

SIMULATIONS OF NON-STEADY FLOW IN A GLACIAL OUTWASH AQUIFER,
SOUTHERN FRANKLIN COUNTY, OHIO

By Allan C. Razem

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 83-4022

Prepared in cooperation with the
CITY OF COLUMBUS, OHIO



Columbus, Ohio

1983

UNITED STATES DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS

For the benefit of readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
mile (mi)	1.609	kilometer (km)
square mile (mi ²)	2.590	square kilometer (km ²)
inch (in)	25.4	millimeter (mm)
million gallons per day (Mgal/d)	0.0438	cubic meters per second (m ³ /s)
cubic feet per second (ft ³ /s)	0.646	million gallons per day (Mgal/d)

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ABSTRACT

A two-dimensional, finite-difference model is used to simulate transient flow conditions in a glacial outwash aquifer in southern Franklin County, Ohio. The model was calibrated by matching observed and simulated water-level changes for December 1977 through March 1980.

Drawdowns for three different hypothetical pumping rates are simulated with the calibrated flow model. An increase in the combined pumping rate from the steady-state rate of 10 cubic feet per second to 48 cubic feet per second results in water-level declines of 10 to 20 feet near the area of the pumping wells. Declines of 20 to 40 feet result when the combined pumping rate is increased to 70 cubic feet per second, and a simulated pumping well goes dry when the combined pumping is increased to 94 cubic feet per second. For the first two cases, steady-flow conditions are reached after 12 years of pumping; infiltration through riverbeds accounts for 28 to 33 percent of the pumpage.

INTRODUCTION

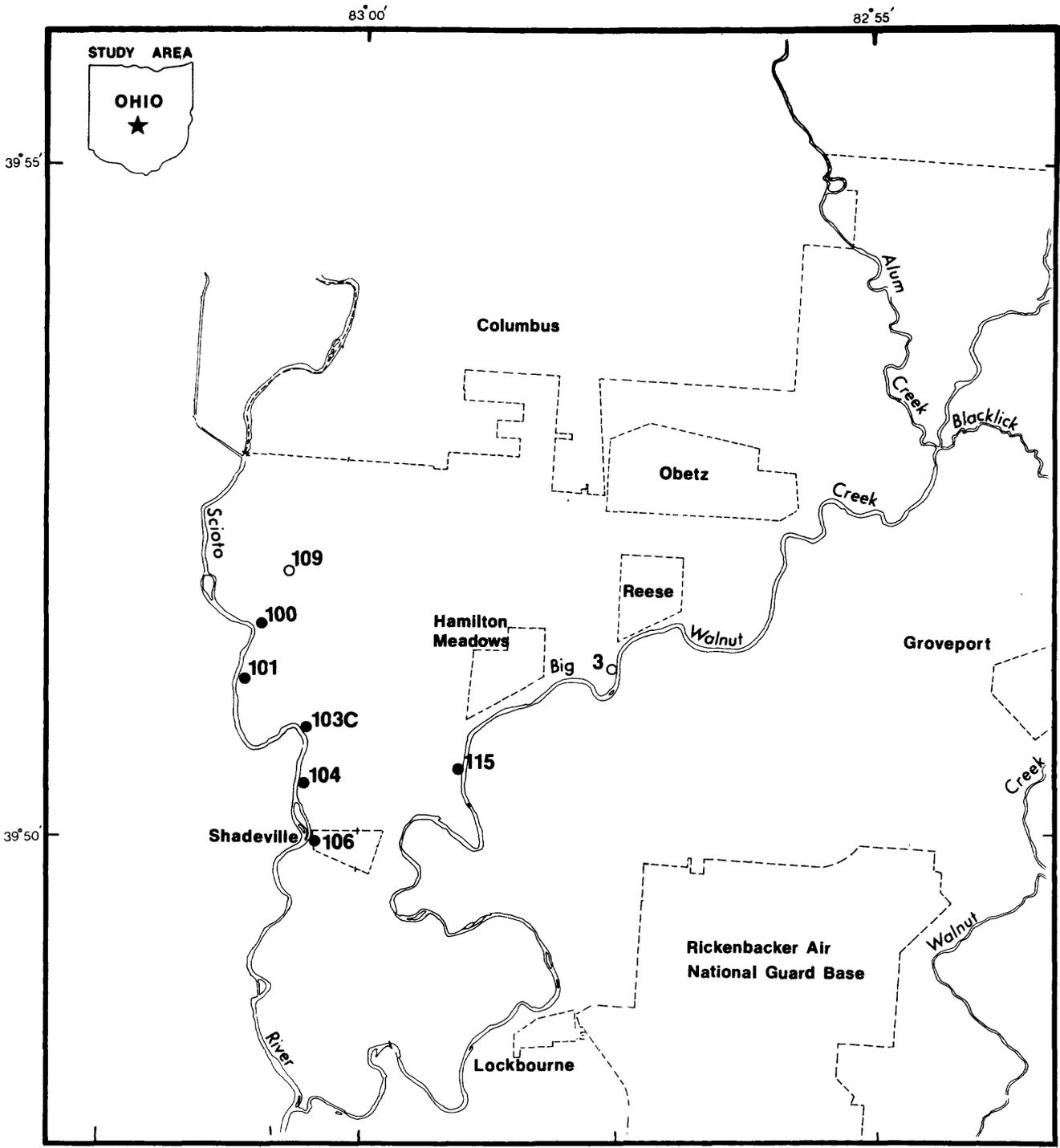
A glacial outwash aquifer in part of the Scioto River basin was evaluated by the U.S. Geological Survey in cooperation with the City of Columbus, Ohio. The purpose of this report is to describe the development of a transient-state digital-computer model and the simulated water-level resulting from anticipated withdrawal by up to six new municipal wells.

The study area (fig. 1), covers approximately 70 square miles in southern Franklin County and a small part of northern Pickaway County in central Ohio. The modeled area (fig. 1) includes the southern part of the city of Columbus, Rickenbacker Air Force Base, and the communities of Obetz, Reese, Hamilton Meadows, and Shadeville. The Scioto River is the major stream in the area. Big Walnut and Walnut Creeks are the principal tributaries to the Scioto.

This report is part of an overall study to model the flow and to describe the water-quality characteristics of the glacial outwash aquifer. An earlier report by Weiss and Razem (1980) described the general hydrogeology of the area and presented the theory and variables used in constructing the preliminary steady-state model. The steady-state model was used as a steppingstone in refining and calibrating the transient-state model presented in the report. A subsequent report will describe the ground-water-quality characteristics in this study area.

DESCRIPTION OF THE MODEL

A finite-difference, two-dimensional ground-water flow model (Trescott and others, 1976) was used to simulate flow in the glacial outwash aquifer for both the transient-state calibration and the predictions of water-level changes due to pumping. Modifications to the program involved output variations that were helpful in interpreting intermediate steps and final results. These modifications are similar to those described in Razem and Bartholoma (1980, p. 16).



Base from U.S. Geological Survey
 Southeast Columbus, 1964, Lockbourne,
 1964, and Commercial Point, 1966

EXPLANATION

0 1 MILE

- Community and military installation boundaries
- Location of observation wells
- Simulated pumping well site

Figure 1.--Study area and well locations.

Model Grid

A variable, block-centered grid (fig. 2) was used to simulate the flow in the glacial outwash. The grid used for the transient-state model consisted of 31 rows and 34 columns, which divided the area into 1,054 rectangular blocks. At each node, or center point of each block, the finite-difference equation of ground-water flow is solved using hydrologic characteristics as input. The variable grid spacing ranges from 313 to 10,039 feet with the smaller grid spacing where wells are located or where the hydrologic characteristics are better known.

Hydrologic Characteristics

The hydrologic characteristics or data input at each node in the model were obtained from the earlier study by Weiss and Razem (1980), by additional data collected since that report, and by varying values for the transient-state calibration until a visual best-fit was achieved. The characteristics (discussed below) include boundary conditions, recharge, aquifer properties, river and riverbed properties, and well discharge.

Boundary Conditions and Areal Recharge

The boundary conditions used for this model are slightly modified from those described by Weiss and Razem (1980, p. 9). The constant-head boundary along the western edge is set to 720 feet, except for nodes 2 through 5 (fig. 2), which range from 690 to 715 feet. The constant head along the northern boundary has been modified to more closely match the more recent water-level measurements collected from 1977 to 1980; those constant heads range from 685 to 725 feet. The eastern boundary is unchanged; the constant head is 730 feet between Blacklick Creek and Walnut Creek, and there is a no-flow boundary along the remainder. The entire southern boundary is a no-flow boundary.

Under these constant-head conditions, a flow of 37.2 ft³/s (cubic feet per second) across the western boundary and a total flow of 49.5 ft³/s across all boundaries was derived from the steady-state simulation. This is very close to the total flow that was estimated by Weiss and Razem (1980, p. 11).

For the steady-state model, areal recharge from precipitation was estimated to be 12 inches a year by hydrograph analysis (Weiss and Razem, 1980, p. 10). The same hydrograph analysis, which determines recharge by multiplying the sum of water-level rises by the specific yield (0.1), was used to estimate areal recharge for each of the 12 pumping periods simulated in the transient-state condition (table 1). The recharge from precipitation for these periods ranged from 0 to 8.64 inches.

An average recharge of 12 inches a year was used for the predictive simulations. This may cause some discrepancies between the observed and predicted drawdowns during extended wet or dry periods.

Aquifer Properties

The hydraulic conductivity, saturated thickness, and specific yield that were used in this model are described by Weiss and Razem (1980). Additional data collected since that report have allowed some of the aquifer-property variables to be modified and refined.

The hydraulic conductivities that produced the best calibration in this report were those equal to the "K-map" described in Weiss and Razem (1980, p. 8). The hydraulic conductivity is 400 ft/d (feet per day) in the highly permeable areas near the well sites. It is 40 ft/d in the low-permeable areas along parts of the northern and western boundaries and in an area south of well 115A and east of well 103C. The hydraulic conductivity is 200 ft/d over the remaining area.

The bedrock altitude, which has been modeled as an impermeable boundary, was obtained from well logs and a bedrock altitude map (Schmidt, 1958). The annual water-level changes since 1976 in the study area have been small; therefore, the saturated aquifer thickness has remained essentially unchanged.

The specific yield of 0.1 (Weiss and Razem, 1980, p. 10) is an estimate that has proved satisfactory during the transient-state calibration. It was also used for the predictive simulations.

Table 1.--Hydrologic variables used in the transient state calibration
(December 1977 to March 1980)

	1	2	3	4	5	6	7	8	9	10	11	12
Pumping period-----	1	30	240	60	30	60	120	30	60	60	30	30
Days-----	60	30	240	60	30	60	120	30	60	60	30	30
Recharge, in inches--	0	6.59	0	3.98	0	8.64	0	6.00	0	3.11	0	3.95

Hydrologic variables held constant for each pumping period: Specific yield - 0.1;
 Hydraulic conductivity range, in feet per day, (low) 40, (middle) 200, (high) 400;
 Riverbed vertical hydraulic conductivity, 4.36 x 10 sec ; and Total pumping
 date, in cubic feet per second, 10.

River and Riverbed Characteristics

River elevations were obtained from U.S. Geological Survey 7 1/2-minute topographic maps; a linear interpolation was used between contours. A river depth of 5 feet was used for all parts of the river for all transient simulations.

The average riverbed vertical hydraulic conductivity of 4.36×10^{-6} ft/s (feet per second) is the same as that used in the preliminary model of the study area (Weiss and Razem, 1980, p. 13). Leakage to each river block or cell has been adjusted to account for streambed areas that are smaller than their representative blocks.

During steady-state simulation, the Scioto River and Big Walnut Creek combined gain a net of $100 \text{ ft}^3/\text{s}$, which compares to a 95-percent duration flow of $139 \text{ ft}^3/\text{s}$ for the Scioto River at Columbus and Big Walnut Creek at Reese.

Well Discharge

The well discharge in the modeled area for transient-state calibration was $10 \text{ ft}^3/\text{s}$ for each pumping period (table 1). The total pumping rates were modified from the earlier study (Weiss and Razem, 1980, p. 14) to account for user variation and pumping at a nearby quarry.

TRANSIENT-STATE MODEL CALIBRATION

The purpose of calibrating the model is to simulate observed ground-water conditions until a best-fit condition is obtained by adjusting variables within hydrologically reasonable ranges. Simulations of future water-level changes probably are reliable, especially within the range of conditions simulated to attain a best-fit condition.

In the preliminary steady-state calibration (Weiss and Razem, 1980), the model was adjusted until it satisfactorily reproduced the potentiometric surface interpreted from water levels measured in December 1977. The more definitive transient-state model calibration was made by simulating water-level changes from December 1977 to March 1980 and comparing them to measured water-level changes in observation wells for the same period.

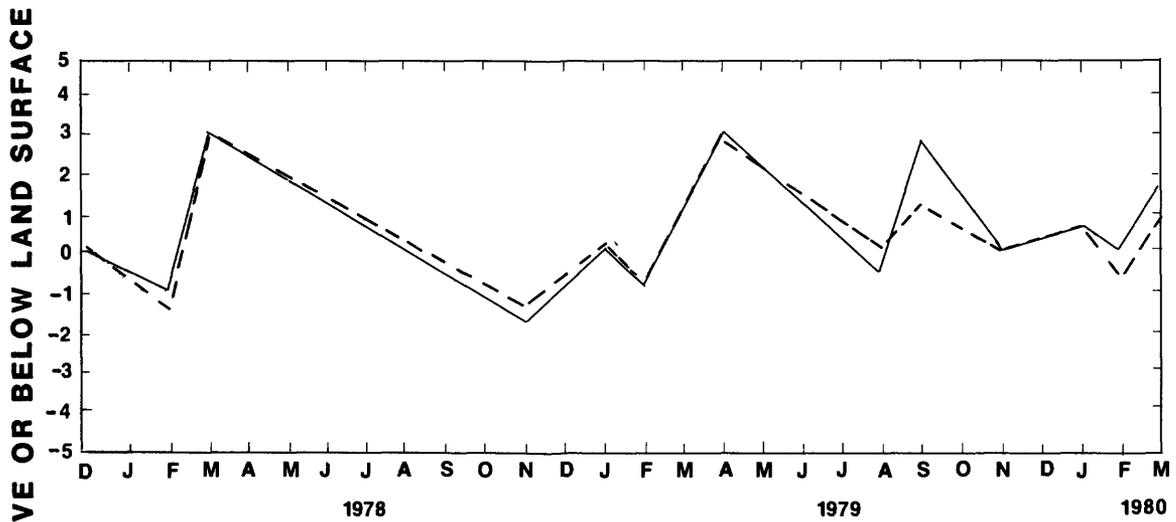
The calibration period of December 1977 to March 1980 was divided into 12 pumping periods based on available water-level data and precipitation patterns. The starting heads used for the first pumping period were the final heads produced by the steady-state model. The comparison of observed water-level changes and computed water-level changes (fig. 3) appears to be good for both well 3 and well 109. (See fig. 1 for well locations.)

The only variable stress applied to the ground-water system during the transient-state calibration was recharge from precipitation. Well discharge in the model was not varied during the transient calibration because pumpage rates were assumed to be constant. Therefore, stresses imposed on the simulated aquifer during transient calibration were small compared to the pumping stress applied during the predictive simulations. This may cause unforeseen discrepancies between the predictions and future observations.

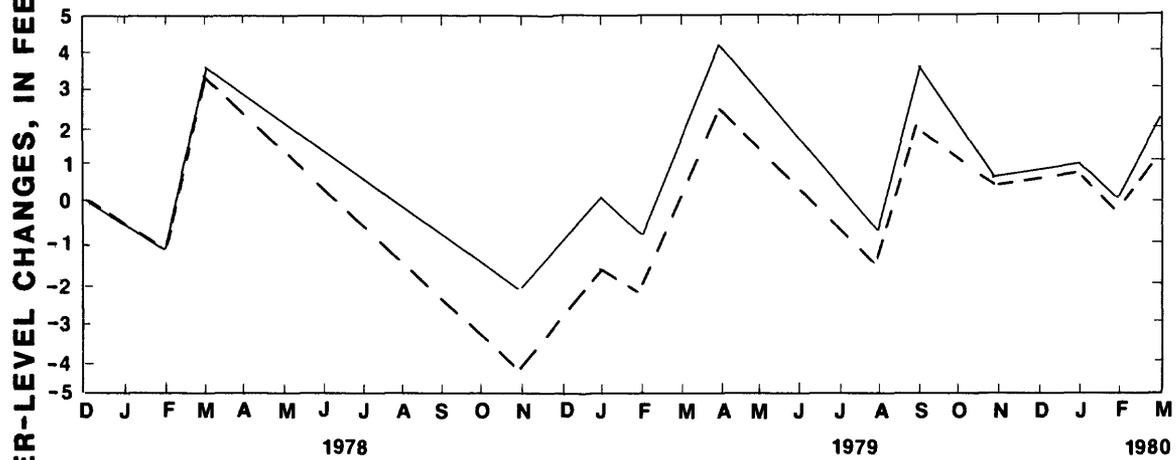
SIMULATED AQUIFER RESPONSE TO FUTURE PUMPING

Future pumping was simulated from wells 100, 101, 103C, 104, 106, and 115A (fig. 1), in addition to existing wells simulated in the transient calibration. Discharge from existing wells was assumed to remain constant at a combined total of 10 ft³/s. Although this discharge may fluctuate slightly, it is not anticipated that any significant change will take place. Simulations were made for combined anticipated well discharges of 48 ft³/s, 70 ft³/s, and 94 ft³/s for 30-year periods.

The following results show predicted water-level changes from the March 1980 computer-generated levels. Areal recharge was kept constant, 12 inches per year, for all time periods in all predictive simulations.



WELL 3



WELL 109

EXPLANATION

- Hydrographs based on actual measurements
- Computed hydrographs

Figure 3.--Comparison of observed and computed water-level changes at wells 3 and 109 from December 1977 to March 1980.

Case I

In the first predictive simulation, pumpage from wells was 48 ft³/s, of which 38 ft³/s was discharged from four of the new wells (table 2). Water-level declines were generally 10 to 15 feet in the area of the four wells. Declines of 5 to 10 feet developed as much as 2 miles away (fig. 4). Water levels declined to 26 feet at well 103C and from 15 to 20 feet at wells 101, 104, and 115A.

Net leakage from the aquifer to the stream was reduced from 100 ft³/s before pumping to 64 ft³/s when pumping at a rate of 48 ft³/s. The decrease of 36 ft³/s represents an increase of 11 ft³/s from the stream to the aquifer and an interception of 25 ft³/s that would have flowed from the aquifer to the stream had there been no pumping. Flow from constant-head boundaries increased by less than 2 ft³/s. Of the 38-ft³/s increase in pumping attributed to wells 101, 103C, 104, and 115A, 28 percent comes as infiltration from the streams, 65 percent comes as intercepted flow, and the remaining 7 percent comes from an increase in constant-head flow and storage.

Case II

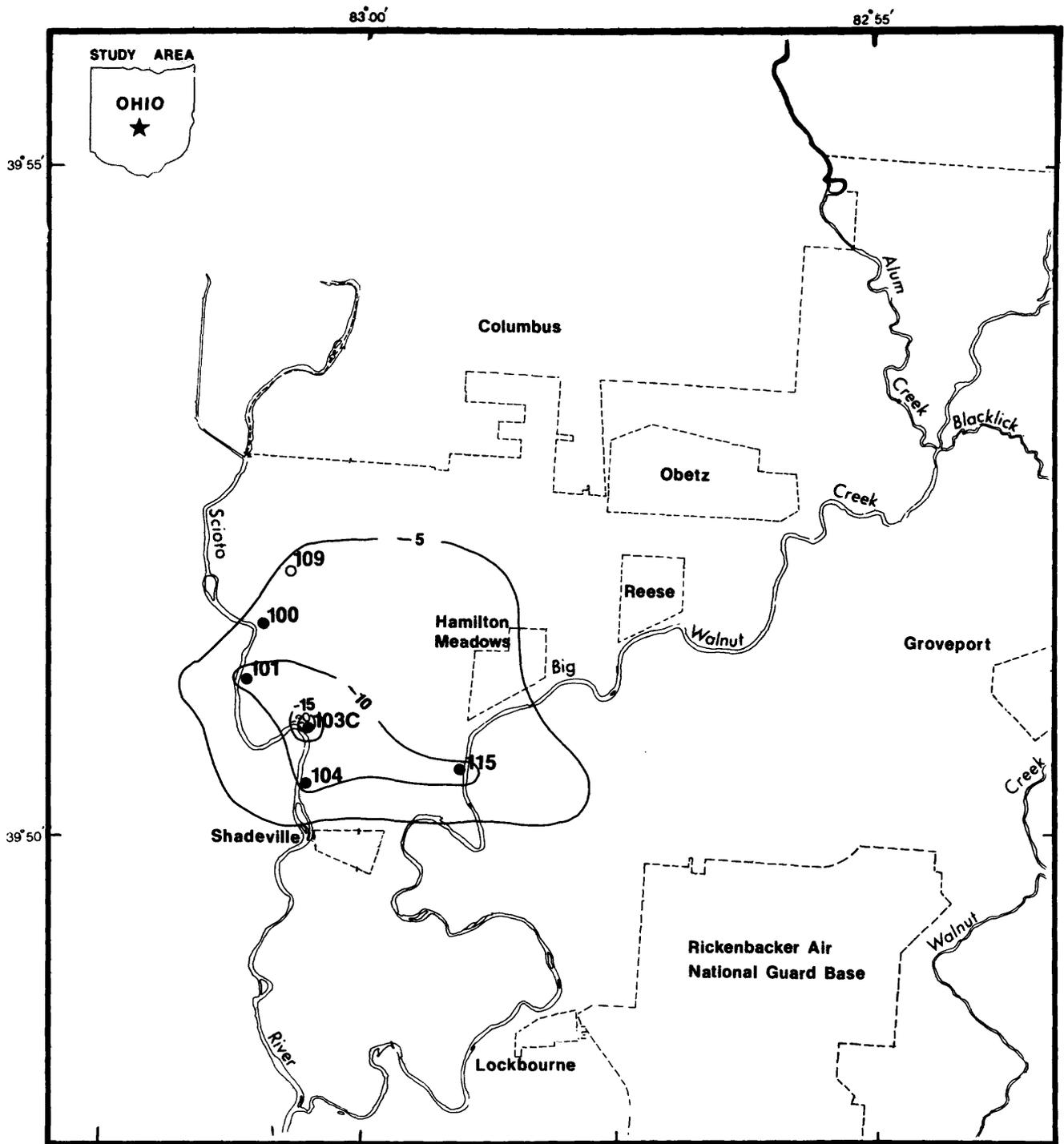
In the second predictive simulation, pumpage from wells was increased to 70 ft³/s, of which 60 ft³/s was discharged from four of the new wells (table 2). Water-level declines were generally 20 to 30 feet in the vicinity of the four wells, 10 to 20 feet about 1 mile away, and greater than 5 feet at 3 miles from well 103C (fig. 5). Water levels declined as much as 57 feet at well 103C and from 20 to 35 feet at wells 101, 104, and 115A. Steady-state conditions were reached after 12 years of pumping.

Net leakage from the aquifer to the stream was reduced from 100 ft³/s in the prepumping condition to 44 ft³/s during pumping. The decrease of 56 ft³/s represents an increase of 20 ft³/s from infiltration from the river and an interception of 36 ft³/s that would have flowed from the aquifer to the stream had there been no pumping. Flow from constant-head boundaries increased by slightly more than 3 ft³/s. Of the 60-ft³/s increase in pumping attributed to wells 101, 103C, 104, and 115A, 33 percent comes as infiltration from rivers, 60 percent from intercepted flow, and the remaining 7 percent from an increase in constant-head flow and initial storage.

Table 2.--Water budgets obtained in the predictive simulations

	Simulation			
	Steady state	Case I	Case II	Case III
Leakage from rivers to aquifer (ft /s) ----	12.0	22.5	31.6	*36.1
Leakage from aquifer to rivers (ft /s) ----	111.7	86.4	76.0	*73.3
Net leakage to stream (ft /s) -----	99.7	63.9	44.4	*37.2
Water from storage (ft /s) -----	0	1.3	1.6	*19.2
Total constant head flow (ft /s) -----	50.1	51.9	53.5	*53.1
Pumpage (ft /s) from:				
Well 100 -----	-	-	-	15
Well 101 -----	-	10	16	16
Well 103C -----	-	12	18	18
Well 104 -----	-	7	12	12
Well 106 -----	-	-	-	9
Well 115A -----	-	9	14	14

*Transient results at time step 1 before well 103C went dry.

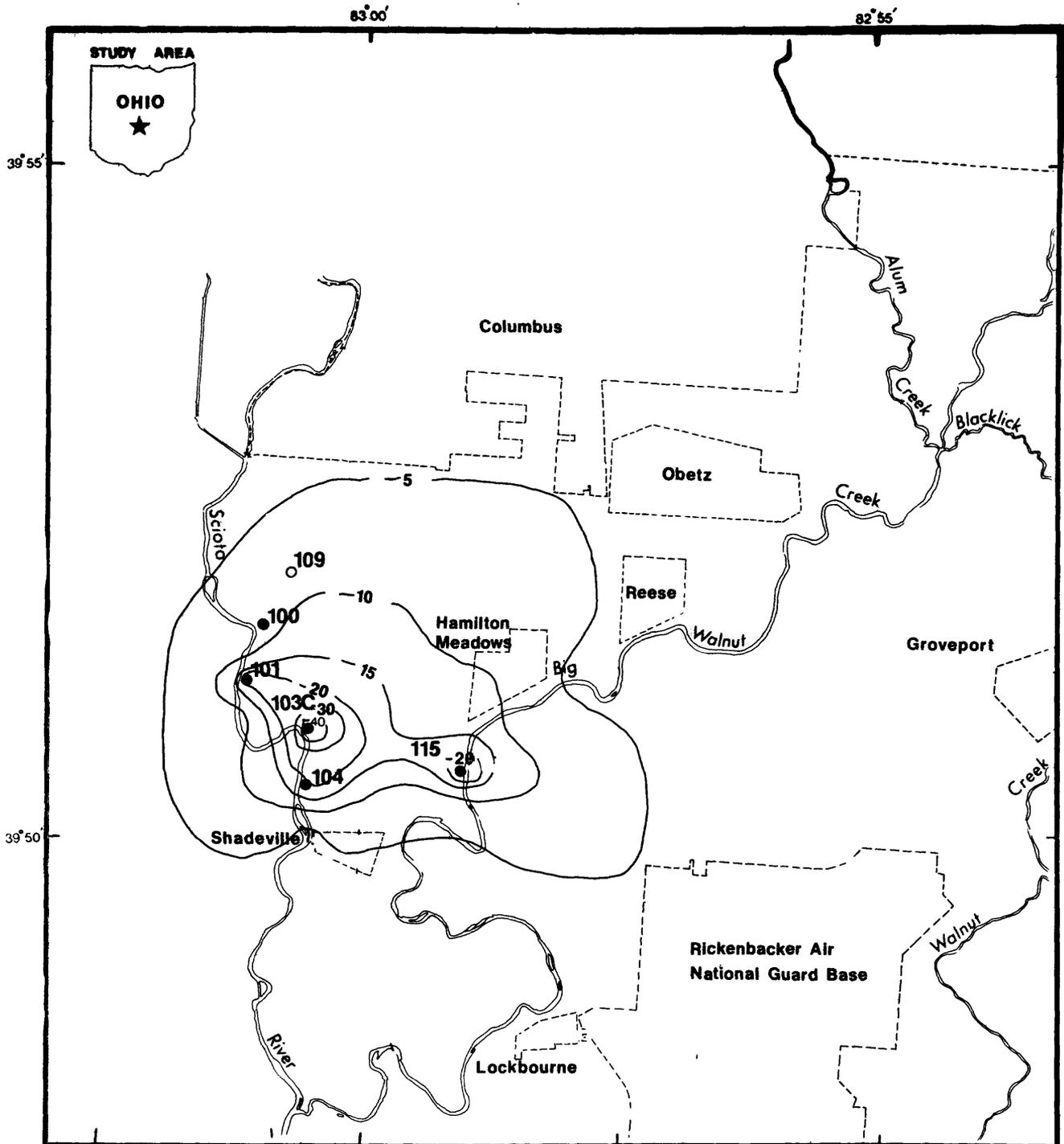


Base from U.S. Geological Survey
 Southeast Columbus, 1964; Lockbourne,
 1964, and Commercial Point, 1966

EXPLANATION

- Community and military installation boundaries
- Location of observation wells
- Simulated pumping well site
- -10 — Drawdown contours

Figure 4.--Predicted drawdowns after combined pumping of 48 ft ³/₄ for 12 years.



Base from U.S. Geological Survey
 Southeast Columbus, 1964, Lockbourne,
 1964, and Commercial Point, 1966

EXPLANATION

0 1 MILE

- Community and military installation boundaries
- Location of observation wells
- Simulated pumping well site
- 10 — Drawdown contours

Figure 5.--Predicted drawdowns after combined pumping of 70 ft ³/₄ for twelve years.

Case III

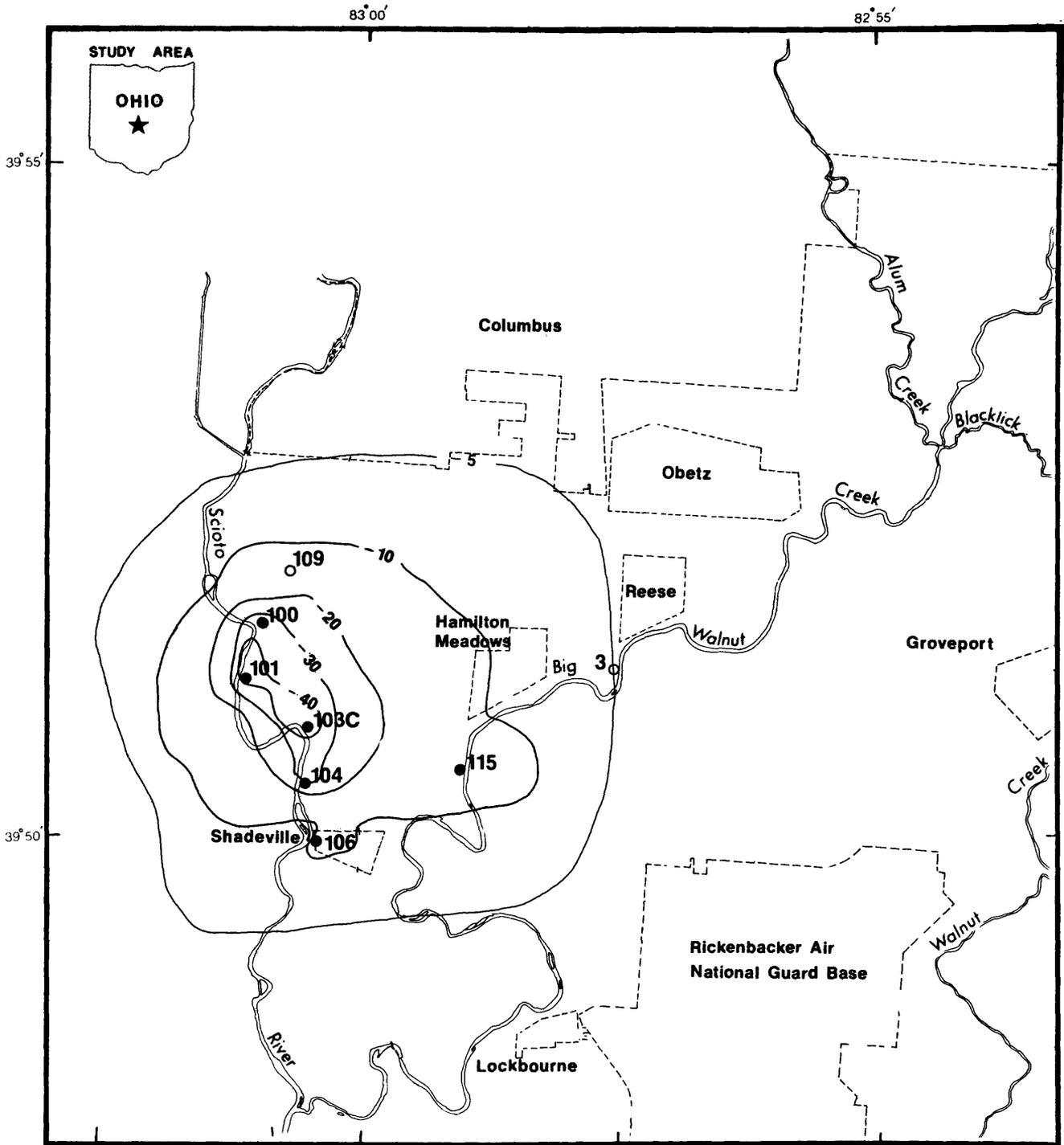
In the third predictive simulation, pumpage from wells was 94 ft³/s, of which 84 ft³/s was discharged from all six new wells (table 2). This simulation was stopped after well 103C went dry during the first year of pumping. The configuration of the drawdown map at the time well 103C went dry (fig. 6) is similar to that shown in figures 4 and 5, except for the much steeper gradient near well 103C.

At the time step before the well went dry, approximately 30 percent of the pumpage was infiltration through the riverbed, 45 percent was intercepted flow, 22 percent was from storage, and the remaining 3 percent was from increased constant-head flow.

SUMMARY

A transient-state digital-computer model was constructed that simulates flow conditions in a glacial outwash aquifer in part of the Scioto River basin. The model is based on a variable, block-centered, finite-difference grid of 31 rows and 34 columns. Constant-head and no-flow boundaries were used along the model perimeter. Uniform recharge from precipitation, 12 inches per year, was applied areally. A variable hydraulic conductivity distribution having an intermediate value of 200 ft/d and a uniform specific yield of 0.1 was used. Vertical hydraulic conductivity of the riverbed, between the river and the aquifer, was uniform at 4.36×10^{-6} ft/s.

The transient model, which was based on an earlier steady-state model, was used for estimating future water-level changes that might result from pumping. The model was calibrated by matching observed water-level changes with simulated water-level changes until a visual best-fit condition was reached.



Base from U.S. Geological Survey
 Southeast Columbus, 1964. Lockbourne,
 1964. and Commercial Point, 1966

EXPLANATION

- Community and military installation boundaries
- Location of observation wells
- Simulated pumping well site
- 10— Drawdown contours

0 1 MILE

Figure 6.--Predicted drawdowns at time 103C goes dry after combined pumping of 94 ft ³/_s.

The well discharge in the modeled area for transient-state calibration was 10 ft³/s for each pumping period. The results of the model indicate that pumping four new production wells at a rate of 38 ft³/s (a combined rate of 48 ft³/s) would lower the water level 10 to 15 feet in the area of the wells. Infiltration through the riverbed would account for 28 percent of the pumpage. Pumping four new production wells at the rate of 60 ft³/s (a combined rate of 70 ft³/s), would cause water levels to decline 20 to 30 feet in the area of the wells; infiltration through the riverbed would account for 33 percent of the pumpage. If all six new production wells were put into production at 84 ft³/s (a combined rate of 94 ft³/s), one of the wells (103C) would go dry before 1 year of pumping time.

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