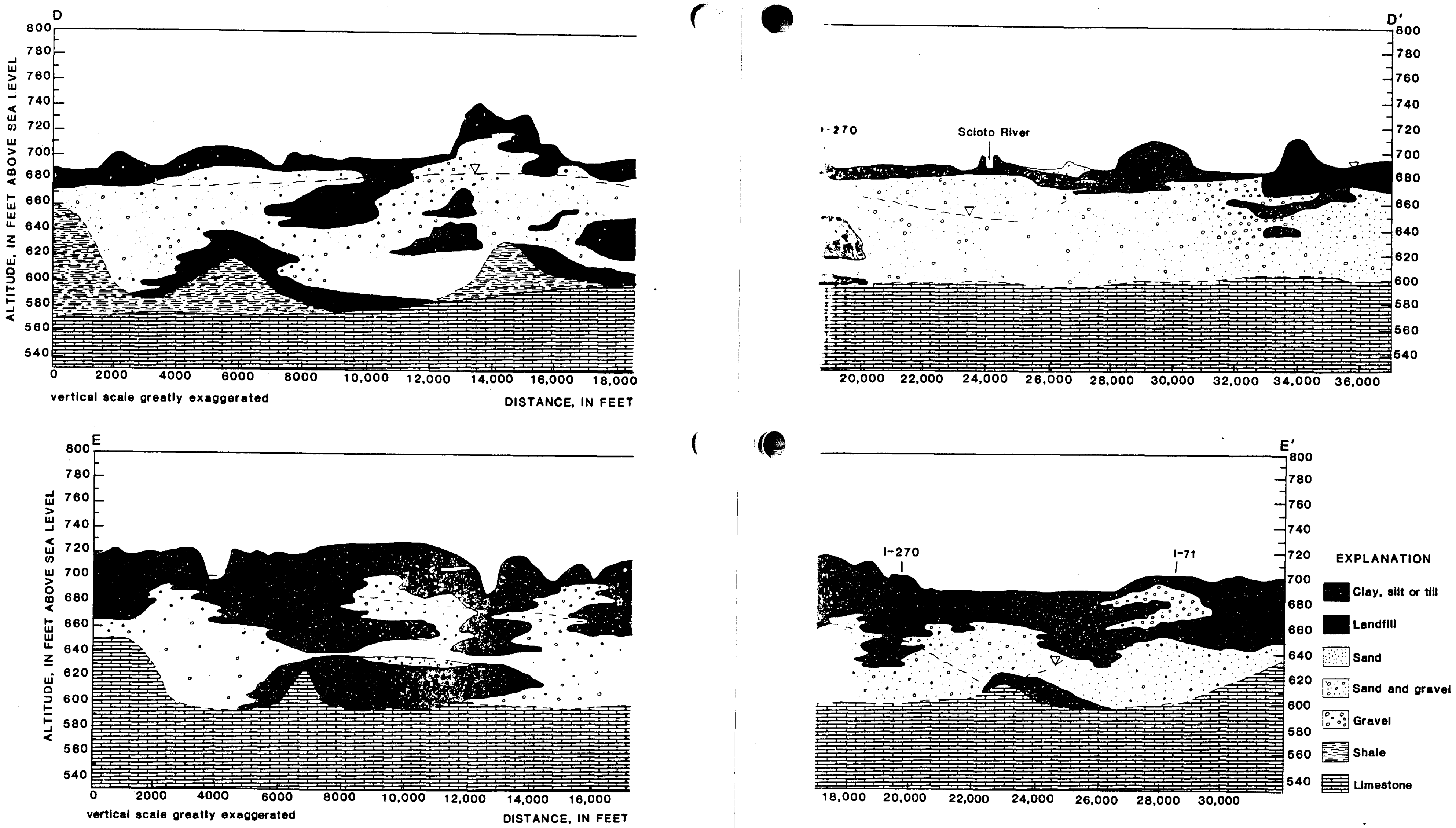


Figure 6. Geologic sections D-D′ and E-E′ (Sedam et al., 1989).

and Goldthwait, 1958) cover the Scioto River floodplain in a layer 10 to 15 feet thick (Weiss and Razem, 1980). Below the alluvium are extensive outwash deposits that are greater than 115 feet thick in the study area (Stilson and Associates, 1976). These deposits are heterogeneous in mineralogic composition and hydraulic characteristics. Grain sizes range from clay-size particles to boulders up to five feet in diameter (Schimdt and Goldthwait, 1958). Drillers' logs indicate that within the outwash, sands and gravels predominate with some interlayered clay lenses that increase in frequency to the east near Big Walnut Creek (Eberts, 1987). Sands and gravels are common in the immediate area of Big Walnut Creek. Between the Scioto River and Big Walnut Creek, surficial deposits consisting of kames and eskers act as recharge areas to the underlying glacial-drift aquifer (Schimdt and Goldthwait, 1958).

Hydraulic conductivity generally ranges from 400 ft/day in the outwash composed of well-sorted sands and gravels, to 35 ft/day in areas of poorly-sorted ground moraine (Eberts, 1987). Estimated values of porosity range from 5 to 20 percent (fig 7) for the geologic materials in the study area (Bair et al., 1990).

The glacial deposits are underlain by the Olentangy Shale, the Delaware Limestone, and the Columbus Limestone in the area of Big Walnut Creek. The strata dip gently to the

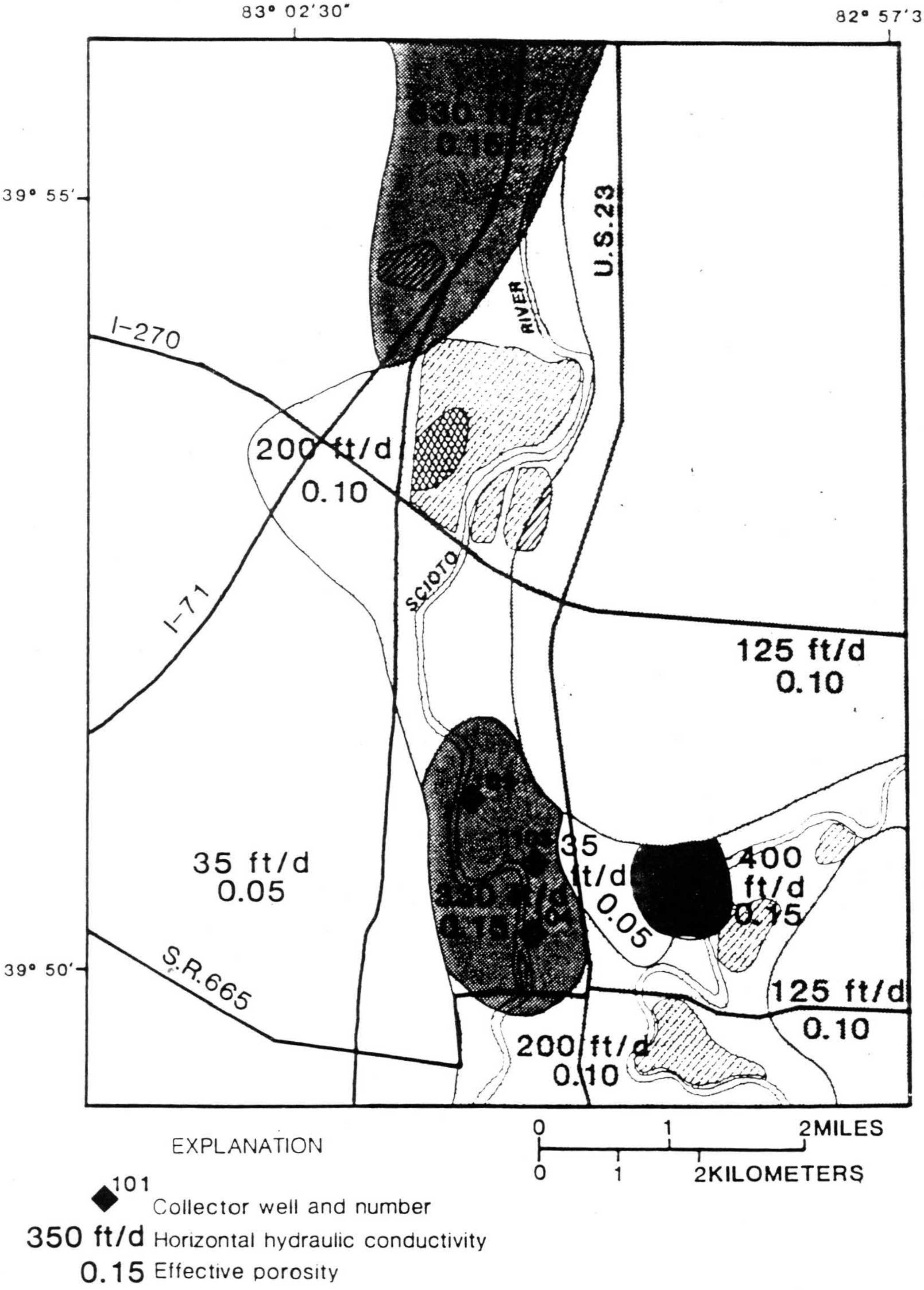


Figure 7. Distribution of hydraulic conductivity and effective porosity in the study area and vicinity (Bair et al., 1990).

east (see Fig. 2 and Table 1). The shale, however, is absent in the area of the Scioto River where it has been eroded (Fig. 2). Sedam et al (1989) refer to the carbonate strata as a separate aquifer with limited hydraulic connection to the overlying glacial materials. Because the hydraulic conductivity of the carbonate rocks ranges only from 5 to 20 ft/day (Eberts, 1987), the effects of pumping at the South Well Field are believed to be negligible on the local and regional flow regimes in the carbonate rocks.

Average precipitation in the study area is 36.6 in/year (Sedam et al., 1989). Recharge to the municipal wells consists of regional ground-water flow, infiltration induced from streams, and a minor amount of vertical leakage from bedrock (Sedam et al., 1989).

LAND USE

Approximately 1.5 miles north of the study area are several quarries and a number of closed landfills. A rendering plant and a sewage-treatment plant also share this area (Fig. 8) which is adjacent to many residential, commercial, and manufacturing establishments. Current pumping at two quarries creates a local ground-water divide between the quarries and the South Well Field. Agriculture

Table 1. -- Stratigraphy of south-central Franklin County, Ohio (After Stowe, 1979).

System	Series	Group or Formation	Maximum Thickness, ft.	Lithology
Quaternary	Holocene		20	Silt, clay and sand deposited on the flood plains of major streams, alluvium
	Pleistocene		200	Glacial outwash deposited as surficial valley trains during Wisconsinan time, sand and gravel
			250	Lenses of sand and gravel up to 50 feet thick beneath thick tills, deposited in buried valleys
			250	Till, heterogenous mixture of silt, clay and sand and gravel, scattered with lenses of sand and gravel
Devonian	Upper	Ohio	450	Blue-black to dark-brown carbonaceous shale, grading from massive to thinly bedded
		Olentangy	30	Soft, argillaceous, blue shale with some argillaceous limestone
	Middle	Delaware	35	Thinly bedded to massive blue-gray limestone and calcareous brown shales
		Columbus	105	Brown dolomitic limestone and gray calcareous crystalline limestone
Silurian	Upper	Bass Islands	200	Fine-grained compact limestones, dolomites

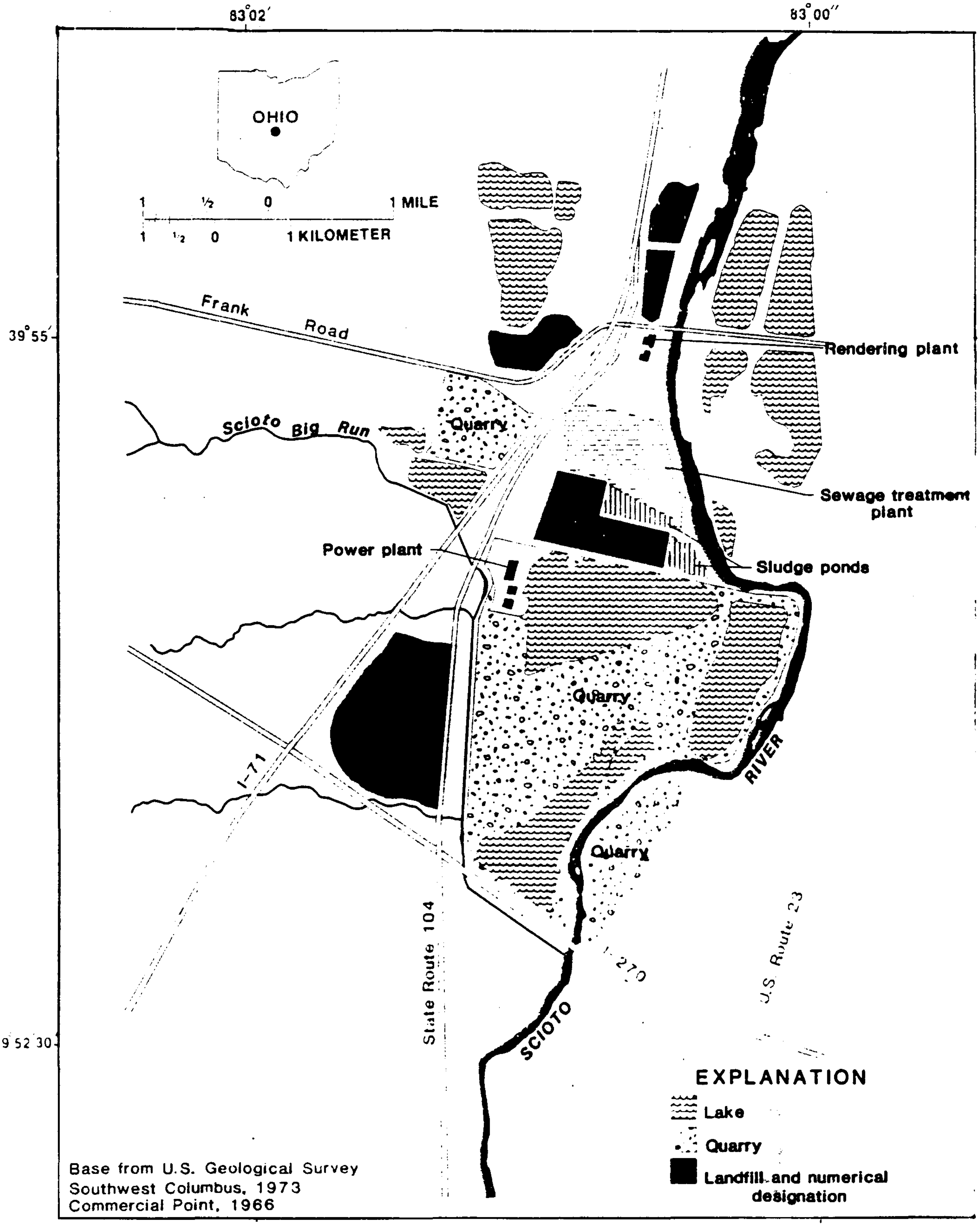


Figure 8. Locations of landfills, industrial sites, quarries, and the sewage treatment plant (de Roche, 1985).

is the dominant land use in the vicinity of the collector wells. The quarries near CW-115 on Big Walnut Creek are no longer operational and are present as ponds.

WELL FIELD INFORMATION

The four collector wells in the study area are completed in the glacial-drift aquifer and have similar design characteristics. The caissons are 30 feet in diameter and have lateral well screens extending outward in a radial pattern (fig. 9) in two or three tiers. Some laterals extend beneath the riverbeds and induce infiltration from the waterways, thereby augmenting the yield of the glacial-drift aquifer. The following specifications are given in Sedam et al (1989), although some parameters are modified (personal communication, Steve Hainan, 1991).

Collector well 101 (fig. 1) is about 35 feet from the east bank of the Scioto River and 2.2 miles downstream from Route I-270. Ten laterals radiate outward in two tiers 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 the four laterals directed toward the river, three extend to positions below the west bank of the river; only one penetrates a significant distance because the other two were

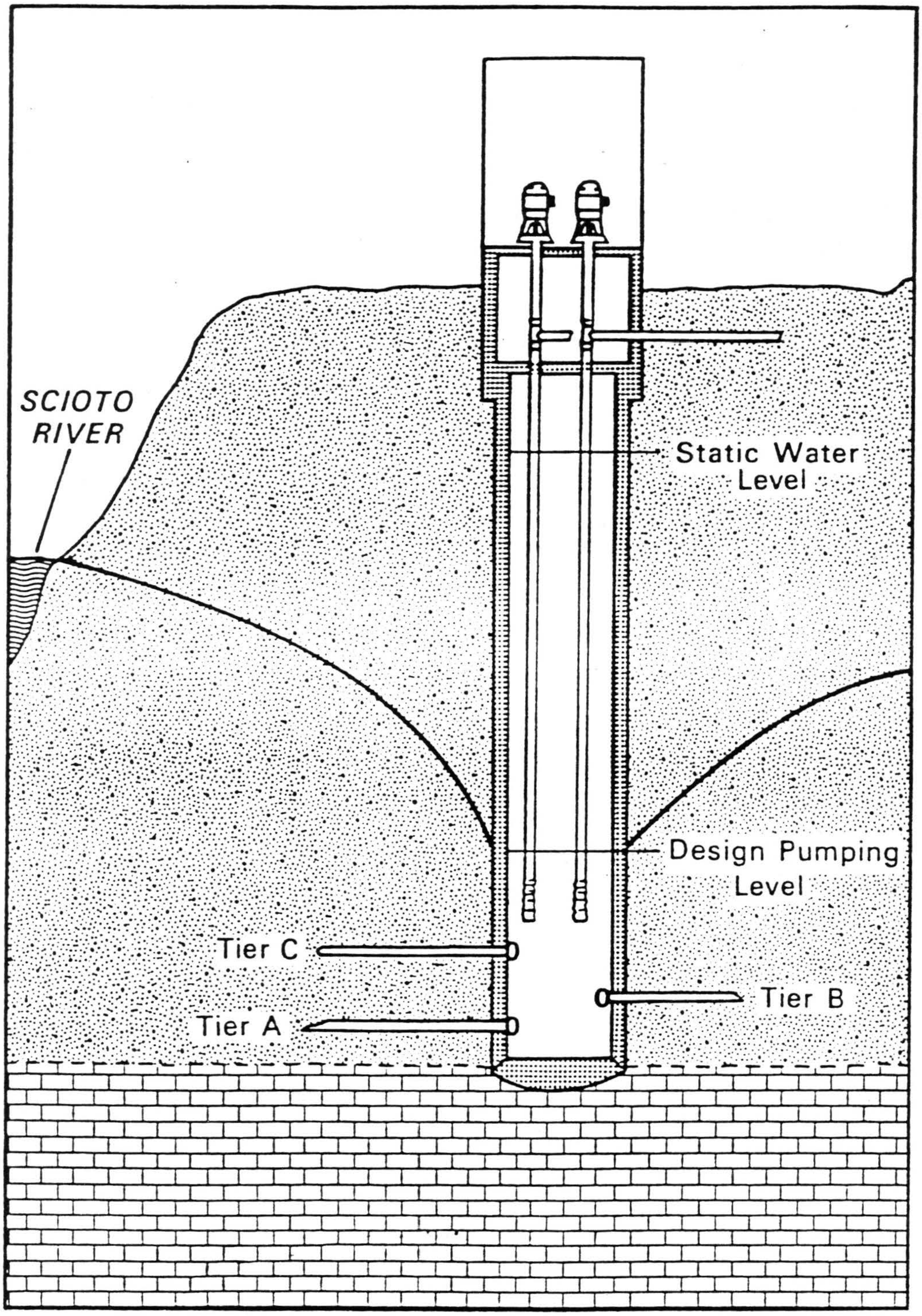


Figure 9. An example of a radial collector well (Bair, written communication, 1989).

impeded by obstructions during construction, presumably by large boulders.

Collector well 103 is located about 75 feet from the east bank of the Scioto River, 3.4 miles downstream from Route I-270. At depths ranging from 96 to 106 feet below ground level, a three-tiered system of fourteen laterals radiate from the caisson. The average length of the laterals is 77 feet with only one lateral reaching a position below the river.

Located about 100 feet from the east bank of the Scioto River, collector well 104 is 3.9 miles downstream from I-270. A two-tiered system of fifteen laterals 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. The average length is 91 feet with three laterals extending to positions below the river.

Collector well 115 is located three miles south of Route I-270, about 150 feet from the west bank of Big Walnut Creek. Averaging 152 feet in length and arranged in a two-tiered system, seven laterals are located about 65 feet below ground level or about 46 feet below the bottom of the stream. Only one lateral reaches a position below the stream.

The well field originally was designed for a maximum combined yield of 45.6 Mgal/day (million gallons per day).

The well field serves the southern part of the City of Columbus and its suburbs and accounts for about 25 percent of the City's total water supply. Current estimates, however, indicate that the maximum yield of the well field is about 30 Mgal/day.

PREVIOUS STUDIES, DATA COLLECTION, AND ANALYSIS

Previous Studies

In the past two decades, several studies have been conducted in the South Well Field. The need for these studies has been driven not only by the increasing number of federal, state, and local regulations, but also by the increasing level of reliance on the South Well Field to meet the water demand of the City of Columbus. There has been an increase in demand of 10 percent in past two years alone (Bair et al., 1990). The studies show a shift in emphasis from ground-water resource development toward ground-water protection. Current research efforts are directed at developing models which are able to predict with reasonable accuracy the response of the aquifer under steady-state stressed conditions with an emphasis on understanding flow paths and travel times of hypothetical contaminant particles. The following describes the two studies which are most relevant to this study.

Eberts (1987) constructed a three-dimensional, steady-state flow model using the McDonald-Harbaugh finite-difference program (McDonald and Harbaugh, 1988), referred to hereafter as MODFLOW. The model was constructed in response to the concern of contamination from the nearby uncontrolled landfills with special consideration given to the effects of cessation of dewatering operations at the two nearby quarries and the effects of chemical spills in the vicinity of the well field. The following is an overview of MODFLOW and its application by Eberts (1987) to the South Well Field.

MODFLOW consists of several highly independent subroutines which can be customized for a given hydrogeologic setting (McDonald and Harbaugh, 1988). Rivers, discharge points, wells, evapotranspiration, and other types of boundaries can be simulated in discrete "modules" which are grouped into "packages." This allows for separate layers within a flow system to be characterized as confined, unconfined, leaky-confined, or a combination thereof. Flow behavior is simulated using finite-difference algorithms in a block-centered grid which allows the incorporation of geologic and hydraulic parameters that vary spatially.

Eberts (1987) divided her model into two layers. The upper layer described flow in the unconfined glacial aquifer and the lower layer described flow in the confined carbonate-bedrock aquifer. Each layer is represented by a 32 by 42 block-centered grid with a uniform 1000-foot grid spacing. Parameters used in MODFLOW include hydraulic conductivity of the glacial-drift aquifer, transmissivity of the bedrock aquifer, vertical conductivity between the aquifers, pumpage, recharge, and hydraulic conductivity of the riverbeds. Parameter values were obtained from a variety of sources. Some values were extrapolated from known values in the vicinity of the study area.

The numerical flow model was calibrated using historic water levels which pre-date pumpage at the quarries at the well fields, and water levels that were measured in March 1986 during average pumping rates at the quarries and at the South Well Field (Sedam et al., 1989). The historic water levels were measured and recorded in drillers' logs from wells constructed prior to 1967 (i.e. prior to operation of the quarries and the South Well Field). The water levels do not correspond to a specific time but are collectively used to construct a generalized, pre-pumping potentiometric surface.

Simulations of the numerical flow system under pumping and non-pumping conditions achieved reasonable values for March 1986 and historic conditions. Comparisons of measured heads against simulated heads generally agree within +/- 5 ft. In some cases, agreement is within +/- 10 ft (Eberts and Bair, 1990).

Eberts (1987) drew the following conclusions from the model: the cessation of dewatering at the quarries north of the South Well Field would cause ground water levels to rise and saturate some of the adjacent landfills. Leachate from the landfills is unlikely to migrate to the capture zones of the well field and will go either to a quarry dewatering system or the Scioto River. At the time of the study, quarry-dewatering accounted for 60 percent of the ground water discharged from the study area and induced stream infiltration accounted for about 13 percent of the yield of the collector wells.

Using the simulated potentiometric surface for the pumping rates present in March 1986, the numerical model indicates that chemical spills on major highways or contaminants generated within the study area will eventually migrate toward the Scioto River, one of the quarry dewatering systems, or the South Well Field. Contamination of the carbonate aquifer is unlikely due to upward hydraulic gradients and the presence of shales overlying the carbonates in portions of the study area (Eberts, 1987).

In response to the uncertainties concerning the fate of migrating contaminants, Bair et al (1990) did a study based on Eberts' flow model (Eberts, 1987) using a particle-tracking program to delineate capture zones of the South Well Field and to determine the trajectories of particles within the study area from hypothetical spill sites. Using the particle-tracking program, STLINE (Geotrans, 1987), velocity vectors in the cells in each model layer were resolved on the basis of computed inter-cell flow rates. The velocity vectors are converted into average linear flow velocities by dividing the effective porosity value assigned to the cell into the magnitude of the vector (GeoTrans, 1987).

Results show that flow paths and advective traveltimes of particles from hypothetical spills along some segments of highways are highly dependent on the pumping rates of the South Well Field. The municipal wells capture flow from some highway segments in the study area, whereas the Scioto River, Big Walnut Creek, and the quarry-dewatering systems capture flow from other highway segments. The 2000-day capture zone of the well field is about 30 percent larger and includes about 4.5 more miles of highway under the projected maximum rates versus the March 1986 rates (Bair et al., 1990).

Data Collection and Analysis

The historic potentiometric surface prior to major pumping at the quarries or the well field was constructed from data compiled by Eberts (1987; see above section, Previous Studies). Figure 10 shows the locations used as well control (the lower 26 locations apply to this study) for pre-1967 and March 1986 pumping conditions. Water levels are not adjusted for seasonal variations or changes in discharge rates at the well field or the quarries and do not reflect changes in river stage. Therefore, figure 11 is an approximate representation of the potentiometric surface prior to major pumping and is sufficient for the purposes of this study for years of average precipitation. Water levels were taken from drillers' logs on file at the Ohio Department of Natural Resources, readings taken by the Water Department of the City of Columbus, data previously compiled by different consultants, and data on file from previous work done by the USGS.

Original mylar transparencies (first assembled by S. Eberts for her study) at the USGS office in Columbus were used to transfer the equipotential lines, well locations, and water levels onto 7.5 minute topographic quadrangle maps of the region. Using the computer program DESIGNCAD and a digitizer, data from the topographic maps were transferred into file formats compatible with SURFER, a contouring program. All subsequent model simulations use these files to portray geographic features and equipotential lines.

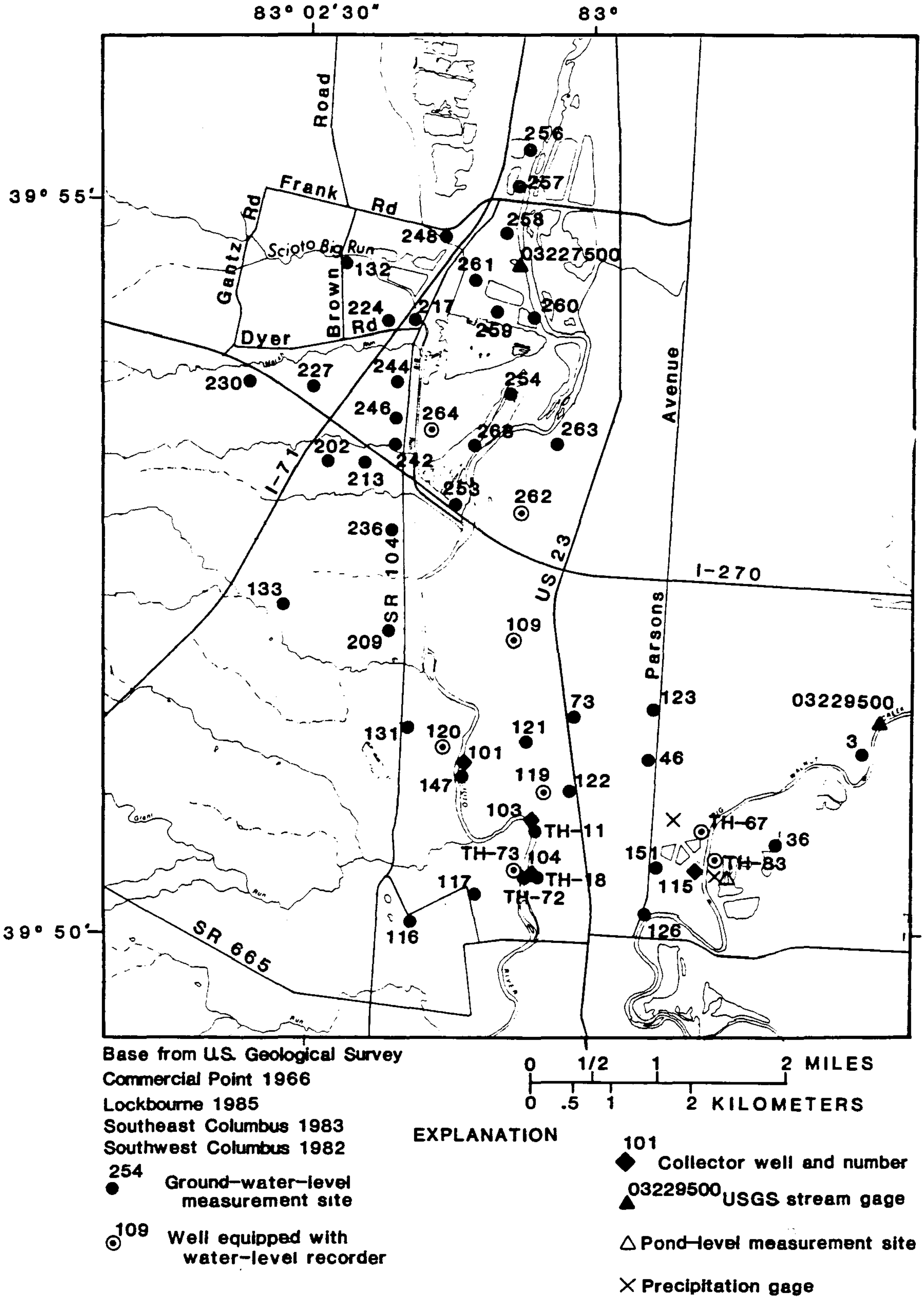


Figure 10. Locations of water level measurement sites; sites north of I-270 do not apply (Sedam, et al., 1989).

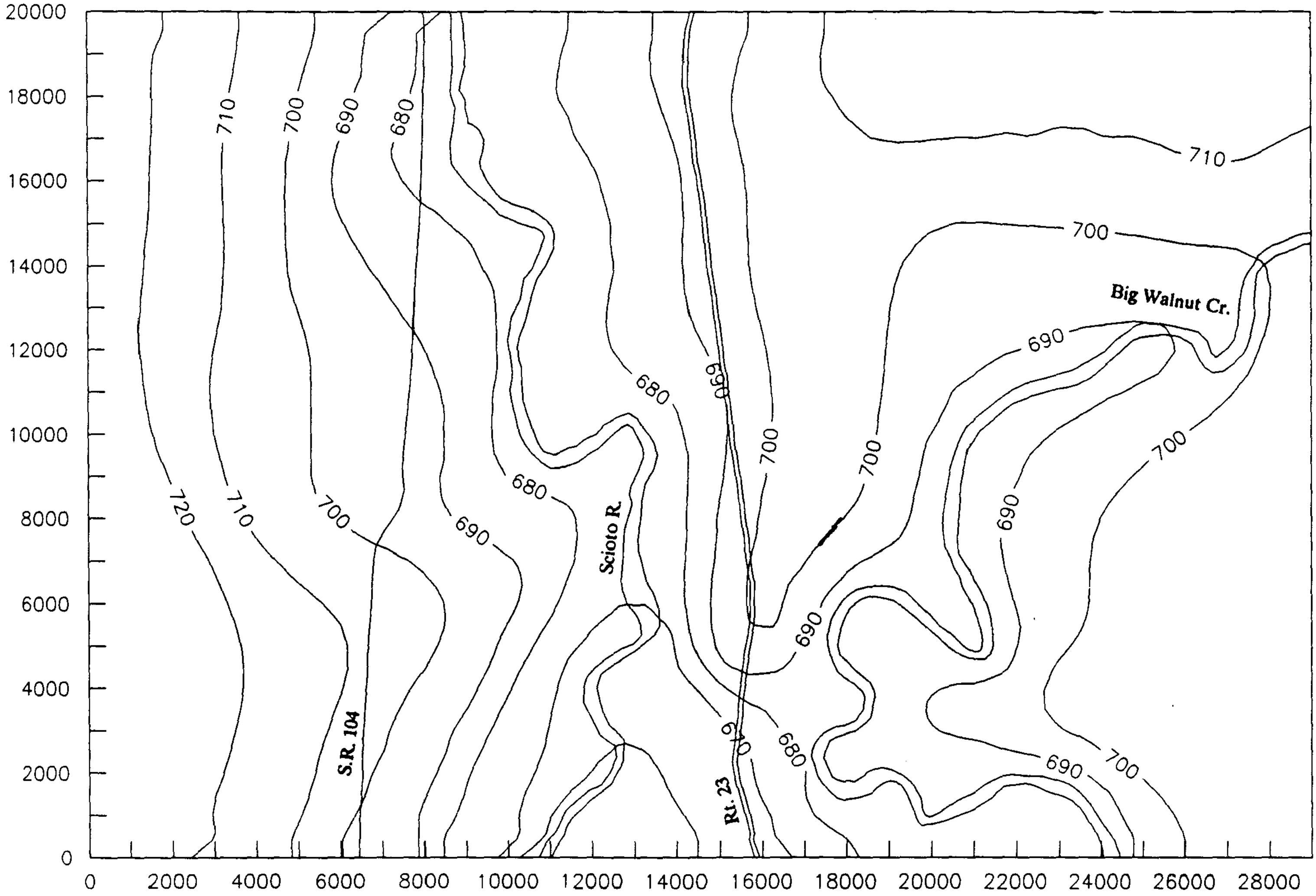


Figure 11. Generalized historical potentiometric surface prior to pumping at the quarries or the South Well Field. (scales in feet)

—Equipotential lines Contour interval: 10 ft

Grid Construction Summary

Using DESIGNCAD, a rectangular grid with dimensions of 29,000 by 20,000 feet was constructed. The various pumping and monitoring wells were assigned coordinates within a Cartesian coordinate system defined by the grid. All other programs required this rectangular area to be gridded. To maximize use of CAPZONE, a 41 row by 49 column grid was adopted using a 500-foot spacing in the north-south direction and a 604.17-foot spacing in the east-west direction. Calculations of drawdowns and heads were performed at the intersections of this grid.

Description of Computer Programs

DESIGNCAD was used to digitize equipotential lines and the locations of wells from data compiled by the USGS on topographic maps. Roads and waterways also were digitized and formatted into files compatible with SURFER.

SURFER is a contouring program consisting of subroutines, among others, known as UTIL, PLOT, GRID and TOPO. These subroutines were used to construct a general map of the study area, contour maps of drawdown and head, and plot locations of well control. Each subroutine contains several variables that are used to set user-defined options for contouring and map construction. GRID transforms the files (x-y-z format) from DESIGNCAD and

CAPZONE into files to be contoured. TOPO further transforms these gridded files into files which PLOT accesses, modifies, and sends to an output device. UTIL computed the amount of error between measured well levels and modelled levels.

CAPZONE uses transient analytical well-hydraulics equations developed by Theis (1935) for unconfined and fully confined aquifers and Hantush-Jacob (Hantush and Jacob, 1954) for leaky-confined aquifers which have the following general assumptions: the aquifer is infinite, isotropic, homogeneous, horizontal flow, and underlain by an impermeable layer; the pumping well is fully penetrating, has an infinitely small diameter, and discharge is constant (see appendix A). Drawdowns are computed at the intersections of a user-defined rectangular grid and files of drawdown and/or head are generated that can be contoured by SURFER and used by GWPATH. CAPZONE has the capability of using image-well theory to incorporate simple aquifer boundary conditions such as rivers, lakes, or adjacent impermeable formations. CAPZONE also can subtract computed drawdowns from compatible files of background head data, thus generating new files incorporating regional flow gradients that can be downloaded in formats compatible with GWPATH.

GWPATH (Shafer, 1987) calculates two-dimensional fluid pathlines and traveltimes in saturated flow domains. Input files of hydraulic head are coupled with user-defined options which set grid parameters, locations of hydraulic sources and sinks, and values of hydraulic parameters. Hydraulic parameters include hydraulic conductivity, effective porosity, and hydraulic head distribution. Hydraulic conductivity can differ between the X and Y-directions. However, variations in vertical hydraulic conductivity cannot be accounted for in GWPATH. Thus, it is assumed all particles move horizontally with identical trajectories and velocities. A series of algorithms compute inter-cell velocities which specify the pathlines of hypothetical particles. A specified number of particles distributed around a hydraulic sink can be tracked upgradient (reverse pathlines) or a similar number of particles downgradient (forward pathlines) can be tracked for a given time period. The loci of the pathline endpoints delimits the capture zone of the sink (well) within the specified time.

Methodology

The following describes the construction of the four sets of figures which correspond to two different pumping rates at the South Well Field. The first set of figures corresponds to March 1986 pumping rates and the second set of figures corresponds to the presently larger pumping rates for which no data are available at the time of this study. Each set is divided into two parts which demonstrate the difference obtained by accounting for induced stream infiltration using modified image-well theory (Fetter, 1988). Table 2 summarizes the parameters used in CAPZONE and GWPATH for each set of computed drawdowns. Table 3 summarizes discharge rates of the collector wells used in this study.

Discharging wells were assigned node coordinates closest to their actual location. Translations not exceeding 250 feet. However, initial simulations computed drawdowns exceeding the saturated thickness of the aquifer. (This is due, in part, to the extremely large pumping rates of the collector wells.) Through trial-and-error, it was found that four "ghost wells" uniformly spaced at 100 foot intervals around the assigned nodes representing pumping well centers, with each "ghost well" discharging at 25 percent of the actual rate of the actual collector well, produced drawdowns comparable to levels measured in the caissons at similar pumping rates.

The location and injection rates of image wells representing leakage from the Scioto River also required adjustment. Previous studies show that approximately 20

Table 2. Hydraulic parameters used in CAPZONE and GWPATH

Parameter	Value used in CAPZONE/GWPATH
Saturated Thickness	75 feet
Porosity	15 percent
Hydraulic Conductivity	330 feet/day
Transmissivity	185,000 sq feet/day
Time Period	182 days

Table 3. Summary of discharge rates from the South Well Field

Well	Discharge rate (cu.ft./day)	
	March 1986	March 1991
101	2,101,880	7,560,000
103	3,500,640	5,890,000
104	1,892,000	4,390,000
115	748,000	4,010,000
Totals	8,242,520	21,850,000

percent of well discharge is supplied by the Scioto River (de Roche and Razem, 1984; Eberts and Bair, 1990). This value also was assumed for Big Walnut Creek. The close proximity of the caissons to the river banks and the lateral screen penetration beneath riverbeds required the injection image wells to be of equal proximity on the opposite side of the rivers with an injection rate equal to 20 percent of the discharge rate of the corresponding collector well. Single injection wells, imaged on the opposite side of the Scioto River, could not be used because the excessive injection rates produced heads that exceeded the land elevation in the vicinity of the image wells. Two "ghost" image wells, each assigned injection rates 10 percent of the discharge rate and translated 100 feet to the north and south of the center of the actual image well, alleviated the problem. A single image well for CW-115 sufficed due to its lower discharge rate.

COMPARISON OF MODELS

Comparison of Flow Models

The difference in accuracy between the numerical flow model constructed by Eberts (1987) and the flow model constructed using CAPZONE can be measured by comparing the amount of error in the two models against measured heads.

Figure 12 shows the drawdowns computed by CAPZONE and contoured by SURFER using best-estimate geologic and hydraulic parameters and normal (March 1986) pumping rates. Figure 13 shows the simulated head distribution after superposition of the regional head distribution (Fig. 11). Figure 14 shows the locations and water levels of wells measured during the pumpage conditions of March 1986. Using the SURFER subroutine, UTIL, residual differences were computed between simulated heads as calculated by CAPZONE and actual water levels measured during March 1986 (Fig. 15). The mean of the residuals is 5.21 feet with a standard deviation of 5.55 feet. The relatively poor agreement between measured and simulated heads in the immediate vicinity of the wells is due, in part, to a steep cone of depression. Factors affecting the shape of the cone of depression are large discharge rates, aquifer heterogeneity, and the number and extended length of the laterals. The simulated cone of depression is affected by the above factors as well as by the grid density. Poor agreement away from the wells is due to large variations in values of hydraulic parameters versus the simplified assumptions in the model (see Fig. 7).

Figures 16 and 17 the show the results of drawdown and head distribution when image wells are used to account for induced infiltration from the rivers. As expected,

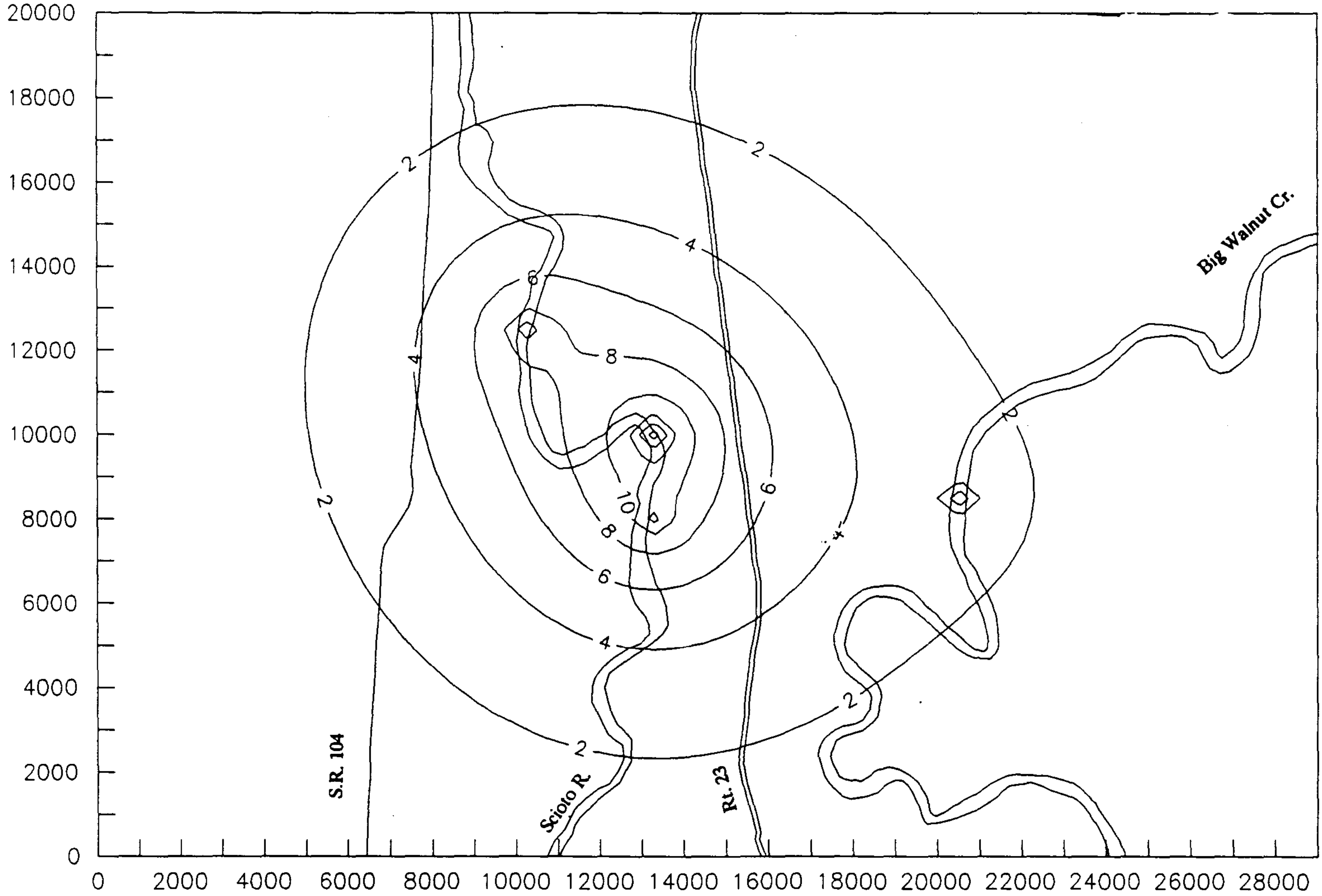


Figure 12. Predicted drawdowns around the collector wells of the South Well Field. (scales in feet)

—Equipotential lines Contour interval: 2 ft

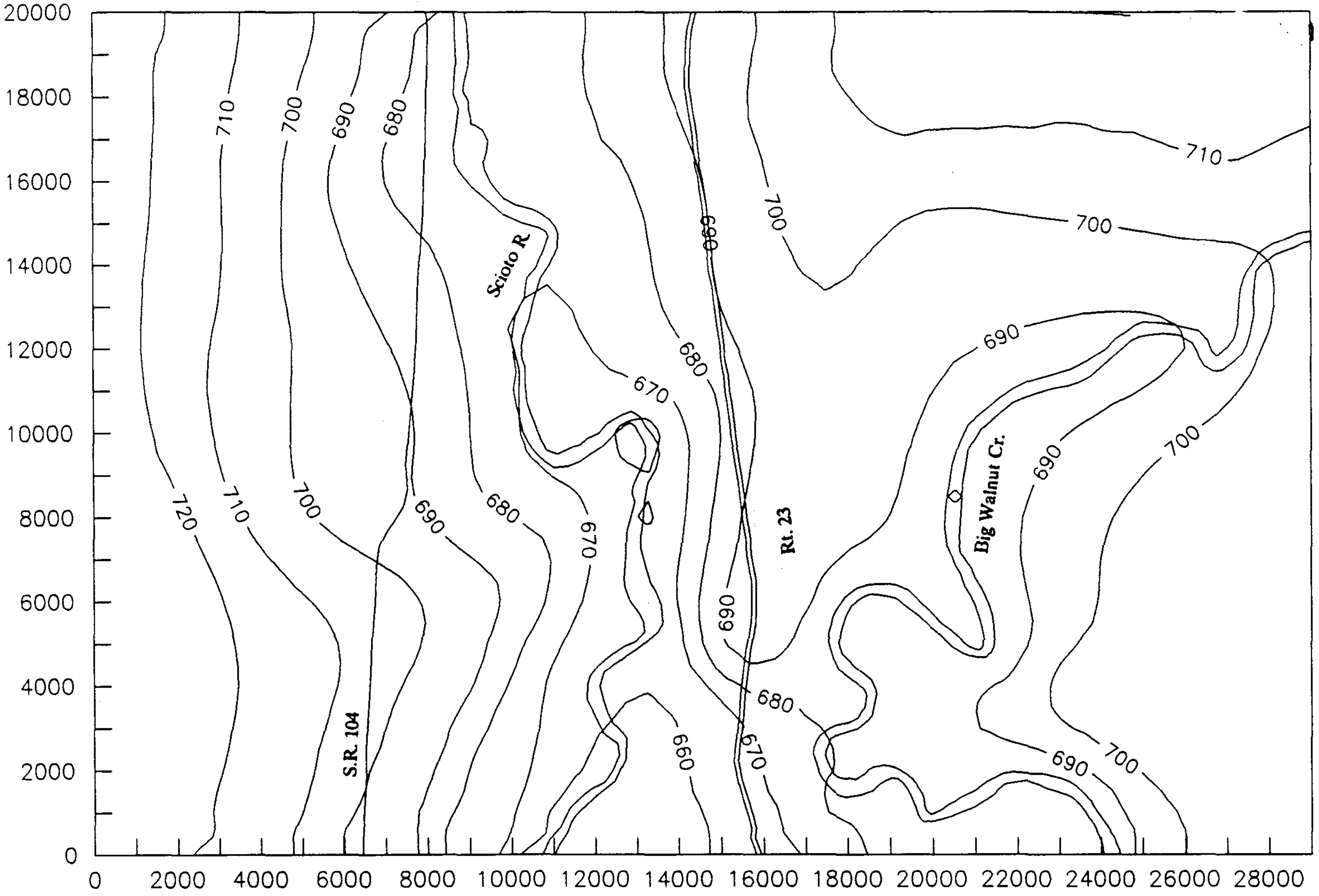


Figure 13. Predicted potentiometric surface after subtraction of drawdowns as calculated by CAPZONE. (scales in feet)

——Equipotential lines

Contour interval: 10 ft

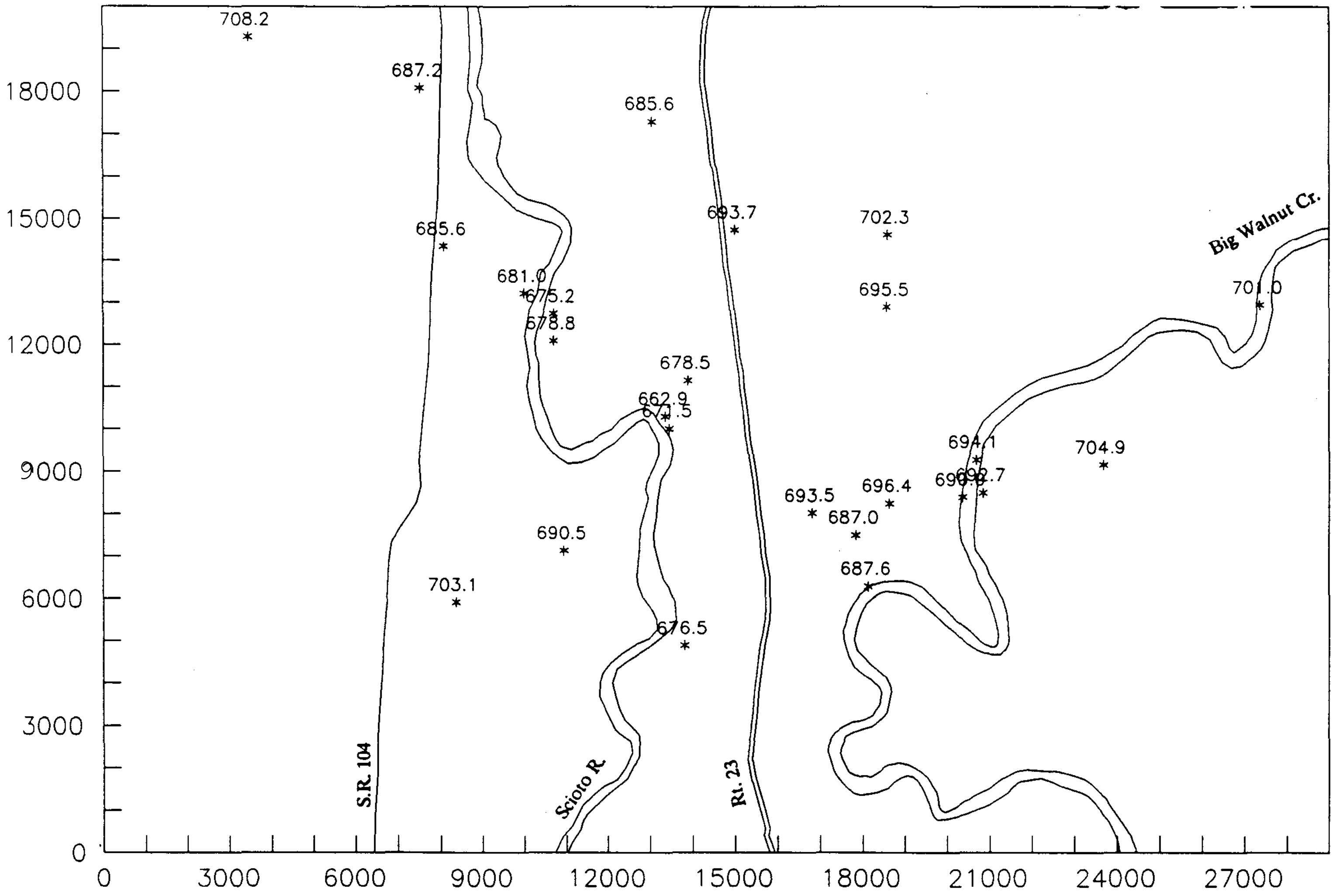


Figure 14. Water levels and their locations during stressed conditions. (scales in feet)

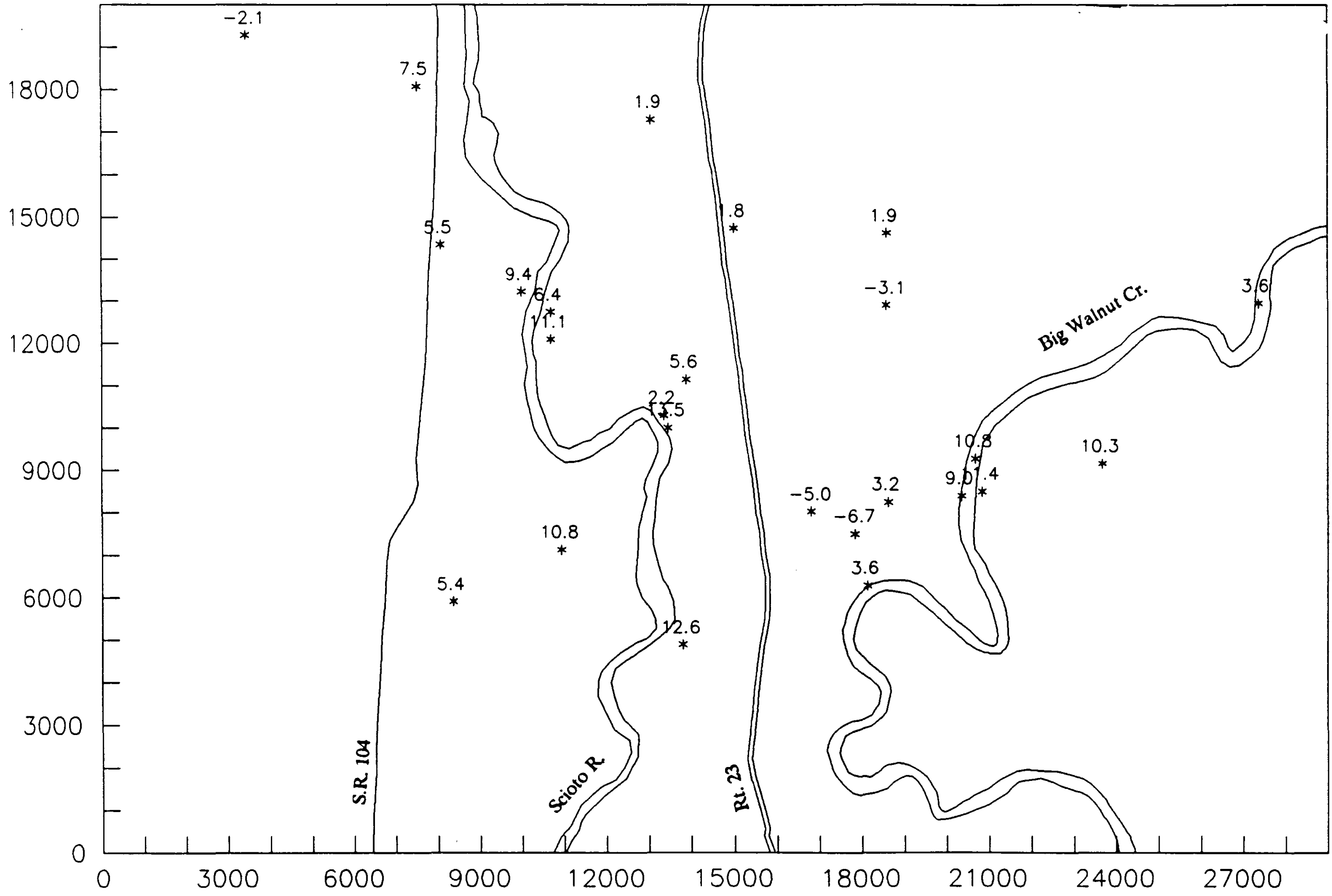


Figure 15. Calculated difference between measured and simulated heads. (scales in feet.)

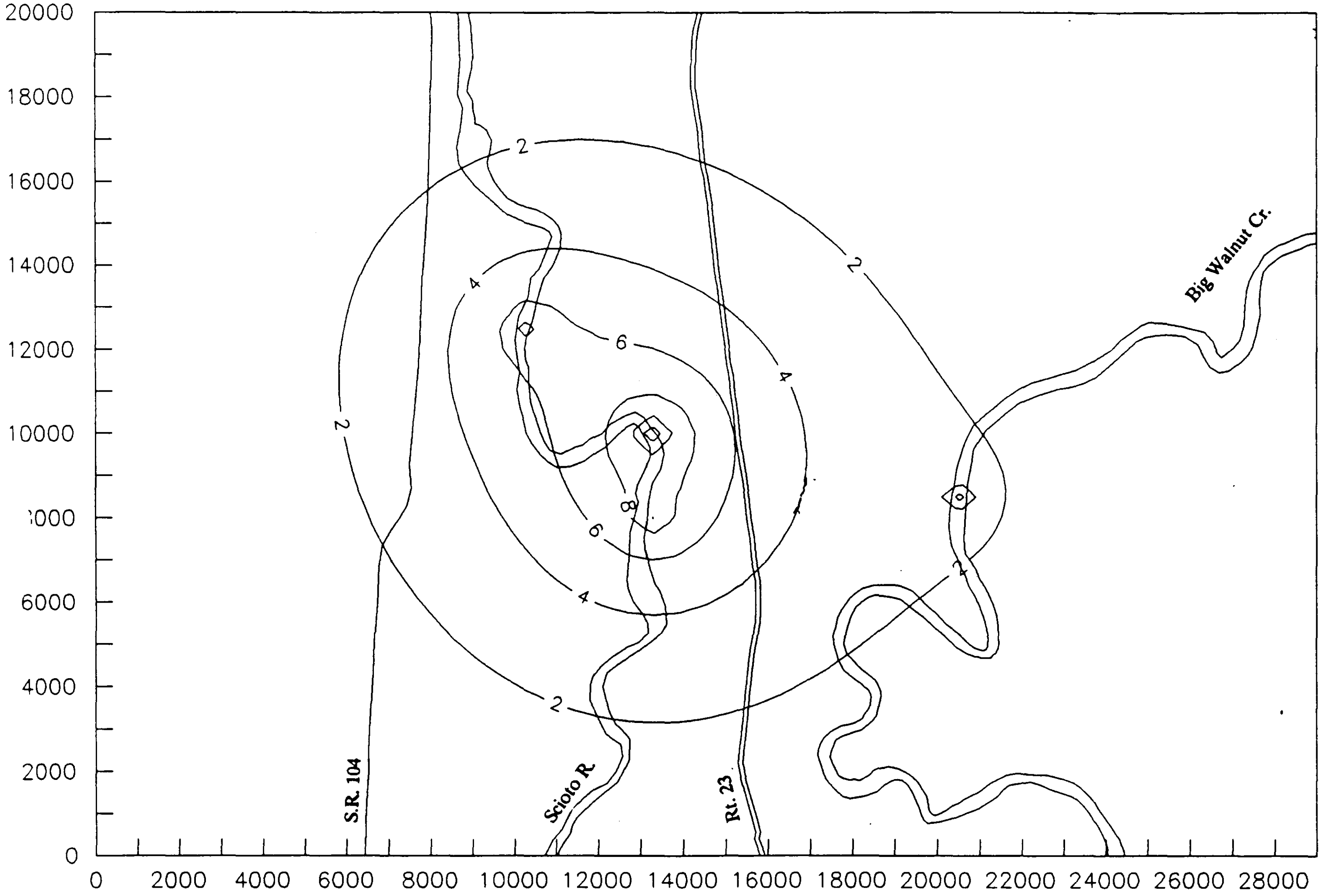


Figure 16 Predicted drawdowns around the collector wells of the South Well Field after the incorporation of image wells. (scales in feet)

——Equipotential lines Contour interval: 2 ft

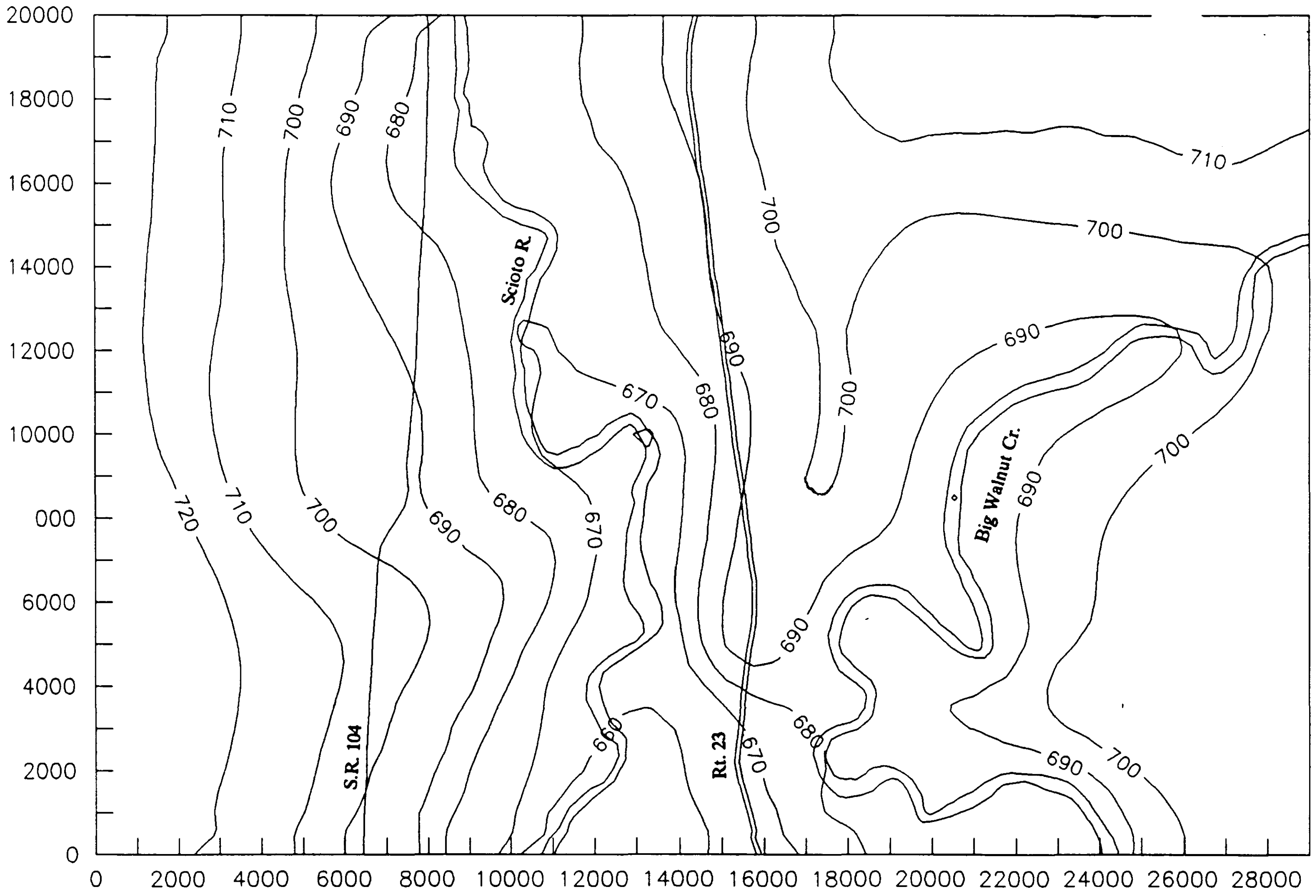


Figure 17. Predicted potentiometric surface after subtraction of image-modified drawdowns as computed by CAPZONE. (scales in feet)

——Equipotential lines

Contour interval: 10 ft

decreases in drawdowns and gradients appear but figure 18 shows only slightly better agreement between simulated and measured heads (March 1986). The mean of the residuals is 4.26 feet with a standard deviation of 5.36 feet.

In the numerical model, simulated heads generally agree with measured heads within +/- 5 feet with a few locations within +/- 10 feet for March 1986 pumping rates (Eberts et al., 1990). Thus, comparison of the amount of error between measured and simulated heads indicates a level of comparable accuracy for predicting the head distributions for the pumping conditions of March 1986.

Comparison of Capture Zones

Reverse-tracked pathlines emanating from each collector well are shown in figures 19 and 20 representing March 1986 pumping rates. The capture zones in figure 19 are slightly larger than the capture zones in figure 20 which incorporates river leakage using image wells. Twenty-four half-year pathlines emanate from each collector well, with each pathline following the steepest hydraulic gradient based on the simulated head distribution computed by CAPZONE. The pathline distribution is a generalized representation that does not account for seasonal variations in hydraulic gradients, spatial variation in hydraulic conductivity, or changes in pumping rates. The loci of the

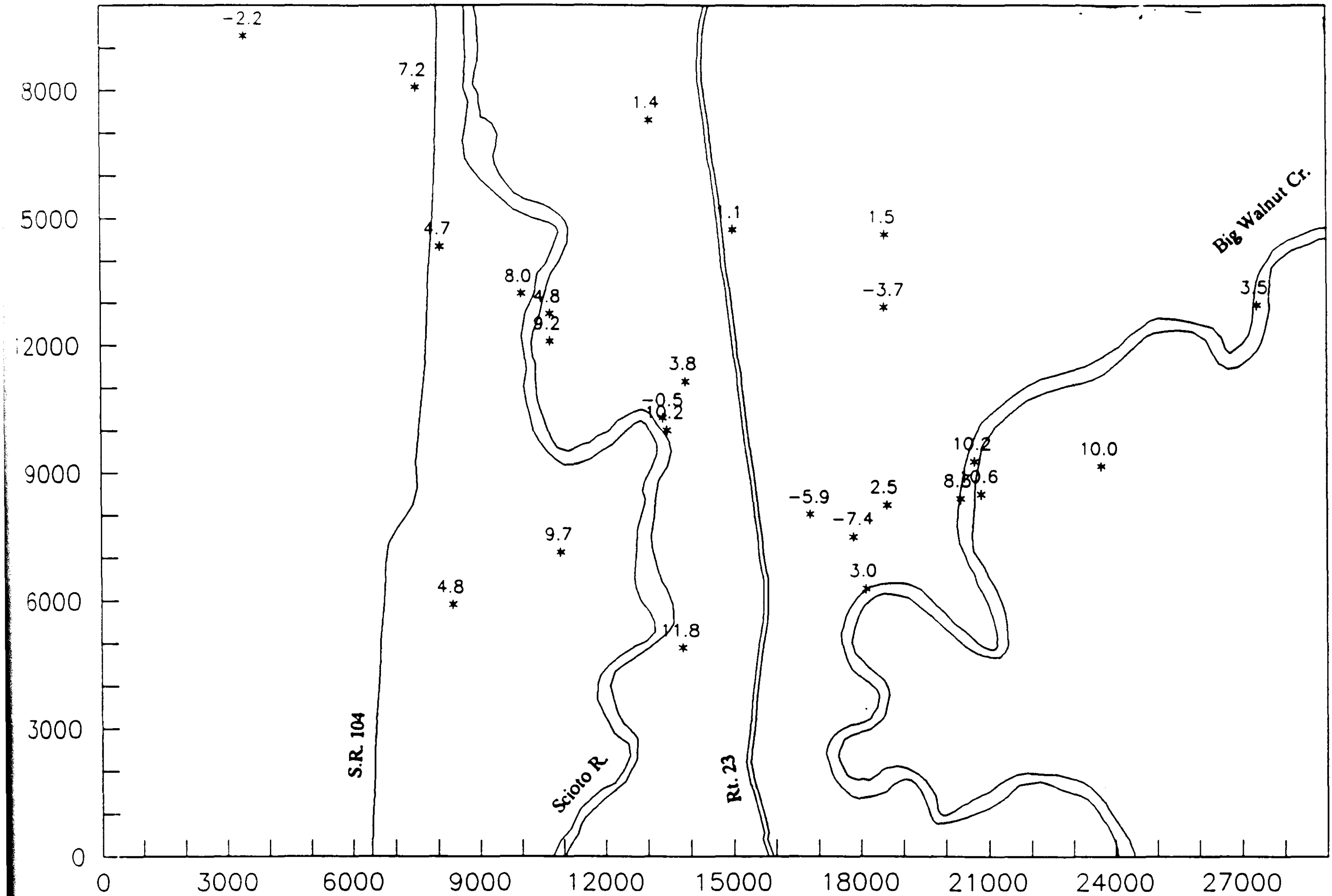


Figure 18. Calculated difference between measured and simulated heads with the incorporation of image wells. (scales in feet)

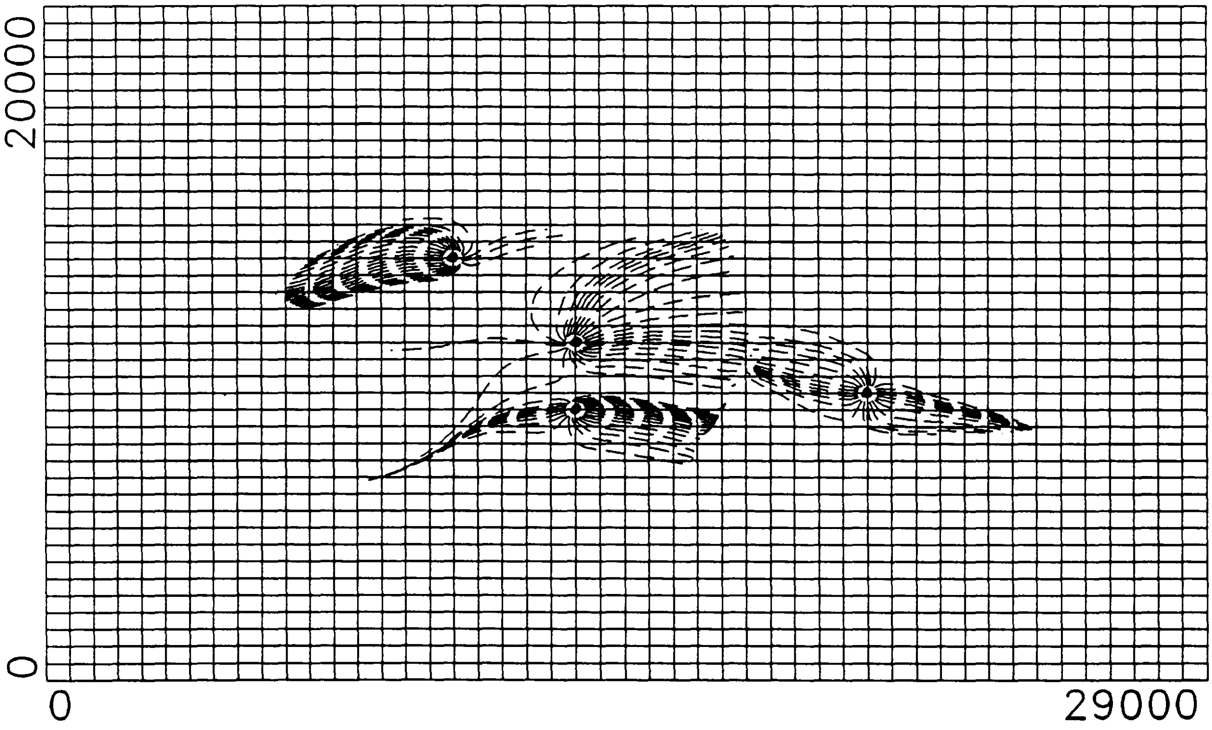


Figure 19. Half-year traveltime capture zones of the South Well Field based on best-estimate hydraulic parameter values. (scales in feet)

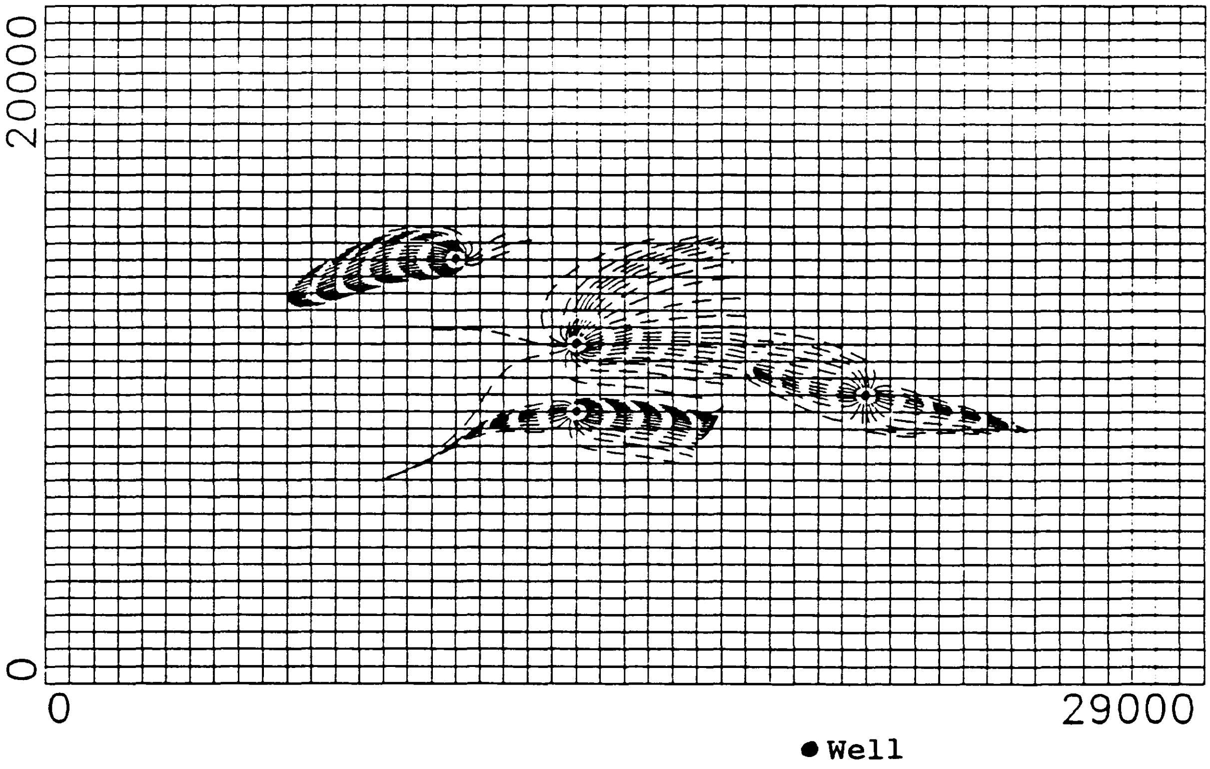
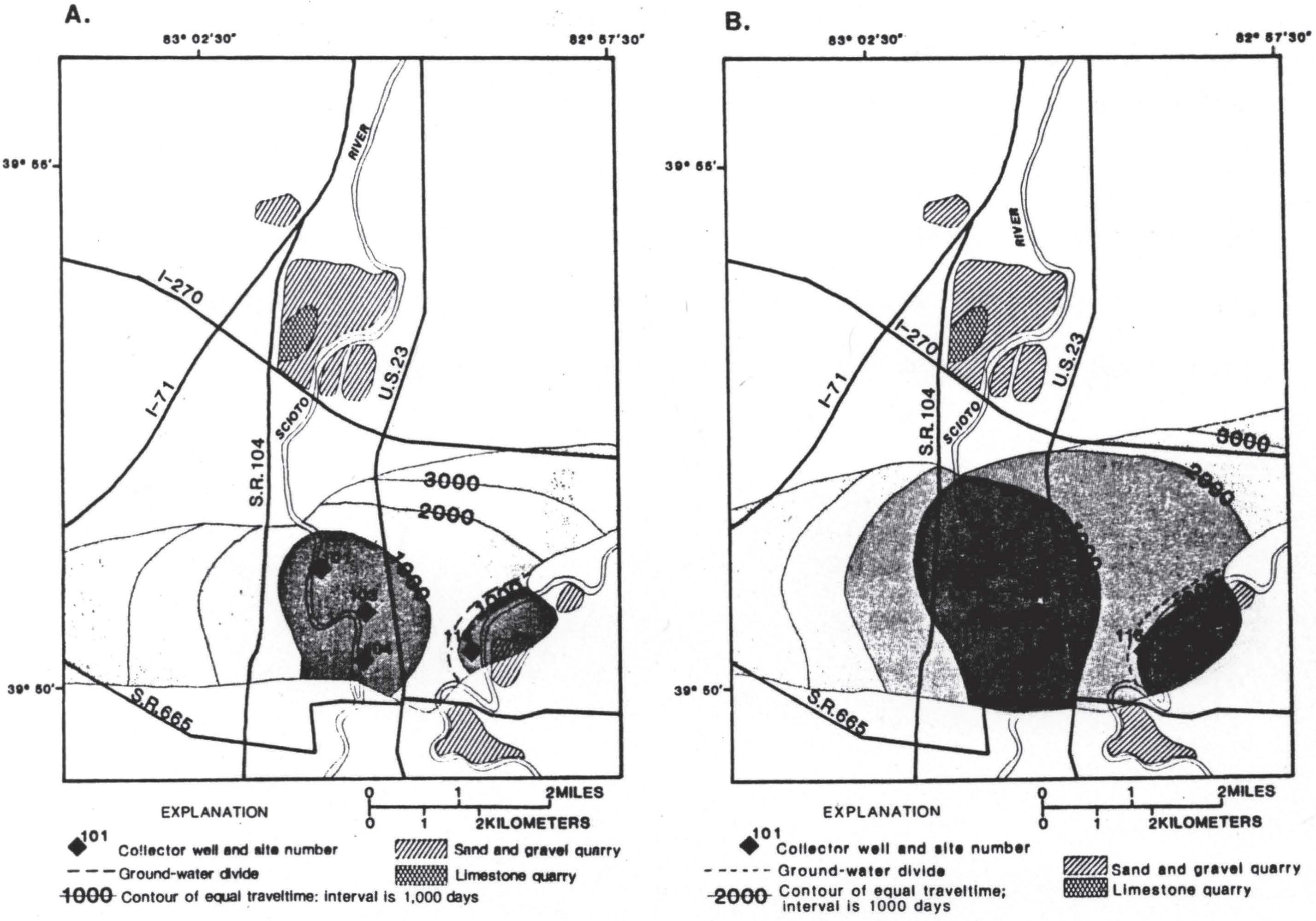


Figure 20. Half-year capture zones of the South Well Field based on image wells and best-estimate hydraulic parameter values.

endpoints of the pathlines define the capture zone of each well. The shape of the capture zones are oblate reflecting well interference and the primary upgradient flow directions.

The difference in accuracy between the capture zones constructed in this study with those in Bair et al (1990) are reflected in the capabilities of GWPATH and STLINE and the capabilities of the flow models on which they are based. Figure 21 shows the of 1,000 2,000, and 3,000-day capture zones of the South Well Field as calculated using MODFLOW and STLINE (Bair et al., 1990). For March 1987 pumping rates, the westward boundary of the 1000-day capture zone falls short of State Route 104 by several hundred feet. Figure 20, however, shows the westward lobe of the 182-day capture zone of CW-101 extending beyond the position of State Route 104 by about 100 feet. (A 1000-day capture zone exceeds the boundaries of the model.) Furthermore, Bair et al (1990) show a ground-water divide near CW-115, separating its capture zone from those of the other three collector wells. Figure 20, however, shows the ground-water divide to be significantly further west than should be present under actual field conditions. The large error between the size of the two capture zones and the position of the ground-water divide is primarily due to the limitations of CAPZONE and GWPATH which require the use of uniform values of



A: Capture areas and isochrones based on normal pumping rates at the South Wellfield. B: Capture areas and isochrones based on estimated maximum pumping rates at the South Wellfield.

Figure 21. Capture areas according to Bair et al. (1990), and the ground-water divide between CW-115 and the other collector wells.

hydraulic conductivity and porosity for the entire flow domain. The heterogeneous character of the aquifer materials is accounted for in MODFLOW/STLINE by assigning different values of hydraulic conductivity and porosity to various regions of the flow domain (Fig. 7).

Figures 22 through 27 are simulations of drawdown, head distribution, and capture zones based on current, larger pumping rates. The effects of almost tripling the discharge rate of the well field are clearly reflected in resultant drawdowns and head distributions. Figures 25 through 27 incorporate river leakage using image wells. These simulations can be compared to future sets of field data that reflect current pumping rates.

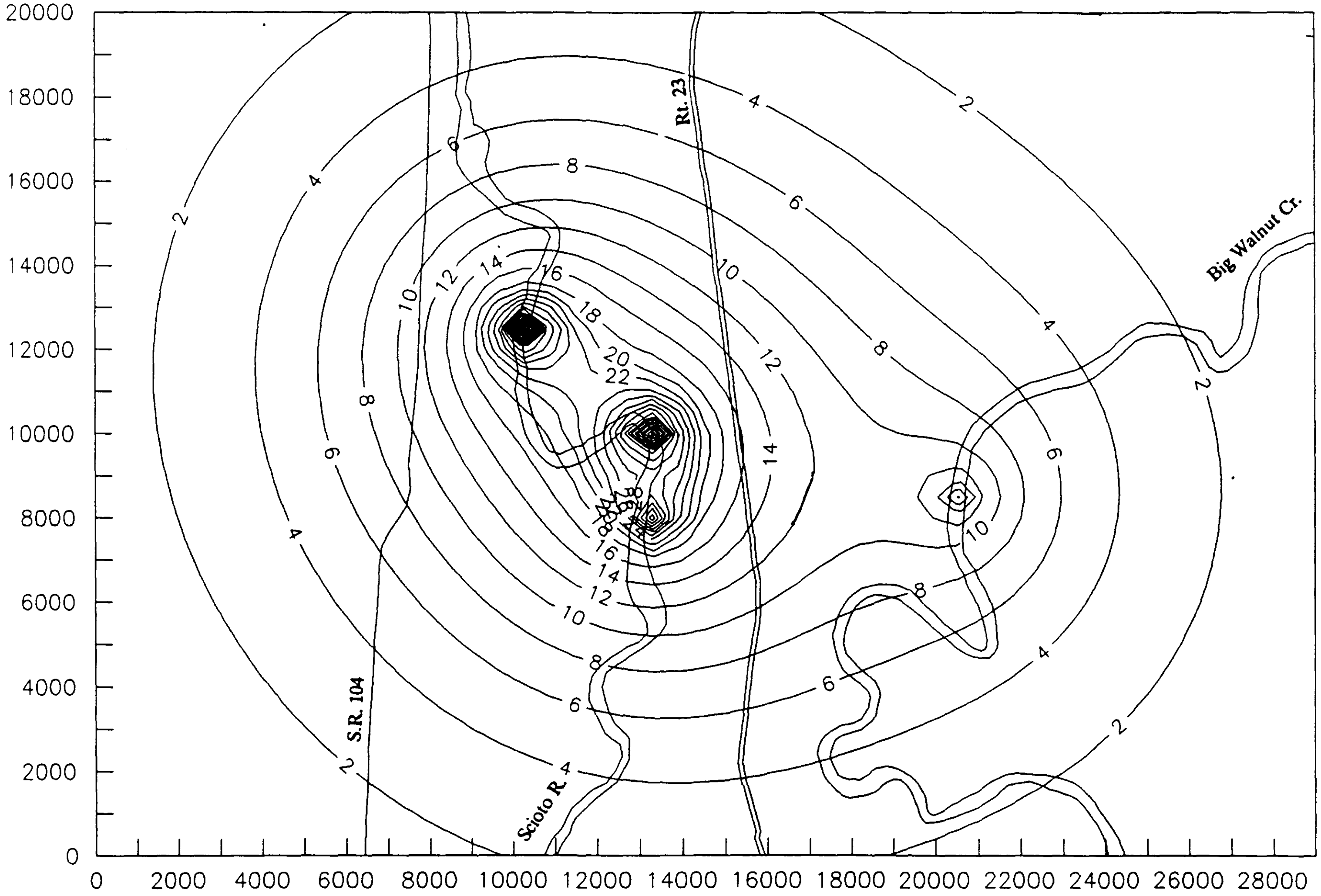


Figure 22. Predicted drawdowns around the collector wells of the South Well Field at current pumping rates. (scales in feet)

——Equipotential lines

Contour interval: 2 ft.

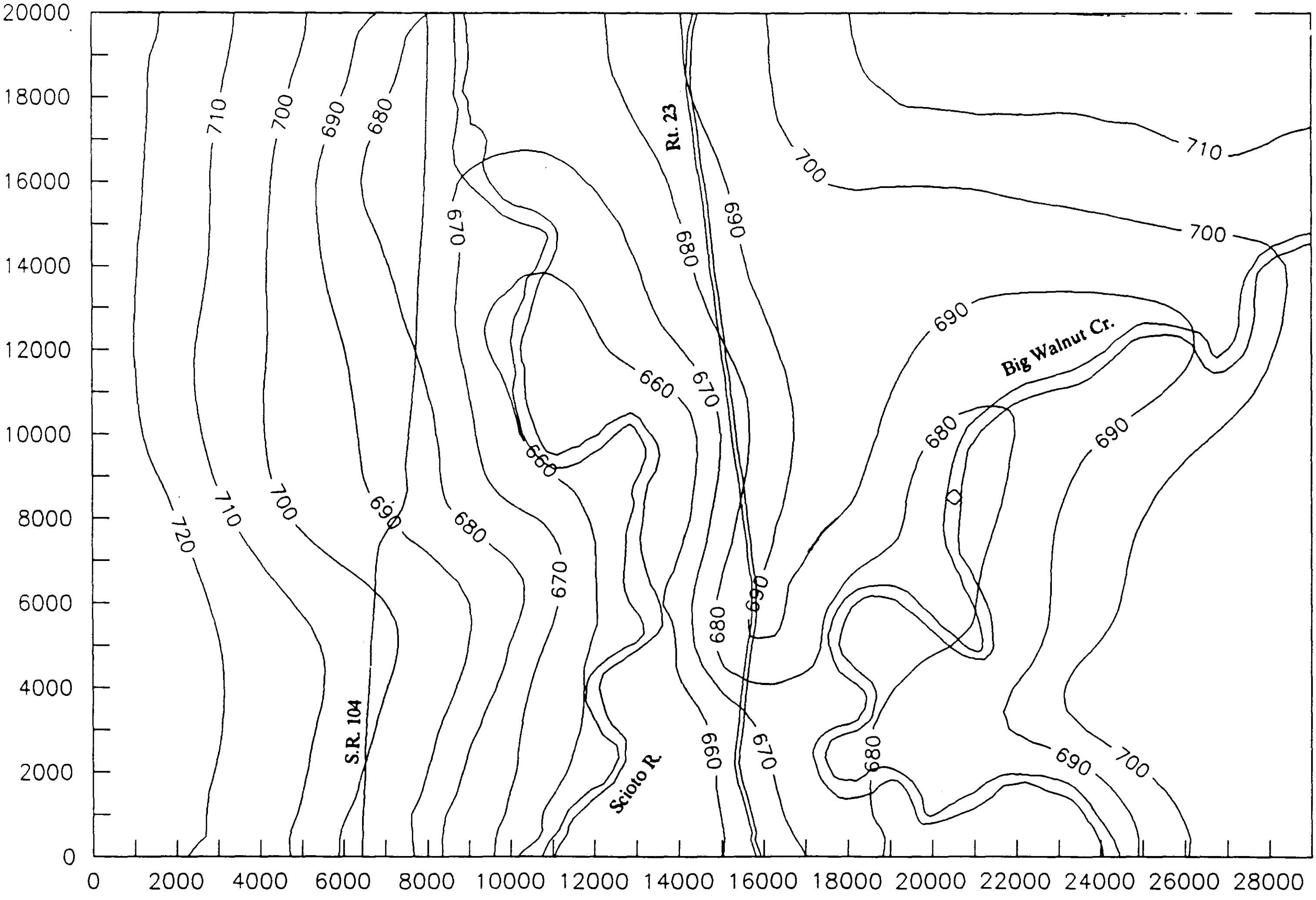


Figure 23. Predicted potentiometric surface after subtraction of drawdowns as calculated by CAPZONE at current pumping rates. (scales in feet.)

——Equipotential lines

Contour interval: 10 ft

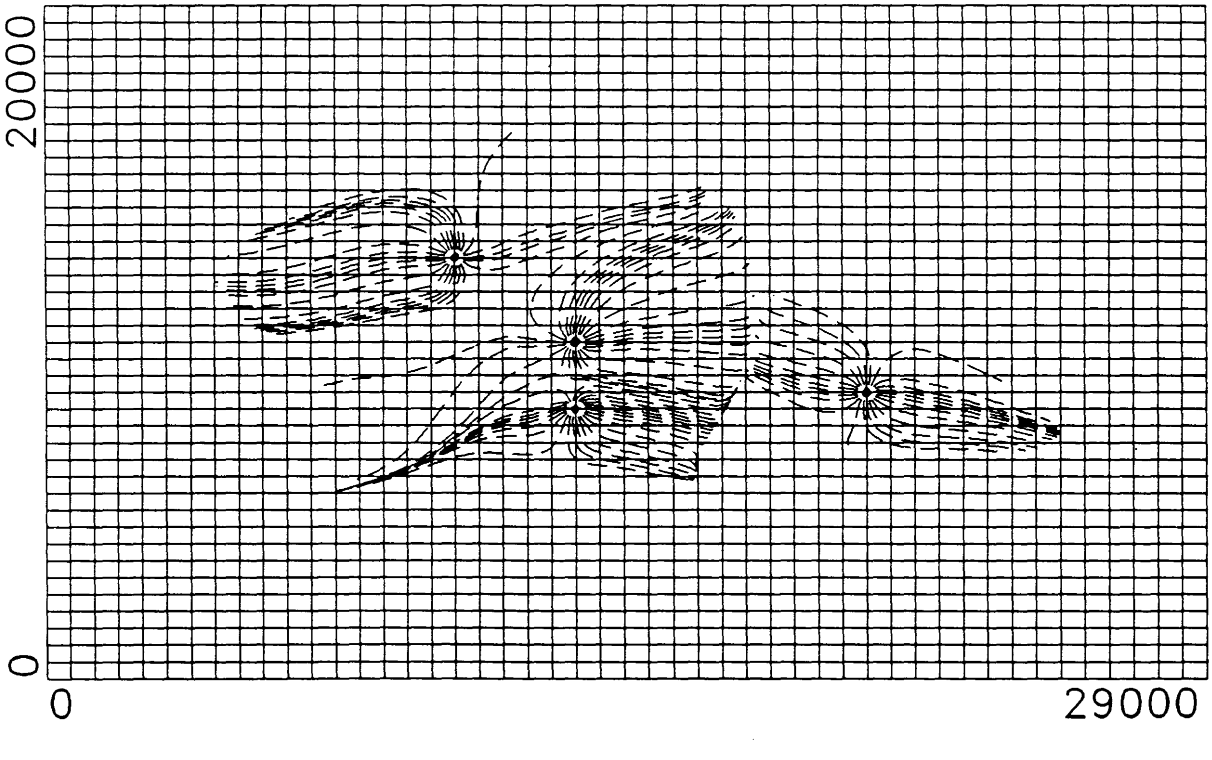


Figure 24. Half-year traveltime capture areas of the South Well Field based on best-estimate hydraulic parameter values at current pumping rates. (scales in feet)

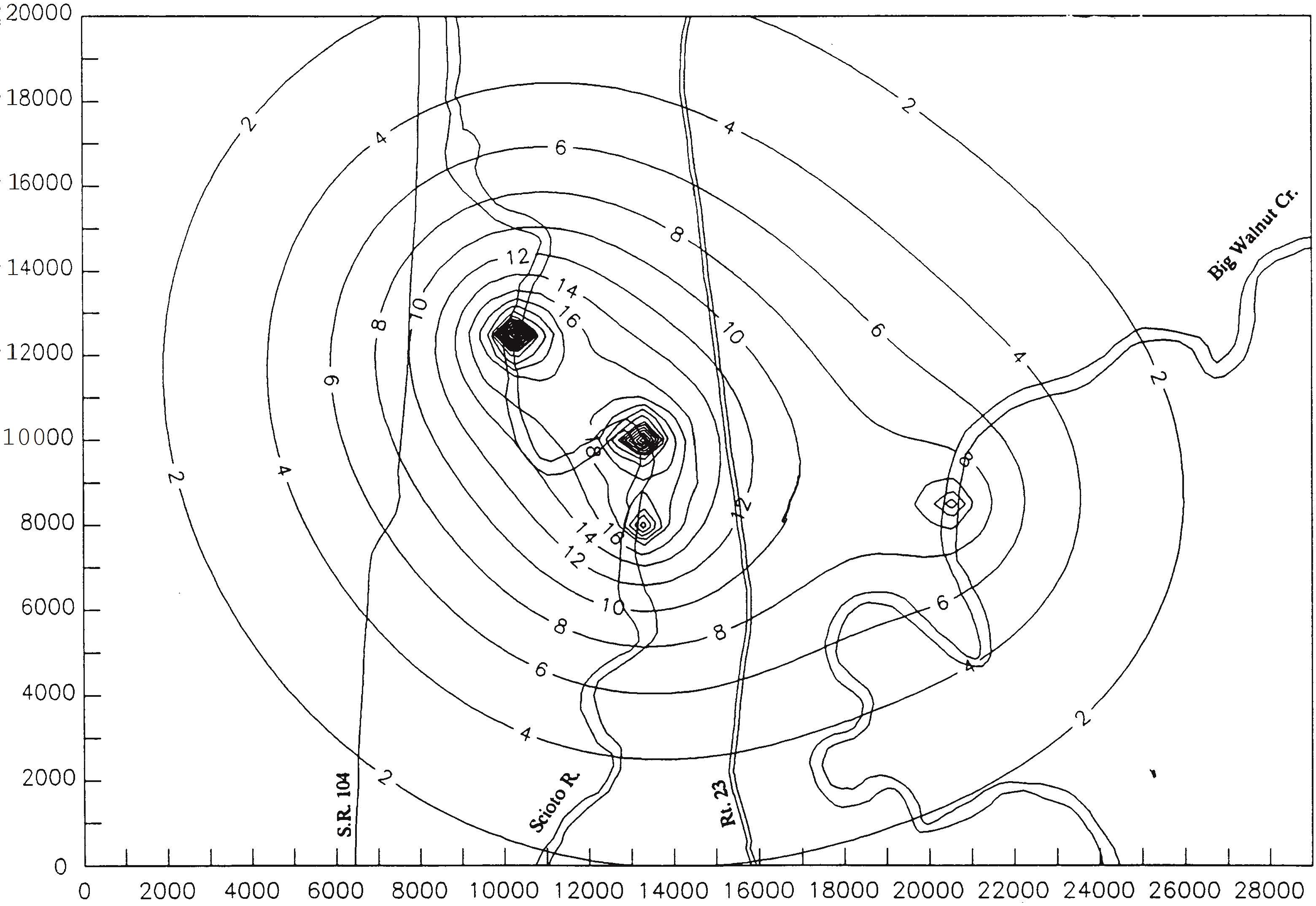


Figure 25. Predicted drawdowns around the collector wells of the South Well Field at current pumping rates and incorporating image wells. (scales in feet)

——Equipotential lines

Contour interval: 2 ft

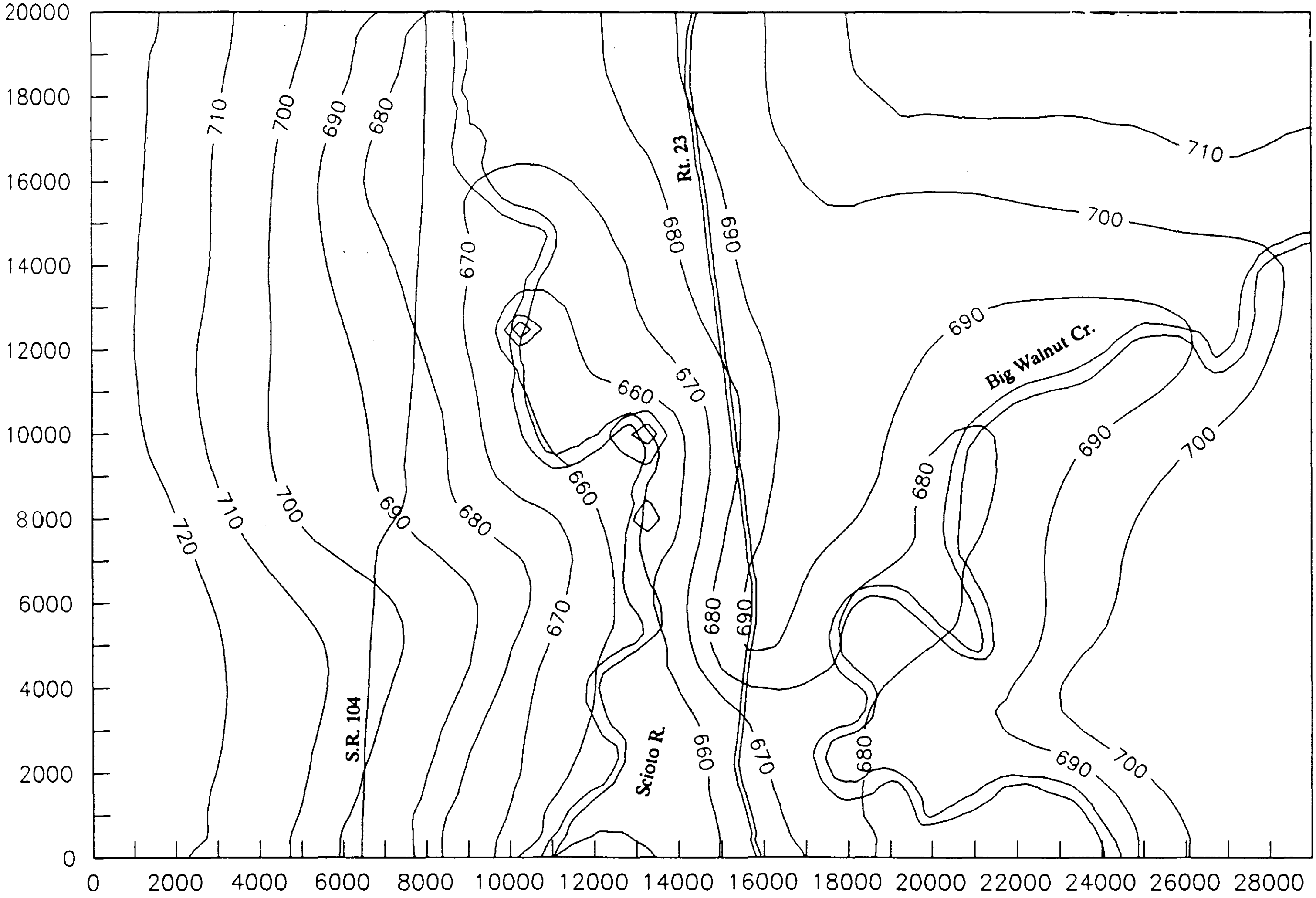


Figure 26. Predicted potentiometric surface after subtraction of drawdowns as calculated by CAPZONE with current pumping rates and image wells. (scales in feet)

———Equipotential lines

Contour interval: 10 ft

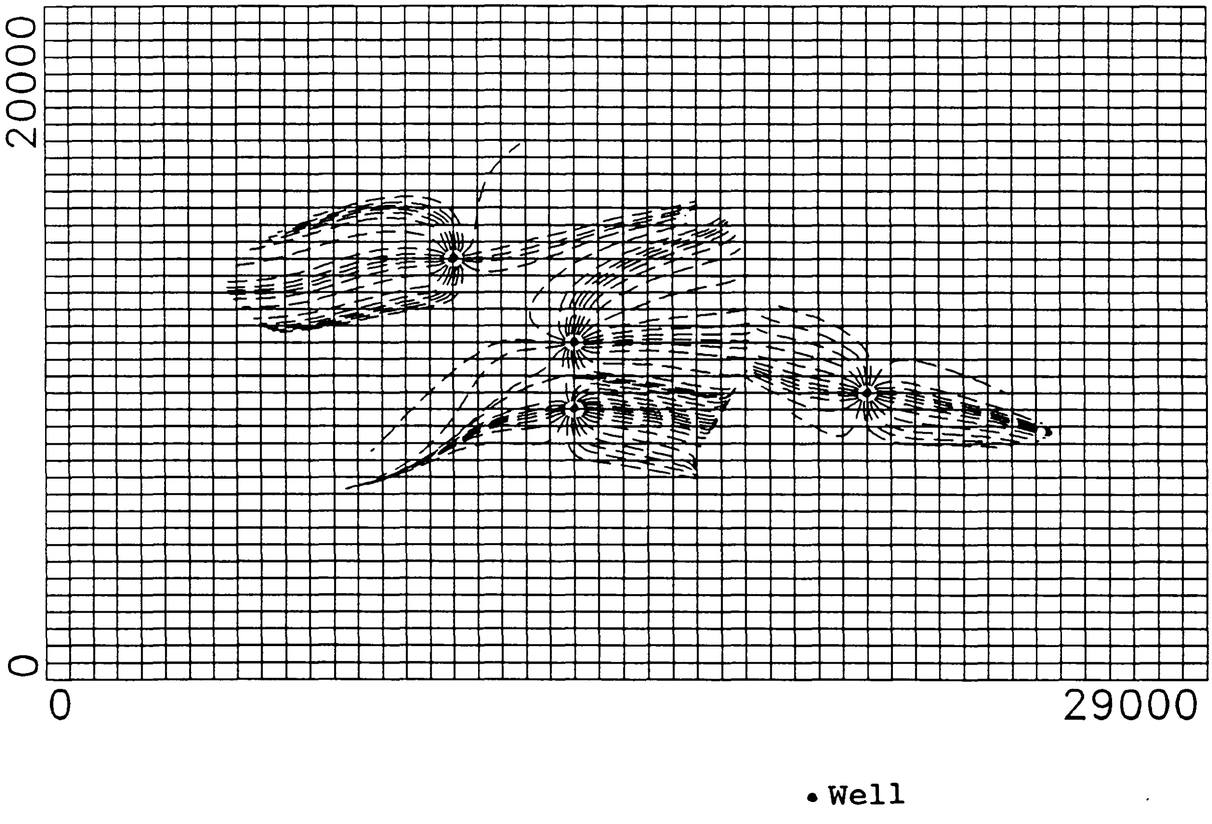


Figure 27. Half-year capture zones of the South Well Field based on image wells and best-estimate hydraulic parameter values at 1990 pumping rates.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The South Well Field in Southern Franklin County, Ohio, abstracts water from a surficial aquifer and induces infiltration from rivers and supplies about 25 percent of the water needs of the City of Columbus. The saturated thickness of the aquifer exceeds 60 feet with the principal portion of the aquifer consisting of highly permeable sands and gravels of glacial origin. Four large capacity collector wells are completed in the aquifer.

Using CAPZONE in conjunction with GWPATH, head distributions and half-year capture zones were computed for two different pumping rates at the South Well Field. Induced infiltration from rivers was accounted for using modified image-well theory by injecting approximately 20 percent of the discharge rate of each collector well. The results of the flow simulations and particle tracking were compared to previous studies in the same study area which were made using a numerical model (Eberts, 1987; Bair et al., 1990).

Comparison of CAPZONE simulations to MODFLOW simulation show good agreement in simulated heads between the two models. However, the capture zones of the South Well Field computed by CAPZONE/GWPATH are significantly larger than those computed by MODFLOW/STLINE. One thousand day capture zones could not be calculated using CAPZONE/GWPATH because the capture zones exceeded the boundaries of the modelled area. Half-year capture zones were successfully constructed but were still larger than the 1000-day capture zone predicted by MODFLOW/STLINE.

Additionally, the shape of the CAPZONE/GWPATH capture zones were significantly more elongated in the east-west direction. This is due to the head distribution calculated by CAPZONE. Achieving reasonable values of simulated drawdown required a value of hydraulic conductivity that was close to the actual values near the collector wells. A value of 330 ft/day is realistic for the area immediately adjacent to CW-101, CW-103, CW-104 and CW-115. In the study area, much lower values of hydraulic conductivity occur in a north-south direction and even lower values in the east-west direction, especially west of the Scioto River. Thus, capture zones based on more accurate flow models should appear more elongated in the north-south direction (see Fig. 21).

Because the City of Columbus varies which pumps it operates and their respective discharge rates, it is important that the lateral variations in subsurface geology be accounted for in models which estimate capture zones of wells which are used to site "sentinel" wells in a wellhead-protection program. Thus, comparison of the results of the two models show use of MODFLOW and STLINE are more appropriate for this type of complex hydrogeologic setting. If other communities use CAPZONE and GWPATH in this type of hydrogeologic setting, land-use controls could be imposed over too large an area. Although the error may appear to be conservatively favorable, it may nevertheless cause the positioning of "sentinel wells" in non-optimal locations around the capture zone.

The selection of a suitable flow model for delineation of traveltime-related capture zones is most dependent on the model which represents the flow system without over-simplifying it. This reduces conceptual errors caused by insufficient depiction of the actual flow system. In this case, communities with smaller fiscal resources in hydrogeologic settings less complex than the South Well Field may find, in terms of cost and accuracy, that CAPZONE and GWPATH may be suitable for developing their wellhead protection programs.

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APPENDIX A

The following is a general form of the Theis equation used to describe flow in unconfined aquifers as modified from Fetter (1988) and used in CAPZONE.

$h_0 - h = Q/T4pi*W(u)$

where W(u) is the well function for the unconfined aquifer, and

$u = r^2 S/4Tt$

where

h_0 - h is the drawdown,

Q is the pumping rate,

T is the transmissivity,

r is the radial distance from the pumping well,

S is the storativity,

t is the time, and

b is the initial saturated thickness of the aquifer