Effect of Increased Pumping of Ground Water in the Fairfield–New Baltimore Area, Ohio—A Prediction by Analog-Model Study

GEOLOGICAL SURVEY PROFESSIONAL PAPER 605-C

Prepared in cooperation with the Miami Conservancy District and the Ohio Department of Natural Resources, Division of Water, Columbus, Ohio

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By ANDREW M. SPIEKER

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EFFECT OF INCREASED PUMPING OF GROUND WATER IN THE FAIRFIELD–NEW BALTIMORE AREA, OHIO—A PREDICTION BY ANALOG–MODEL STUDY

By Andrew M. Spieker

ABSTRACT

A recent proposal by the Cincinnati Water Works Department to develop a large ground-water supply in the Great Miami River valley near Fairfield, Ohio, has caused concern among the area's civic leaders, who fear that the new well field may endanger existing ground-water supplies. Analysis of the area by electric analog model has been undertaken to ascertain the hydrologic feasibility of Cincinnati's proposal under prolonged conditions of low streamflow. The 32-square-mile area being considered is underlain by a sand-and-gravel aquifer whose transmissibility is mostly about 400,000 gallons per day per foot. The aquifer averages 2 miles in width and is bounded on both sides by steep walls of bedrock of low permeability. A 15-miles reach of the Great Miami River traverses the area. Total pumpage of ground water at present is about 23 million gallons per day. Recharge by induced stream infiltration is limited in most of the analog-model analyses to 325,000 gallons per day per acre of streambed.

Several runs of the model simulating various pumping and recharge rates and alternate well spacings indicated that the hydrologic system can sustain pumping of 40 million gallons per day at the proposed Cincinnati well field in addition to all present pumping. The interference at the pumping well nearest to the proposed field after 10 years of pumping under the stated conditions should not exceed 9 feet. Total drawdown at the Cincinnati well field under these conditions does not exceed 30 feet. Further analysis indicated that the hydrologic system in this area should be able to sustain a total pumping rate of at least 84 million gallons per day, which would include 40 million gallons per day at the Cincinnati well field plus 44 million gallons per day, or double the 1952 rates, at all existing well fields. Pumping at this rate will not cause excessive water-level declines.

INTRODUCTION

PURPOSE AND SCOPE OF THE INVESTIGATION

In the spring of 1961 the Water Works Department of the city of Cincinnati announced plans to develop a large ground-water supply in the Great Miami River valley near Fairfield in Butler County, Ohio (fig. 1). Cincinnati presently draws its water supply from the Ohio River, which during periods of low flow sometimes yields water of poor quality. Average withdrawal from the supply is about 100 mgd (million gallons per day), or 155 cfs (cubic feet per second), with peaks, usually in the summer months, of as much as 153 mgd, or 237 cfs. Cincinnati's proposal is to pump 40 mgd (62 cfs) from the new well field for a 120-day period during the summer and 10 mgd (15.5 cfs) during the rest of the year. The proposed well field would be the largest single source of ground-water supply in the lower Great Miami River valley.

The proposed ground-water supply offers several advantages to Cincinnati over an expansion of the existing surface-water supply. First, the Cincinnati metropolitan area is expanding into the northwestern part of Hamilton County (fig. 1), much of which will eventually require municipal water service. The proposed well field would be closer to this growing area than the existing intake station on the Ohio River near California, about 6 miles east of downtown Cincinnati. Second, chemical quality of ground water from the Great Miami River valley is superior to that of water from the Ohio River in every respect except hardness, so water from the new well field would require less treatment than the existing supply. Third, the proposed well field could serve as an emergency supply if, at one of the many chemical plants along the Ohio River, there were an accidental release of a slug of contaminant which rendered the river water temporarily unusable. Fourth, the uniform temperature of the ground water of about 55°F renders it more desirable—particularly during the summer, when the water temperature in the Ohio River reaches 80°F. Finally, and perhaps most important, the lower pumping head at the proposed well field would reduce distribution costs.

Cincinnati selected for the general location of its proposed well field an area in Ross and Fairfield Townships of Butler County, near a right-angle bend in the Great Miami River (fig. 2), midway between the Hamilton South well field and the well field of the Southwestern Ohio Water Co. The selection of a site outside Hamilton County (in which Cincinnati is located) has cre-

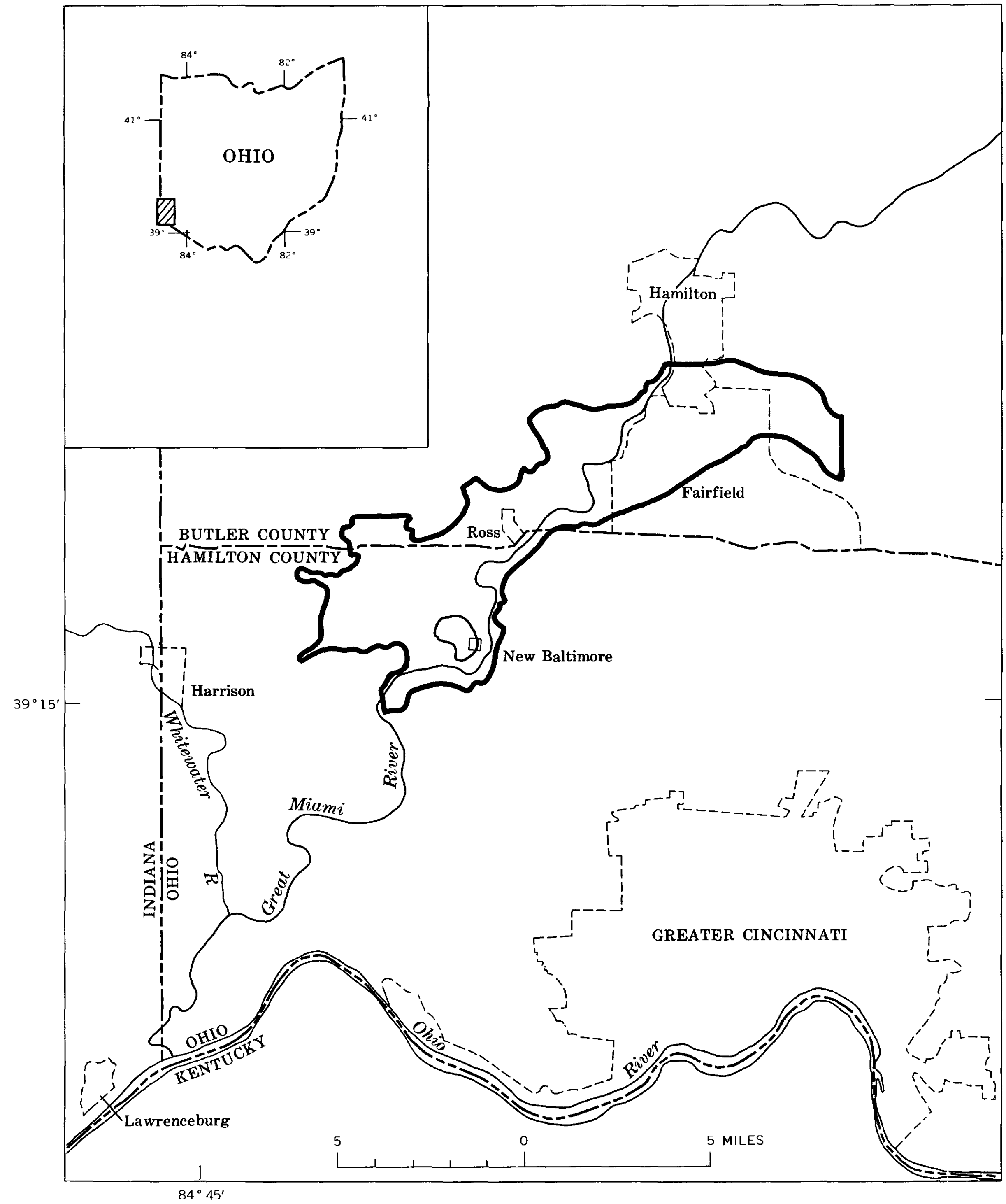

FIGURE 1.—Location of the Fairfield–New Baltimore area, lower Great Miami River valley.

ated a legal and political controversy involving the water rights of Butler County, where the proposed water supply would be located. From the first announcement of Cincinnati's plans, civic leaders of Butler County and the city of Hamilton have expressed doubts that the proposed well field can be operated without seriously endangering Hamilton's water supply; hence, they have opposed its development. Water has always been an important factor in the economy of the Great Miami River valley; much of the area's industry is dependent on a reliable supply of good-quality water. It is thus appropriate that civic leaders should show concern about any proposal to pump a large amount of water where it might adversely affect the economy of the area.

Owing to the controversy created by the proposal, officials of Cincinnati and of Butler County agreed that a thorough investigation of the hydrologic system should be made before any land acquisition or construction is begun on the project. Both parties in the controversy retained consultants to advise them on technical aspects of the problem. The Division of Water of the Ohio Department of Natural Resources and the Miami Conservancy District, which are the U.S. Geological Survey's principal cooperating agencies in Ohio, were requested to assist in the technical investigation and to act as impartial observers, or referees. Personnel of the U.S. Geological Survey gave technical assistance in the investigation.

A program of test drilling was begun, and in June 1962 an aquifer test for the Cincinnati Water Works was made under the supervision of consultants to both parties near the proposed site (fig. 2). Personnel of the Cincinnati Water Works, Hamilton Water Works, Southwestern Ohio Water Co., Miami Conservancy District, Ohio Division of Water, and U.S. Geological Survey assisted with the test. A well was pumped at 3,000 gallons per minute (4.32 mgd, or 6.7 cfs) for 3 days; drawdowns were measured in 15 observation wells, 12 shallow drive points, and 8 drive points in the riverbed. Based on the results of this test the consultants mutually concluded that after 120 days of pumping at 40 mgd, the well interference at the center of the Hamilton South well field caused by the proposed withdrawal would not exceed 5 feet and would not endanger Hamilton's water supply. Late in 1962 Cincinnati acquired land along the south bank of the Great Miami River (fig. 2) for the purpose of construction of a well field and a water-treatment plant.

After completion and analysis of the aquifer test, the Miami Conservancy District and the Ohio Division of Water asked the U.S. Geological Survey to make an analysis of the problem by use of an electric analog model. These cooperating officials were aware that the Survey had pioneered in the application of such analog models to hydrogeologic problems and believed that this technique might be beneficially applied to their problem. For these reasons, in 1962 the U.S. Geological Survey undertook the construction and analysis of an analog model of the Fairfield–New Baltimore area as part of the overall investigation of the ground-water resources in the lower Great Miami River valley being made in cooperation with the two above-mentioned State agencies. The model was constructed in 1963, and the initial analysis was made during 1963–64. Significant results of this initial analysis are included in the present report.

The purpose of this investigation is to determine the probable long-term regional effects, under conditions of low streamflow, of Cincinnati's proposed withdrawals on existing ground-water supplies in the Fairfield–New Baltimore area, with due consideration for the likely expansion of these existing supplies. Direct simulation of the hydrologic system by an electric analog model is ideally suited to the problem. Complex hydrologic boundaries are the dominant factors controlling the movement of ground water in the lower Great Miami River valley. Exact solution to these boundary problems by conventional analytical methods would be so time consuming as to be virtually impossible; however, approximate solutions by analog simulation is relatively quick and simple. If enough simplifying assumptions are made, one can predict with fair accuracy the effects of future pumping at a few selected points by mathematical methods. The analog model can provide a complete regional analysis of the effects of this pumping. The flexibility of the analog model permits analysis of the system under a wide range of conditions. Also, once the model has been built and verified, it is permanently available for making further analyses. Of all the tools available to the hydrologist, the electric analog model is the best suited for solving a problem such as the one in the Fairfield–New Baltimore area.

PREVIOUS INVESTIGATIONS

The first chapter of the present series of reports (Spieker, 1968b) contains a comprehensive summary of previous investigations in the lower Great Miami River valley. The following summation considers only those investigations covering the Fairfield–New

Baltimore area that are pertinent to the analog-model study discussed in the present chapter.

Klaer and Thompson (1948) made a study of the ground-water resources of Hamilton and Butler Counties, which include the Fairfield–New Baltimore area. The fieldwork for their investigation was completed prior to World War II, but publication of the results was delayed by the war until 1948. The investigation by Bernhagen and Schaefer (1947) was made in 1946 to bring the results of the Klaer and Thompson investigation up to date; owing to the delay in publication mentioned above, however, Bernhagen and Schaefer's report (1947) actually appeared in print first. It contains more detailed information on the Fairfield–New Baltimore area, including a water table contour map (pl. 6) of part of the area, based on measurements made in June 1944. Klaer and Kazmann (1943) conducted a quantitative investigation of the eastern part of the area. Their report includes the results of several aquifer tests and detailed logs of wells at the former Federal Works Agency well field, now the Hamilton South well field.

Dove (1961) conducted a quantitative investigation of the hydrology of the Southwestern Ohio Water Co. well field near Ross (referred to in Dove's report as Venice, the town's former name). Included in this report are determinations of the rate of infiltration of water through the bed of the Great Miami River. The Ohio Division of Water (1961) conducted a reconnaissance investigation of the area of the proposed Cincinnati well field and included in its report the logs of several auger holes.

ACKNOWLEDGMENTS

The analysis on which the present report is based is part of a comprehensive program of investigation of the ground-water resources of the lower Great Miami River valley conducted by the U.S. Geological Survey in cooperation with the Miami Conservancy District and the Division of Water of the Ohio Department of Natural Resources. The Conservancy District is represented by Max L. Mitchell, chief engineer, and the Division of Water is represented by C. V. Youngquist, chief. Fieldwork and report preparation by the author were under the supervision of Stanley E. Norris, Water Resources Division [Columbus, Ohio], U.S. Geological Survey, and under the general direction of the Ohio Water Resources Division Council. The analog model was constructed and analyzed by personnel of the Survey's Analog-Model Unit at Phoenix, Ariz., under the supervision of E. P. Patten. The analog model is based on hydrogeologic data collected and interpreted by the author.

The author is grateful to the many representatives of industry and cities who made available the information used in analysis of the analog model. He particularly thanks Harold W. Augenstein, superintendent of the Hamilton Water Works, Charles M. Bolton, superintendent of the Cincinnati Water Works, Robert C. Lewis, general manager of the Southwestern Ohio Water Co., and Leroy Williams, superintendent of the Water Plant at the Feed Materials Production Center of the U.S. Atomic Energy Commission, for their full and wholehearted cooperation throughout the investigation. Paul Kaser, principal hydrologist of the Ohio Division of Water, assisted the author in analyzing the aquifer test conducted for the city of Cincinnati and in compiling water-level records. Robert C. Smith and R. M. Leggette, consultants to Cincinnati and Hamilton, respectively, were most cooperative in making available to the author the data collected in the course of their surveys.

UNITS OF MEASURE

No single consistent system of units of measure is in general use by people concerned with water resources in the United States. The ground-water hydrologist, the municipal-waterworks superintendent, and the industrial plant engineer think in terms of million gallons per day. The surface-water hydrologist thinks in terms of cubic feet per second. The farmer or rancher who irrigates his land thinks in terms of acre-feet per day or acre-feet per year. A person accustomed to using one system finds it most difficult to think in terms of any other. Thus, "million gallons per day" is as foreign to the surface-water hydrologist as "cubic feet per second" is to the ground-water hydrologist. To remedy this dilemma somewhat all rates of discharge in the present report are stated as both million gallons per day and cubic feet per second. Measurements in acre-feet are not in general use in Ohio and are therefore not used in this report. Values of the coefficient of transmissibility (T) are stated in the standard U.S. Geological Survey units of gallons per day per foot.

THE HYDROLOGIC SYSTEM

An analog model, as used in this study, is in effect a working scale model of a particular hydrologic system. Thus, the construction of such a model requires, first, a definition of the various elements which make up the system, and, second, the simulation of these elements by using appropriate scale factors. This section of the report gives a description of the hydrologic system in the Fairfield–New Baltimore area. The following section gives a brief review of the principles of analog simulation and a description of the analog model and scale factors used in the present analysis.

The elements of the hydrologic system which must be simulated are as follows:

1. Extent of the area to be modeled.
2. Transmissibility (T) and storage (S) coefficients.
3. Recharge by induced stream infiltration.
4. Induced recharge from boundaries.
5. Pumping history.
6. Drawdown caused by pumping over a specified period of time; that is, effects of pumping on the water table.

A few of these elements can be defined by direct measurement or observation (for example, boundaries of the model and pumping history), but the definition of most of them requires considerable inference on the part of the hydrologist. The results of an analysis, regardless of how promising the method may be, can be no more reliable than the definition of the system on which the analysis is based. Great care must therefore be taken in defining the hydrologic system to obtain the best possible results from the data available.

EXTENT OF THE MODELED AREA

The area modeled in the present report, referred to in this report as the Fairfield–New Baltimore area, consists of 32 square miles of the Great Miami River valley southwest of Hamilton, Ohio (fig. 2). Underlying the modeled area, and extending beyond it, is a sand-and-gravel aquifer that is bounded by the bedrock walls of the valley. These bedrock walls form the boundary of most of the area, but on the west and north, the boundaries are arbitrary (fig. 2). The western limit is the Dry Fork of the Whitewater River, about 2 miles west of New Baltimore; the northern limit, in Fairfield, is near the south city limit of Hamilton.

THE PHYSICAL SYSTEM

GEOLOGY OF THE AQUIFER

The aquifer which underlies the area of the present investigation consists of the glacial outwash sands and gravels of Pleistocene age that fill the buried valley of the ancestral Ohio River. The geology of these deposits and the Pleistocene drainage history of the area are more fully discussed in other reports in the present series (Spieker, 1968b; J. S. Watkins and A. M. Spieker, report in preparation). In the Fairfield-New Baltimore area the buried valley averages about 2 miles in width, and the valley fill averages 150–250 feet thick. Hydrogeologically, the area can be conveniently divided into three parts (fig. 3).

The major, central part of the area is underlain by 150–200 feet of stratified sand and gravel. This material ranges in texture from medium sand to very coarse gravel and even rubble. Widely scattered lenses of clay and silt are present but are not of sufficient areal extent to cause any perceptible confining effects. In the southwest corner of the area, near New Baltimore, the sand and gravel is only about 80 feet thick, or half its thickness in most of the area. Ground water occurs under unconfined, or water-table, conditions in this greater part of the area.

In about 3 square miles at the east edge of the area the sand-and-gravel aquifer is 100–150 feet thick and is overlain by about 100 feet of clay and silt, probably of lacustrine origin. Here the clay acts as a semiconfining layer to the aquifer.

In the 8 square miles which comprise the westernmost part of the Fairfield–New Baltimore area (fig. 3) the aquifer is about 200 feet thick and is capped with a complex layer of till and lacustrine silts and clays. This clay complex is part of the Hartwell Moraine, which marks approximately the farthest extent of the Wisconsin ice sheet. The main water table is below the base of this layer, so no confinement exists. This westernmost part of the area was the main drainage channel prior to the Wisconsin Glaciation, which blocked the original channel and diverted the Great Miami River to its present course through New Baltimore.

Figure 4 is a typical geologic section through the area, showing the sand and gravel of the main, central part of the area and the sand and gravel capped by clay in the western part. The bedrock floor of the buried valley is characteristically flat, and the walls are steep.

TRANSMISSIBILITY AND STORAGE COEFFICIENTS

The coefficients of transmissibility (T) and storage (S) are the basic parameters used to define the hydrogeologic properties of the aquifer which are simulated by the analog model. In order to approach perfect simulation of the aquifer, these parameters would have to be known at every point. This is obviously impossible. Therefore, the hydrologist must use the data available and interpolate these figures through the remainder of the model on the basis of his knowledge of the geology.

Despite the abundance of other hydrogeologic data on the Fairfield–New Baltimore area, relatively few reliable determinations of the coefficient of transmissibility, and none of the coefficient of storage, have been made. Results of four aquifer tests, whose sites are shown in figure 3, were made available to the author. Test 1, conducted by Klaer and Kazmann (1943, p. 40) on well F–11 of the former Federal Works Agency well field, now the Hamilton south well field, yielded a value of the coefficient of transmissibility of 450,000 gpd per ft. (gallons per day per foot). Test 2 was conducted in

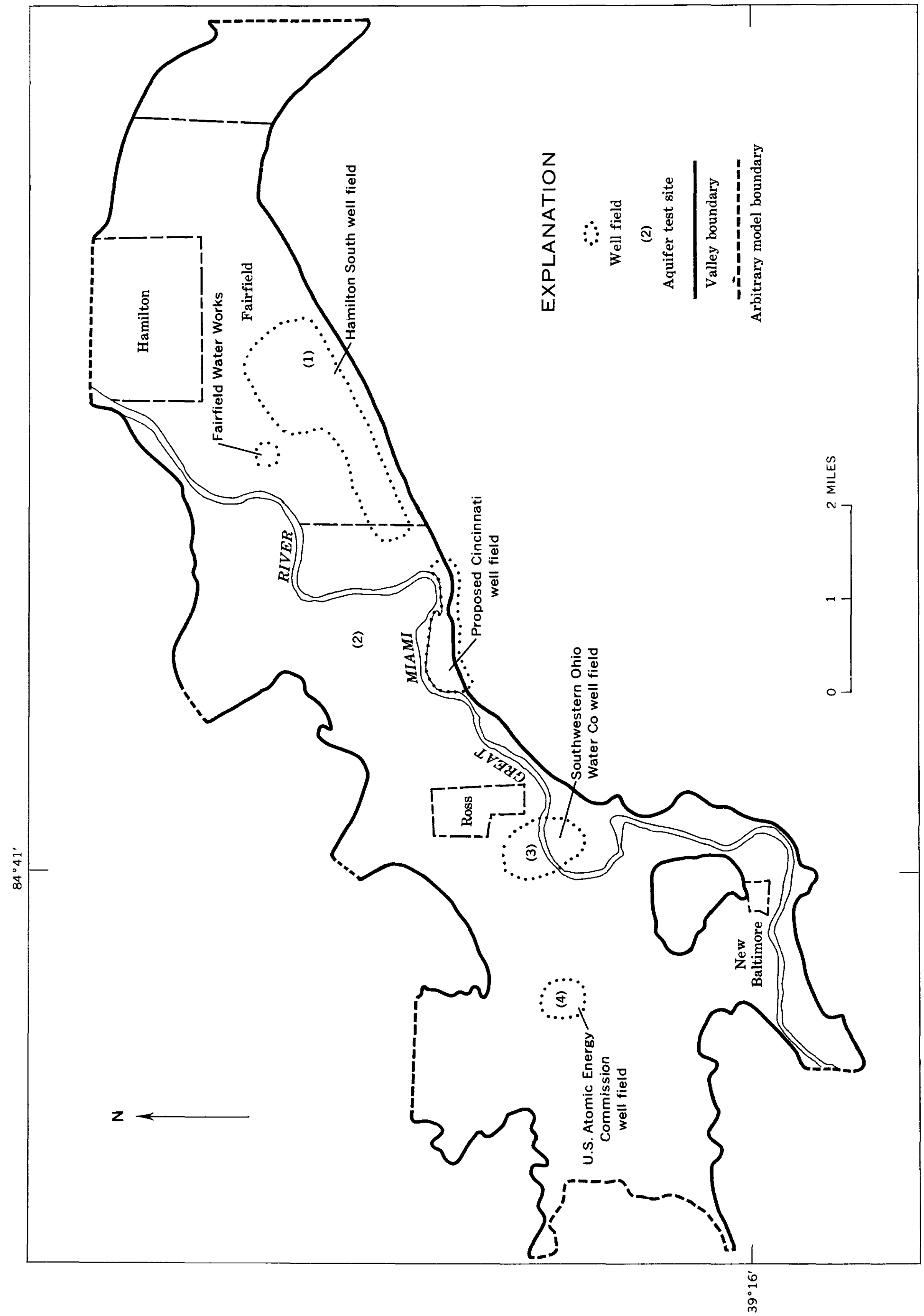

FIGURE 2.—Location of existing well fields and of the proposed Cincinnati well field, Fairfield–New Baltimore area. Arbitrary limits of the modeled area, beyond which the aquifer extends, are indicated by dashed lines.

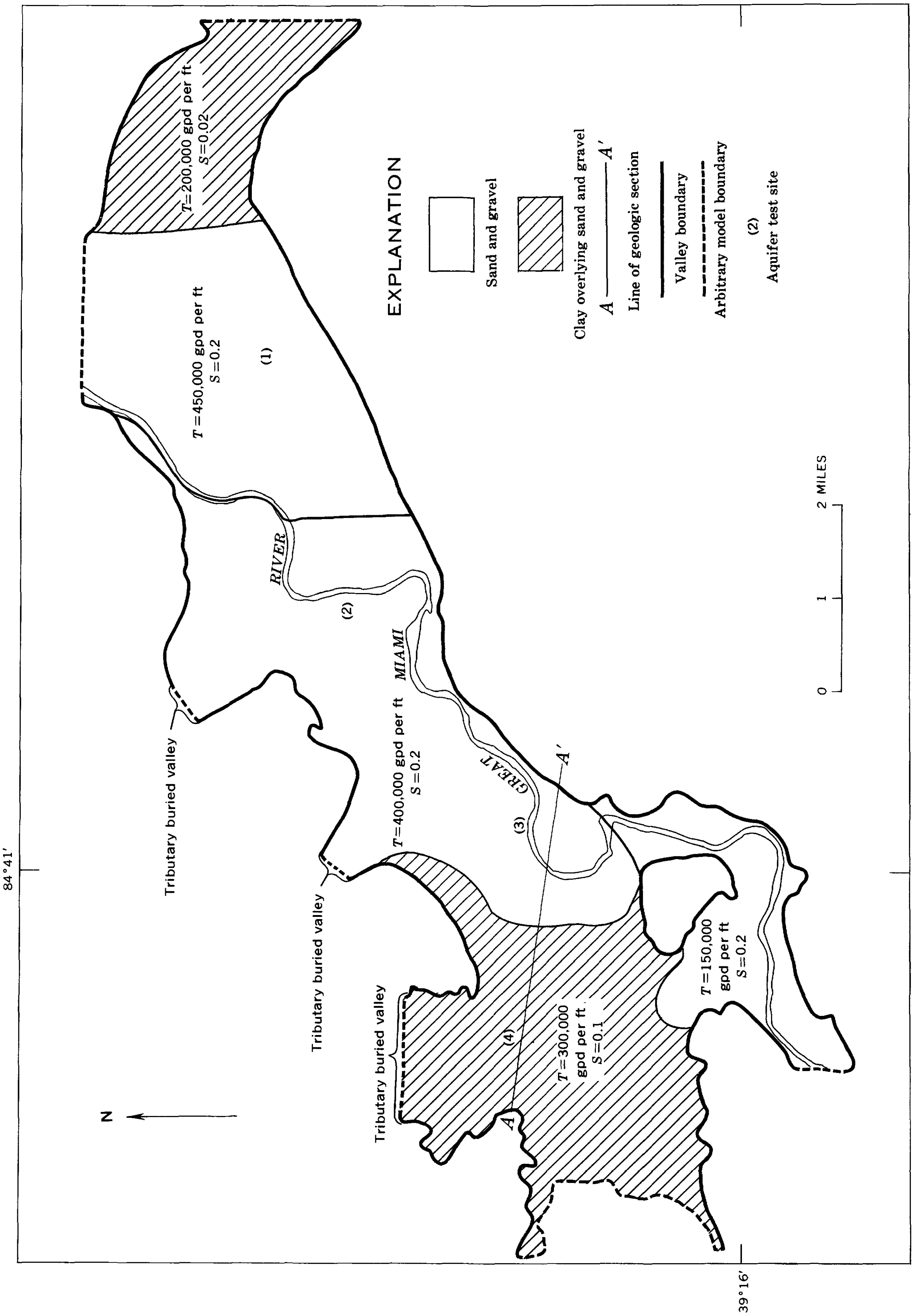

FIGURE 3.—Generalized geology and coefficients of transmissibility (*T*) and storage (*S*) of the Fairfield–New Baltimore area.

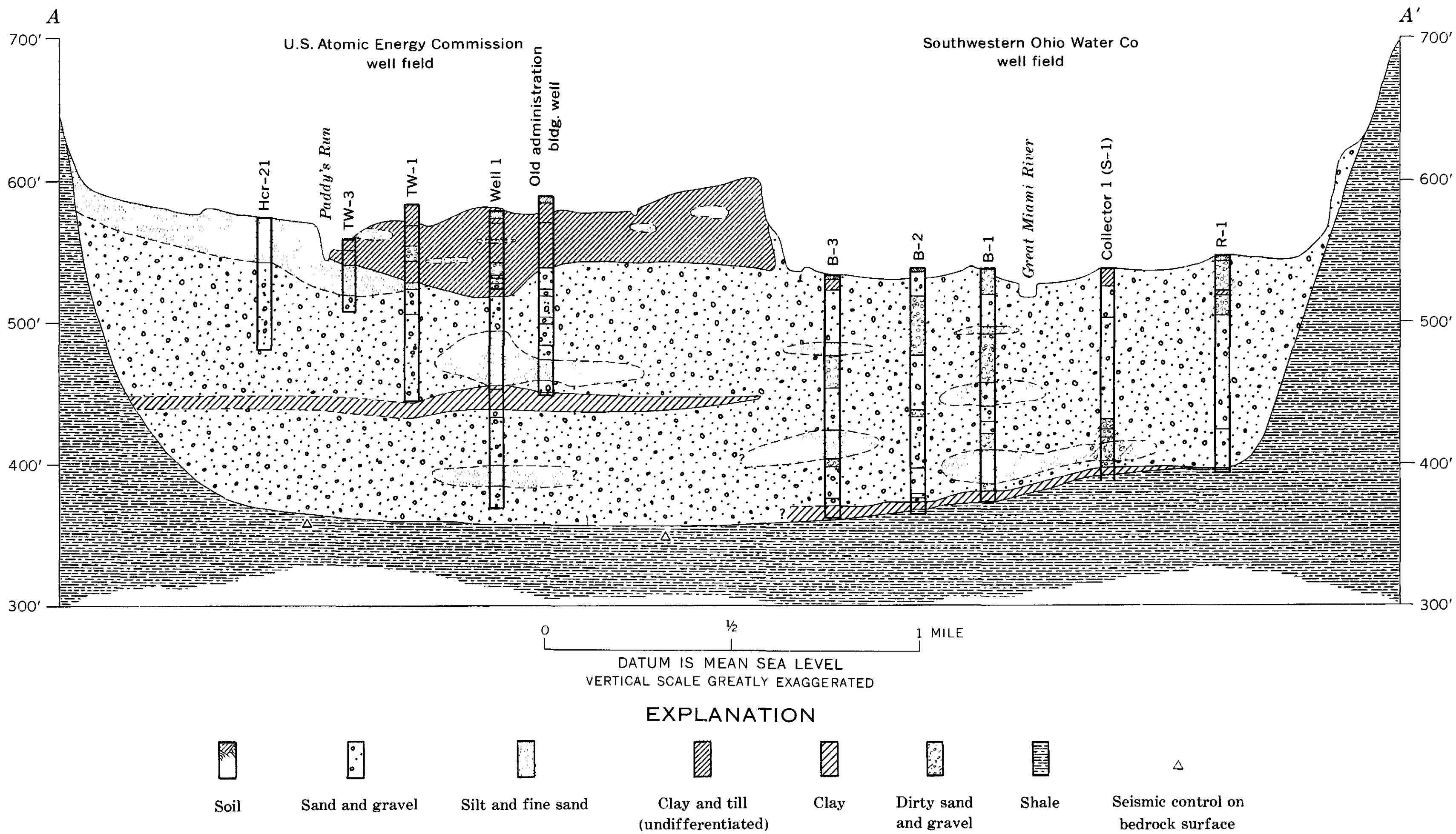

FIGURE 4.—Geologic section of the Southwestern Ohio Water Co. and the U.S. Atomic Energy Commission well fields.

1962 under the direction of Robert C. Smith, consulting ground-water hydrologist, for the city of Cincinnati. Based on the present author's interpretation of the data (Smith, R. C., written commun. to the city of Cincinnati, 1962), the coefficient of transmissibility resulting from this test is about 400,000 gpd per ft. Test 3 was conducted for the Southwestern Ohio Water Co. near the site of their collector well 2 (designated S–2 in the present report). On the basis of data from this test, Dove (1961, p. 47) calculated the transmissibility to be 370,000 gpd per ft. As the saturated thickness of the aquifer at this site is only 125 feet, compared with a typical thickness of 150–175 feet for the area as a whole, Dove's calculated transmissibility is compatible with Smith's determination. Test 4 was conducted and analyzed by A. M. Spieker and S. E. Norris (unpub. data, 1962) at the Feed Materials Production Center of the Atomic Energy Commission near Fernald. The coefficient of transmissibility for the full saturated thickness of the valley-fill deposits, based on this test, is 300,000 gpd per ft.

On the basis of results of these four aquifer tests, estimates made from the specific capacity of several wells, and the known saturated thickness of the aquifer, the Fairfield–New Baltimore area is divided into five segments, each with a characteristic coefficient of transmissibility, as indicated in figure 3. Note that all the above values of the coefficient of transmissibility suggest that the aquifer is capable of yielding large quantities of water to wells.

No reliable determinations of the coefficient of storage have been made in the Fairfield–New Baltimore area, so the value of this coefficient must be estimated. For the bulk of the area, where the ground water occurs under unconfined conditions, the coefficient of storage is estimated to be 0.2—a typical value for an unconfined aquifier. In the eastern part of the area, where the aquifer is semiconfined, the coefficient of storage is estimated to be 0.02. In the western part of the area it is estimated to be 0.1, but here, although the ground water is largely unconfined, a thin layer of clay (fig. 4) locally separates the aquifer into two parts. This separation is considered to reduce the coefficient of storage to slightly less than the normal value of 0.2 associated with unconfined conditions.

HYDROLOGIC BOUNDARIES

The valley-train aquifer in the Fairfield-New Baltimore area is bounded by the nearly vertical bedrock walls of the buried valley, except at its arbitrary limits, as indicated in figure 2. Bedrock in the area consists of shales with thin interbedded limestones of the Cincinnatian Series of Late Ordovician age. The permeability of this bedrock is so low compared with that of the valley fill that the valley walls would at first seem to form a truly impermeable boundary. A medium of seemingly negligible permeability can, however, over a large area, contribute a significant amount of water to the system. For this reason, leakage from the bedrock valley walls must be considered as a source of recharge.

A 15-mile reach of the Great Miami River traverses the Fairfield–New Baltimore area (fig. 3). The river acts as a recharging boundary to the sand-and-gravel aquifer where drawdown is sufficient to reverse the natural hydraulic gradient and thus cause recharge by induced infiltration.

THE HYDROLOGIC CYCLE

NATURAL STATE

The concept of the hydrologic cycle is used by those concerned with water resources to illustrate the various states in which water naturally occurs. Moisture is released from the atmosphere as precipitation. Some of the precipitation which reaches the ground is evaporated or is transpired by vegetation; some of it runs off overland, through streams to the ocean; the remainder infiltrates underground reservoirs, such as the sand-and-gravel aquifer in the Fairfield–New Baltimore area. The sand-and-gravel aquifer can be regarded as a temporary storage reservoir, for while it is being recharged by precipitation, it is discharging water as effluent seepage into the Great Miami River.

Precipitation at Hamilton averages 38.81 inches per year (U.S. Weather Bur. records, based on the period 1931–60), a rainfall rate characteristic for Ohio. The normal distribution of this rainfall (L. T. Pierce, U.S. Weather Bur. State Climatologist, oral commun., 1963) is, under average conditions, 25 inches evapotranspiration, 8 inches runoff, and 6 inches ground-water recharge. Ground-water recharge in the Fairfield–New Baltimore area, however, is probably much higher, as the permeability of the gravelly soil in this area is much higher than average. Furthermore, the water table in much of the area is more than 30 feet below the land surface. For this reason, the evapotranspiration of ground water is minimized. It has been estimated (R. C. Smith, written commun. to the Cincinnati Water Works Dept., 1962) that as much as 21 inches per year of the total precipitation recharges the aquifer in the Fairfield–New Baltimore area. The present author estimates, on the basis of a simple calculation involving the average annual rise of the water level in the aquifer, that the rainfall recharge rate is within the range of 6–21 inches annually. The average annual rise of the water level in observation well Bu–7 for the period of record 1943–62 was 6.35 feet, or 76.2 inches. (See fig. 6.)

Multiplying this rise by the assumed coefficient of storage (S) of 0.2 yields an average annual recharge to the aquifer of 15.2 inches.

The sustained flow of the Great Miami River in the Fairfield–New Baltimore area is high. The discharge equaled or exceeded 90 percent of the time, based on the adjusted period 1921–45, is 490 cfs (316 mgd). This figure is regarded by some hydrologists as a good index of a stream's sustained dry-weather flow (Cross and Hedges, 1959, p. 9). The mean discharge at this station is 3,323 cfs, or 2,147 mgd, and the minimum recorded discharge, measured September 26 and 27, 1941, is 155 cfs, or 100 mgd. The high potential rate of recharge to the aquifer by induced stream infiltration, on which the large ground-water supplies in the area are dependent, is a direct result of the Great Miami River's high base flow.

CHANGES IN THE HYDROLOGIC CYCLE CAUSED BY PUMPING

Ground water in those parts of the sand-and-gravel aquifer underlying the valley of the Great Miami River not affected by pumping is recharged by precipitation infiltrating through the soil. Water from the aquifer in turn discharges by effluent seepage into the Great Miami River. Over a long period of time, total inflow equals total outflow, so the system can be said to be in equilibrium. An effluent regimen of this sort is characteristic of humid regions. The hydrologic regimen of much of the Fairfield–New Baltimore area, however, has been changed by pumping of ground water. If the cone of depression caused by pumping is of sufficient areal extent to intersect a stream and thus alter the natural gradient, water can be induced to flow from the stream into the aquifer. Determination of the rate of recharge to the aquifer by induced stream infiltration is a critical factor in predicting the capacity of the hydrologic system to sustain large withdrawals of ground water.

Similarly, pumping increases the hydraulic gradient at the bedrock valley walls and thus induces additional flow of water from the bedrock to the sand-and-gravel aquifer.

Inasmuch as the water table is 30 feet or more below the land surface in nearly all the area, recharge by precipitation is not changed by pumping—that is, pumping cannot induce additional recharge from precipitation into the ground.

RECHARGE BY INDUCED STREAM INFILTRATION

Recharge to the aquifer by induced stream infiltration is a highly variable quantity. The principal factors governing such recharge are width and depth of the river, velocity of the streamflow, permeability of the streambed, viscosity of the water (dependent primarily on temperature), and drawdown beneath the streambed. All these factors may vary widely over a period of several months or years, so that the determination of the infiltration rate on one day under a given set of conditions may be completely invalid on another day and under another set of conditions. For the purpose of the present analysis, the critical factor is the stream infiltration rate under conditions of low streamflow. Two determinations of the infiltration rate at low flow have been made in the Fairfield–New Baltimore area with fairly consistent results.

Dove (1961, p. 62–66) calculated the infiltration rate at the Southwestern Ohio Water Co. well field near Ross by a flow-net analysis based on measurements made on August 31, 1956. Two horizontal collectors (S–1 and S–2) were being pumped at a combined rate of 16.9 mgd (26.1 cfs). Discharge of the Great Miami River at Hamilton was 587 cfs (379 mgd) on that date. The average infiltration rate was computed (Dove, 1961, p. 64) to be 240,000 gpd per acre of streambed (0.37 cfs per acre). Maximum infiltration rate, however, was considerably higher. Based on a rate of about 115,000 gpd per acre (0.18 cfs per acre) per foot of head loss, the infiltration rate where the maximum of 6.37 feet of head loss was measured was 735,000 gpd per acre (1.1 cfs per acre).

During the pumping test conducted for Cincinnati near the site of the proposed well field on June 26–29, 1962, R. C. Smith (written commun. to the city of Cincinnati, 1962) calculated an average infiltration rate of 492,000 gpd per acre (0.76 cfs per acre) for a reach of about 1,800 feet of streambed. The pumping rate of the well was 3,000 gpm (gallons per minute) (4.32 mgd, or 6.7 cfs). Stream discharge at the test site was 619 cfs (400 mgd). Discharge of Great Miami River at Hamilton ranged from 676 to 624 cfs (437 to 403 mgd) during the test.

Both determinations were made during the summer under conditions of low streamflow. During the colder months, the higher viscosity of the river water would reduce the infiltration rate if all other factors were to remain unchanged. A decrease of river temperature of 1°F would cause the infiltration rate to decrease about 1.5 percent. The river temperature reaches a typical low of about 40°F during the winter, compared with an average of 75°–80°F during the summer. At the time of both the determinations cited above, the temperature of the Great Miami River was about 80°F. Thus, the infiltration rate during the winter might be reduced by as much as 60 percent.

The infiltration rate probably is not often reduced by 60 percent from its typical summer level for any extended period of time, however. Prolonged periods of low streamflow most frequently occur during the late summer and early autumn months—the time at which the river temperature is generally highest. The author believes that the generally higher streamflow prevailing during the winter is sufficient to compensate for the river water's higher viscosity, which has tendency to reduce the infiltration rate. Much more study will be required before the infiltration rate at all times can be predicted with any degree of accuracy; the two determinations cited above, however, form a basis adequate for the present analysis, which is primarily concerned with low streamflow. The infiltration rate of the Great Miami River in the modeled area under conditions of low streamflow can be expected to be in the general range of 240,000 to 500,000 gpd per acre; recharge rates within this range were therefore simulated in the model study.

INDUCED RECHARGE FROM BOUNDARIES

The perimeter of the modeled area is 220,000 lineal feet, of which 180,000 feet is along the bedrock valley walls. The permeability of the shale and limestone which form these walls is low, though just how low has never been reliably determined. Many wells drilled into the shale have failed to yield even 5 gpm, considered adequate for a domestic supply.

Two estimates of the rate of leakage from the bedrock valley walls in terrain similar to the modeled area have been made. Walton and Scudder (1960, p. 34) estimated that in the Fairborn area, northeast of Dayton, 30 gpd per lineal foot of wall leaks from the bedrock walls into the valley-train aquifer. Dove (1961, p. 62) estimated that near the Southwestern Ohio Water Co. well field in the area presently being studied the rate of leakage from the bedrock valley walls is 38 gpd per lineal foot of wall. These rates imply a low permeability, perhaps on the order of 1–5 gpd per sq ft. Although such an apparently small amount of leakage may appear insignificant, if multiplied by the total area of the bedrock valley walls, it assumes significant proportions. At the leakage rate of 38 gpd per lineal foot of wall, 6.8 mgd (10.5 cfs) would enter the sand-and-gravel aquifer from the bedrock.

If the hydraulic gradient at the valley walls is steepened by spreading of the cone of depression, then the flow of water from the bedrock into the gravel aquifer is correspondingly increased. Such induced leakage is a major factor considered in the present analysis.

WATER-TABLE FLUCTUATIONS: A GRAPHIC RECORD OF THE HYDROLOGIC CYCLE

The next step in the simulation of the hydrologic system, now that the aquifer characteristics and the conditions which govern recharge have been considered, is to analyze the history of pumping in the area and the effect of pumping on the water table. The procedure will be, first, to examine the condition of the water table late in 1962 (the end of the period of record on which this analysis is based) and, then, to extrapolate back into the past and attempt to determine how and why this condition came about.

THE WATER TABLE IN NOVEMBER 1962

Figure 5 shows the configuration of the water table in the Fairfield–New Baltimore area late in November 1962. The pumping rates of all wells are given along the margin of the map. These pumping rates are fairly typical of any given day. Discharge of Great Miami River at Hamilton on November 27, 1962, was 1,100 cfs (712 mgd). The map shows a hydraulic gradient which trends toward the southwest, modified by cones of depression around the principal pumping centers.

PUMPING HISTORY

Pumping of large quantities of ground water began in the Fairfield–New Baltimore area in 1943, when the Federal Works Agency installed 11 wells in Fairfield Township of Butler County to supply the Wright Aeronautical Corp. plant at Lockland, in Mill Creek valley (Bernhagen and Schaefer, 1947, p. 19–23). This well field was pumped from 1943 to September 1945, at an average rate of about 7.5 mgd (11.6 cfs). The well field was later purchased by the city of Hamilton.

From 1945 to 1952 there was no significant pumping in the mapped area. In 1952 the Southwestern Ohio Water Co., a jointly controlled corporation whose sole purpose is to supply water to 13 industries in Mill Creek valley, installed a large-diameter radial collector, designated S–1 in this report. The collector about 1½ miles southwest of Ross is inside a horseshoe-shaped bend of the Great Miami River. (See fig. 2.) This collector was pumped at an average rate of 10 mgd (15.5 cfs) from 1952 to 1955. In 1955 a second collector (S–2 in the present report) was installed. The combined pumpage of the two collectors from 1955 through 1962 averaged 13.8 mgd (21.3 cfs).

In 1956 the city of Hamilton constructed a new water-treatment plant and began pumping from the former FWA well field in Fairfield Township, practically replacing its existing well field located north of Hamilton. The North well field, as it is now called, is still maintained for emergency use. The South well field, as the former FWA installation is called, was pumped at an average of 7.5 mgd (11.6 cfs) from 1956 through 1962. This pumpage was from wells F–8, F–10, F–11,

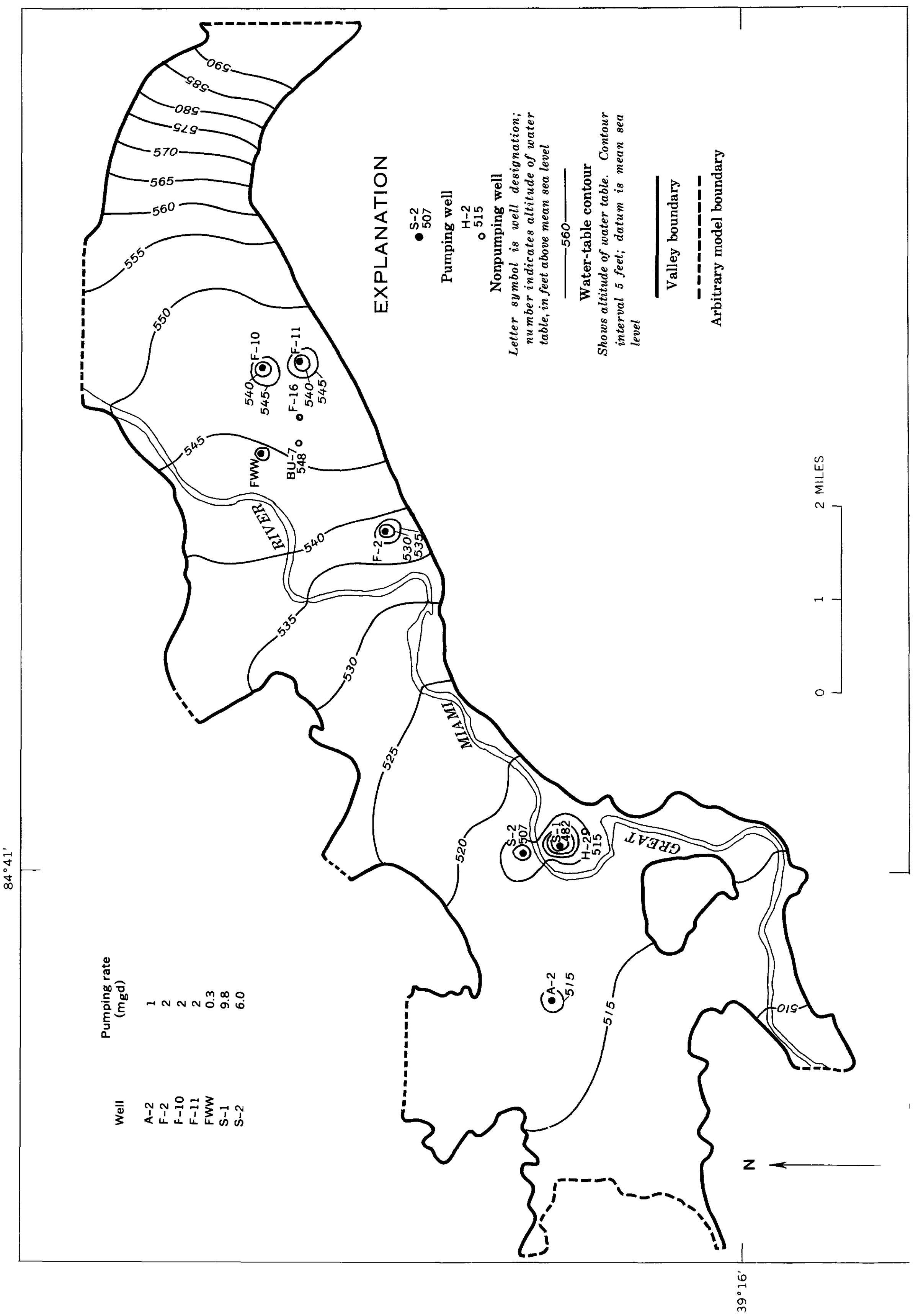

FIGURE 5.—Contours showing altitude of the water table on November 27, 1962, in the report area.

and F–16. Late in 1962 well F–2 was placed in operation in rotation with the four other wells; all remaining wells in the South well field remain inactive.

The Hamilton and Southwestern Ohio Water Co. well fields are the only two large ground-water supplies in the Fairfield–New Baltimore area. Two smaller supplies exist. The Feed Materials Production Center of the U.S. Atomic Energy Commission near Fernald has been pumping an average of 1 mgd (1.55 cfs) from three wells since 1952, and the Fairfield Water Works has been pumping 0.5 mgd (0.77 cfs) from two wells since 1956.

LONG-TERM WATER LEVEL TRENDS

The systematic collection and compilation of water-level records in the Fairfield–New Baltimore area was, unfortunately, not begun until after pumping had started. Thus, there is no sure way to compare the area's present hydrologic regimen with the regimen before pumping started. Figure 6 shows the hydrographs of observation wells Bu–7 and H–2, both in the study area. The average annual cyclic fluctuation of water levels in these wells is from 7 to 10 feet. The effects of pumping are difficult to detect from the hydrographs, for the only period of record in which there was no significant pumping is 1945–52 for well Bu–7. Bu–7 is near the Hamilton South well field, and the slight lowering trend (fig. 6) (about 4 ft.) detectable in the well's water level is a result of pumping at the Hamilton field since 1956. However, the annual fluctuation is generally so great as to completely mask any long-term trends which can be attributed to pumping.

NATURAL AND ARTIFICIAL COMPONENTS OF THE WATER TABLE

Analysis of the water table can be simplified by resolving this surface into two components. The first component represents the surface as it was prior to any alterations in its configuration caused by pumping. The second component represents drawdown (changes in the configuration of the surface) caused by pumping. The following analysis is based on conditions of low streamflow.

THE WATER TABLE UNDER NATURAL CONDITIONS

Figure 7 shows altitudes of the water table assumed to have prevailed in the Fairfield–New Baltimore area prior to the beginning of pumping. The contour map is based on present water-level measurements, river-stage altitudes, and the water-level trends indicated by the two hydrographs shown in figure 6. The hydraulic gradient, which trends generally toward the southwest, is governed largely by the course of the Great Miami River. The gradient is significantly steeper in the eastern part of the area, where the transmissibility is lower, than it is elsewhere in the area.

EFFECTS OF PUMPING ON THE WATER TABLE

The contours in figure 8 represent the average drawdowns caused by pumping in the Fairfield-New Baltimore area under low-flow conditions at the end of the period 1952–62. The pumping history of the Federal Works Agency well field from 1943 to 1945 is omitted from the present analysis on the basis of the assumption that recovery in the area was complete before the beginning of the next pumping period in 1952.

Drawdowns in the Fairfield-New Baltimore area (fig. 8) may vary considerably from day to day for three principal reasons. First, the pumping rates of wells are frequently changed owing to varying water demands. Second, the infiltration rate varies according to the several factors discussed previously. Third, in well-field installations which have several wells, the same wells are not pumped all the time. Thus, a drawdown-contour map based on water-level measurements made on a given day might look quite different from a similar map based on measurements made a week later.

For the present analysis, the most meaningful drawdown map is based on average pumping rates for the period 1952–62. The drawdowns shown are those that occur with the Great Miami River at low flow and with the number of wells pumping which would be pumping on a typical day. Thus, figure 8 shows the effect of several years' pumping under average conditions and would never be exactly duplicated by a map based on measurements made on any given day. Figure 9 illustrates the variability of drawdown. It shows drawdown in collector well S–2 of the Southwestern Ohio Water Co. plotted against the pumping rate on that particular day; the graph is based on 11 measurements made in 1962. A wide range of conditions is represented. The drawdown used in constructing figure 8 is the maximum value of 15 feet (considered to represent conditions of low streamflow) for the average pumping rate of 7.2 mgd (11.1 cfs) of S–2.

Drawdown data for other well fields in the area are unfortunately much less complete than those of the Southwestern Ohio Water Co. Drawdown determinations made on pumped wells form the basis of the following tabulation. The estimated drawdown of 4 feet at observation well Bu–7 (fig. 6) makes possible an approximation of the areal extent of the cone of depression around the Hamilton South well field.

The calculated average drawdown of 15 feet at S–2 is considered the most meaningful determination in the

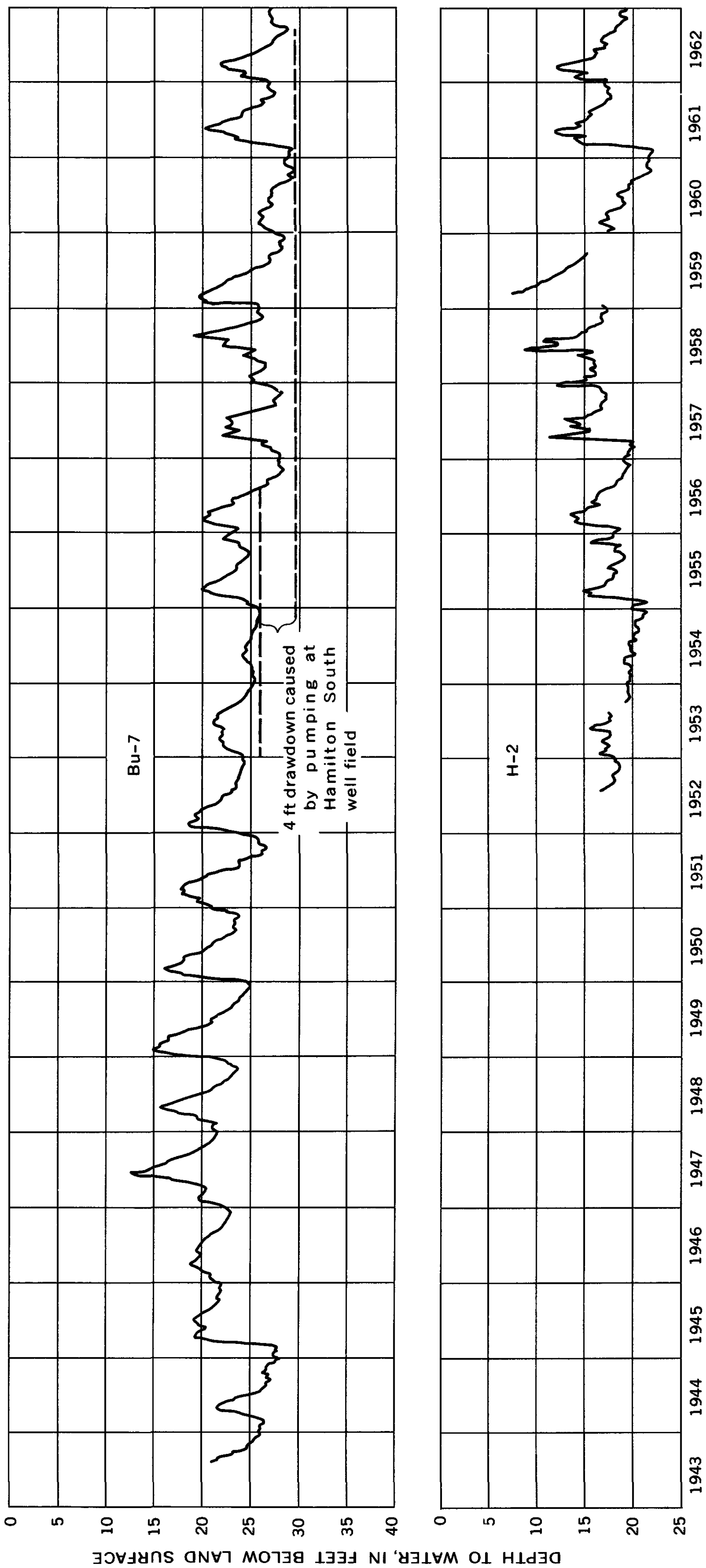

FIGURE 6.—Hydrographs of observation wells Bu-7 and H-2.

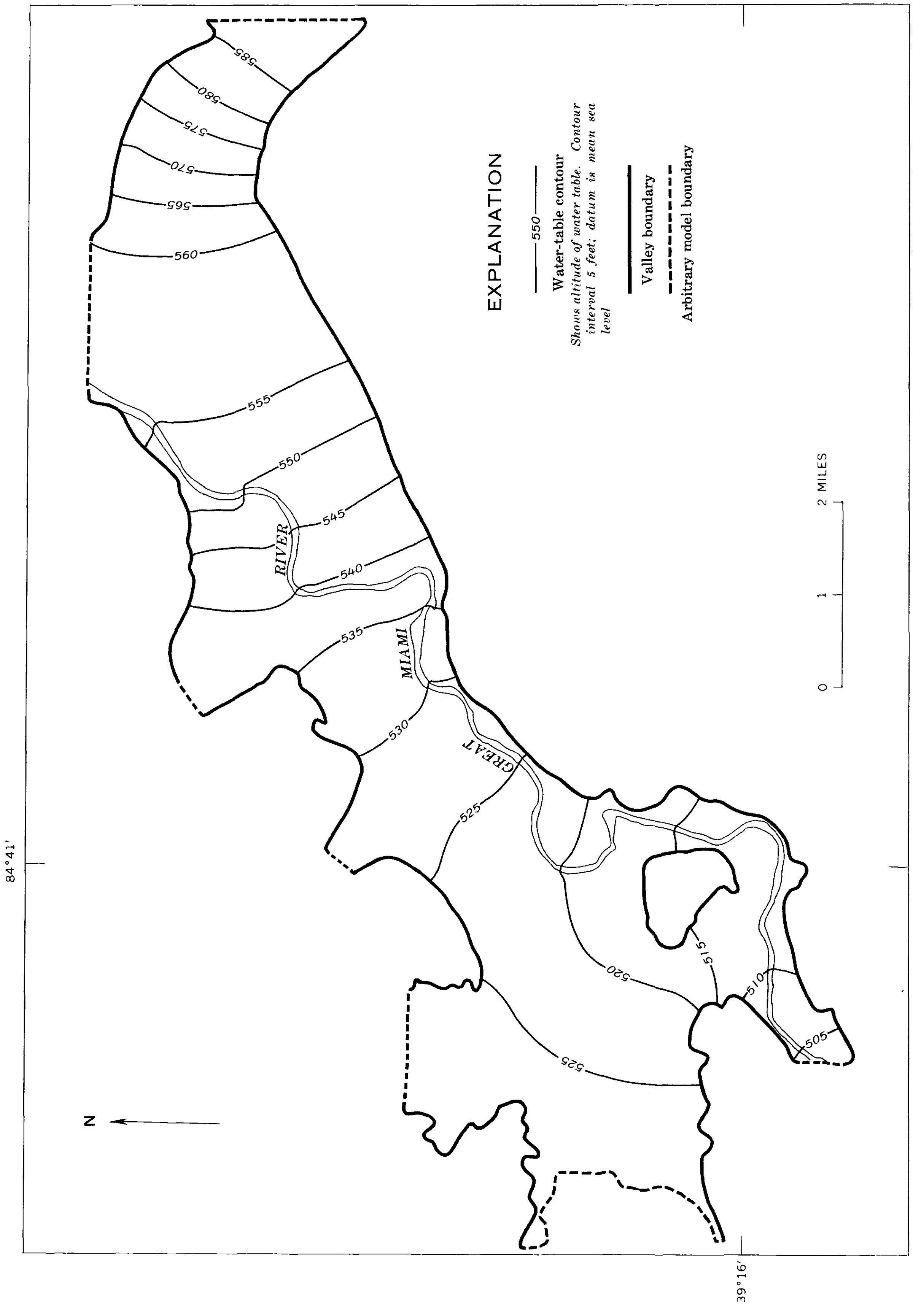

FIGURE 7.—Contours showing altitudes of the water table assumed to have prevailed before pumping was begun in the report area.

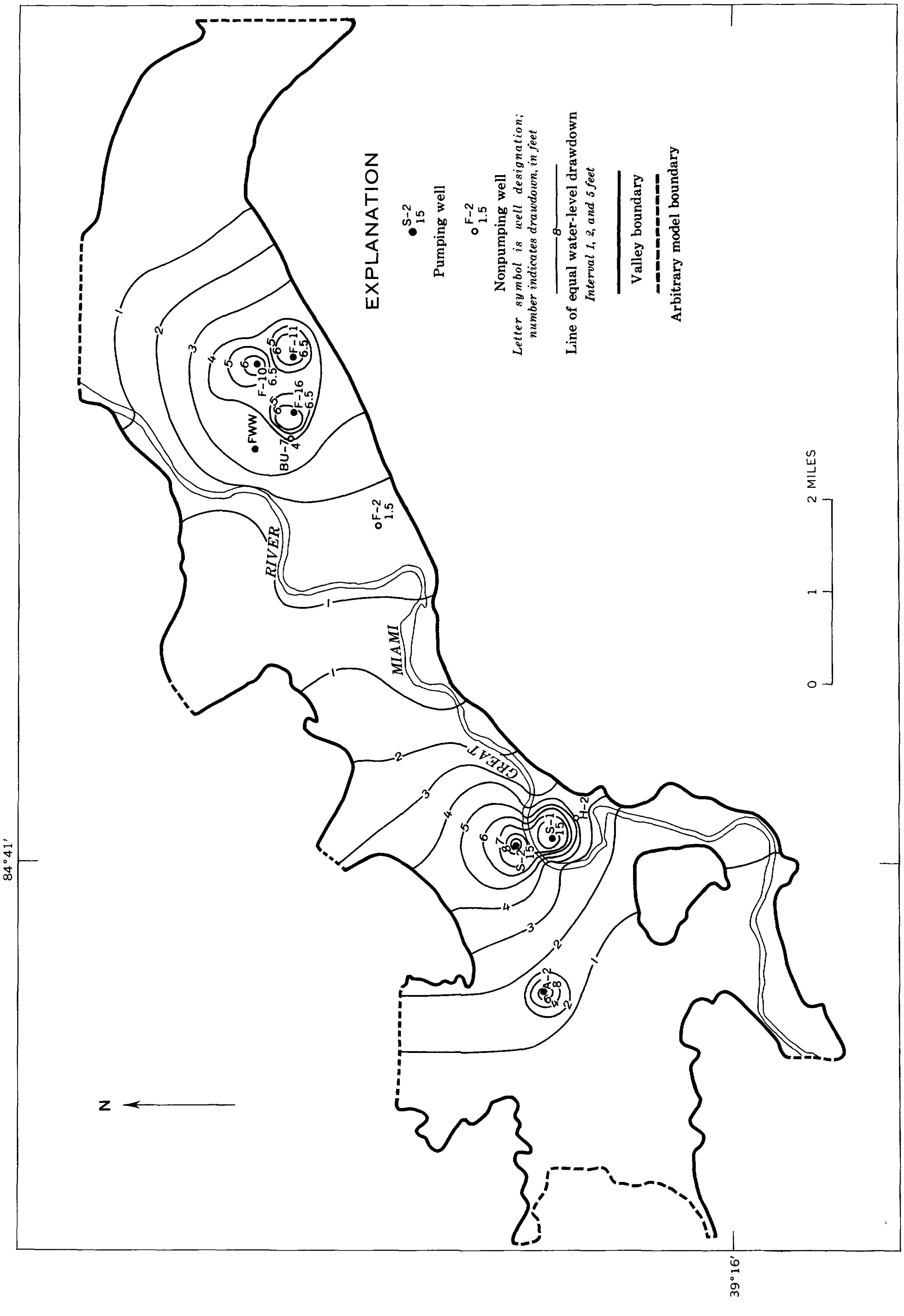

Figure 8.—Average water-level drawdowns caused by pumping, 1952–62.

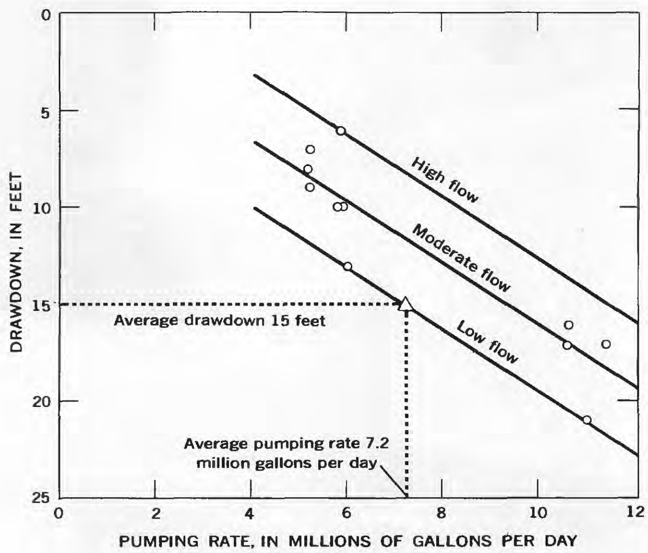

FIGURE 9.—Drawdown at collector S–2 at various rates of pumping and streamflow. Triangle indicates average drawdown at average pumping rate under conditions of low streamflow.

area and is hence used as the primary basis for simulation of the effects of pumping.

Total pumpage of the Hamilton South well field is divided equally among wells F–10, F–11, and F–16 for the present analysis, based on the fact that at any given time only three wells are in operation. Pumpages of the Fairfield Water Works and the U.S. Atomic Energy Commission are each assumed to be concentrated at one well. Following is a tabulation of the average pumping rates and average drawdowns at the end of the calendar year 1962:

Owner and well	Average pumping rate		Average drawdown [1] (ft)
	cfs	mgd	
Southwestern Ohio Water Co.:			
Collector 1 (S–1)	10.25	6.6	15
Collector 2 (S–2)	11.10	7.2	15
Hamilton South Water Works:			
Well F–10	3.87	2.5	6.5
Well F–11	3.87	2.5	6.5
Well F–16	3.87	2.5	6.5
Fairfield Water Works (FWW)	.77	.5	2
U.S. Atomic Energy Commission (A–2)	1.55	1.0	8

[1] The drawdowns represent the water level in the aquifer immediately outside the pumping well and do not include the well loss.

The total average pumpage, 22.8 mgd, was rounded to 22 mgd for convenience of simulation in the analog-model analysis.

On the basis of the foregoing determinations and estimates, figure 8, a map showing average drawdowns at the end of 1962, has been constructed. It indicates major cones of depression around the two principal pumping centers and minor cones around the two smaller centers. The influence of the Great Miami River as a source of recharge is clearly indicated by its effect on the contours.

SIMULATION OF THE HYDROLOGIC SYSTEM BY ELECTRIC ANALOG MODEL

CHARACTERISTICS OF THE MODEL

DESCRIPTION

The model used in the present analysis of the Fairfield–New Baltimore area is a two-dimensional passive-element network of resistors and capacitors constructed to a scale of 1 inch equals 400 feet, with a resistor-junction spacing of 1 inch. It is built on two large Masonite pegboards mounted back to back. The capacitors are connected to the network behind the boards and therefore cannot be seen in the photographs in this report. Various other conductive media can be used to construct electric analog models, but the capacitor-resistor network has advantages over most other media for its components are inexpensive and readily obtainable, and the values of resistance and capacitance can be more closely controlled than with other media.

THEORY

The electric analog model used in the present analysis is a working scale model of the hydrologic system in the Fairfield–New Baltimore area, based on the analogy of the laws governing the flow of water through an aquifer and the flow of electricity through a conductive medium. The theory and practice of analog models of this type have been thoroughly discussed by Skibitzke (1960), Brown (1962), and Walton and Prickett (1963). Excellent nonmathematical treatments of electric analog model analysis have been presented by Stallman (1961) and Robinove (1962). The following statement of the fundamental equations is based on the above-cited sources.

The equations which describe the nonsteady flow of fluid through a porous medium can be expressed as follows:

$$\nabla^2 h = \frac{S}{T}\frac{\partial h}{\partial t},$$

where

∇^2 = the operator $\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)$,

h = the head in the aquifer, expressed as an elevation of water above an arbitrary horizontal reference plane,

S = coefficient of storage,

T = coefficient of transmissibility, and

t = time.

The corresponding equation of electrical current flow through a conducting medium is in the general form of

$$\nabla^2 v = \rho \frac{C}{V_0} \frac{\partial v}{\partial t},$$

where

∇^2 = the operator $\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$,

v = voltage at some point x, y, z,

ρ = specific resistance of the conducting material,

$\frac{C}{V_0}$ = electrical capacitance per unit volume of the conducting material, and

t = time.

The analogy of these two expressions is based on a one-to-one correspondence between the elements of each equation. Thus, an analogy exists between volume rate of flow (million gallons per day) and electrical current (amperes); potential (feet of head) in the hydrologic system and potential (volts) in the model; time (days) in the field and time (seconds) in the model; and length (ft) in the field and length (ft) in the model. By proper scaling of the parameters, it is possible to construct an electrical network whose response to applied stimuli is analogous to the response of a ground-water system to a pumping well.

SCALE FACTORS

In the analysis of the analog model it is therefore necessary to relate each hydrologic quantity as measured in the field to its analogous electrical quantity by an appropriate scale factor. Five basic scale factors are used in the present analysis:

Field measurement	*Equivalent scale factor*
(Volume) 10^{15} gallons (1.34×10^{14} cu ft).	1 coulomb (charge)
(Potential) 10 feet of head	1 volt (potential)
(Volume rate of flow) 10^{10} gallons per day (15,500 cfs).	1 ampere (current)
(Time) 10^5 days	1 second (time)
(Length) 4,800 feet	1 foot (length)

If the model is constructed using these scale factors, the coefficients of transmissibility and storage, which are simulated by resistance (the reciprocal of conductance) and capacitance respectively, are numerically related as shown below:

Transmissibility (gpd per ft)	*Resistance ($K = 10^3$ ohms)*
450,000	2.2*K*
400,000	2.7*K*
300,000	3.3*K*
200,000	5.1*K*
150,000	6.7*K*

Storage	*Capacitance*
0.2	0.0022 μf (μf$=10^{-6}$ farad)
.1	.0012 μf
.02	220 pf (pf$=10^{-12}$ farad)

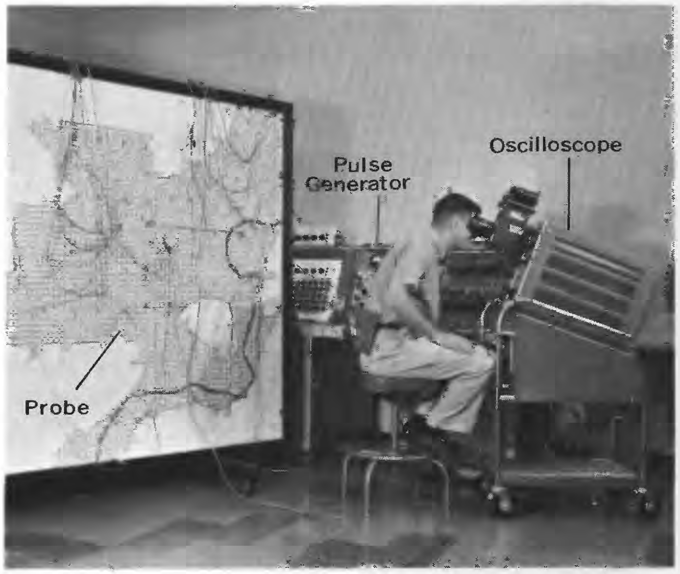

FIGURE 10.—Western part of the study area as set up for analysis on the analog model.

PUMPING AND RECHARGE

PUMPING

Pumping is programed on the analog model by a pulse generator in one or more square-wave pulses of the desired amplitude and duration. The pulse generator is connected to the model network at the sites of pumping wells. The pumping rate is controlled by placing resistors of appropriate value between the generator and the model. The generator is in turn synchronized with an oscilloscope, which can be connected with a probe to any junction on the model. The response of the model to the pumping pulse is thus recorded on the oscilloscope. Figure 10 is a photograph of the model as it is set up for analysis. Figure 11 is a photograph of a typical oscillogram, taken during a run of the analog model, which shows the drawdown resulting from a pumping sequence consisting of three pulses. The oscillogram is analogous to a time-drawdown curve.

RECHARGE BY INDUCED STREAM INFILTRATION

Recharge by induced stream infiltration is simulated by current pulsed into the model net through a bank of 6AL5 dual diodes. A lead from each diode is connected to every second junction along the course of the Great Miami River, and the two junctions are connected by a bus-bar wire (fig. 12). The unit containing the bank of diodes can be programed to deliver to the model any given amount of current, as this amount will vary with the total recharge represented. Therefore, the sum of the currents delivered by each diode at any time cannot excede the limiting current programed on the

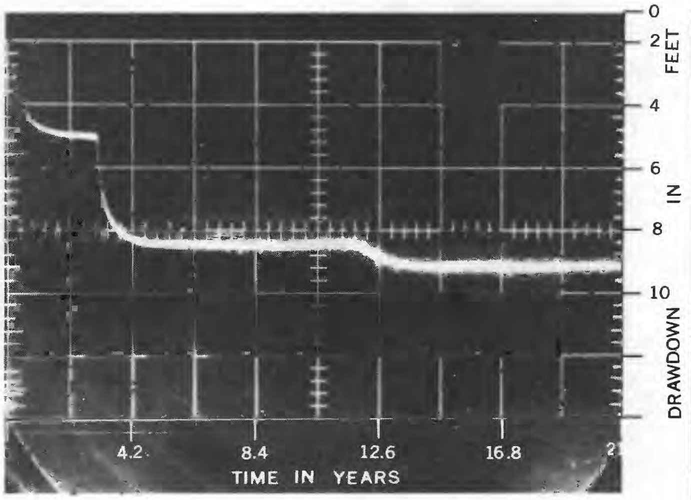

FIGURE 11.—Typical oscillogram taken during a run of the analog model.

unit. A potential drop (drawdown) at any junction connected to a diode lead triggers the diode and causes it to pulse current into the model in proportion to the potential drop, up to the maximum rate for which it is set.

The programed maximum-infiltration rate for the present analysis was determined by duplicating on the model the average, 15-foot drawdown at the collector S–2 (fig. 9) during low streamflow. To achieve this drawdown the rate of recharge from the stream must be programed at 150μa (microamperes) per diode lead. Each diode lead recharges 800 lineal feet of streambed. The average width of the Great Miami River is assumed

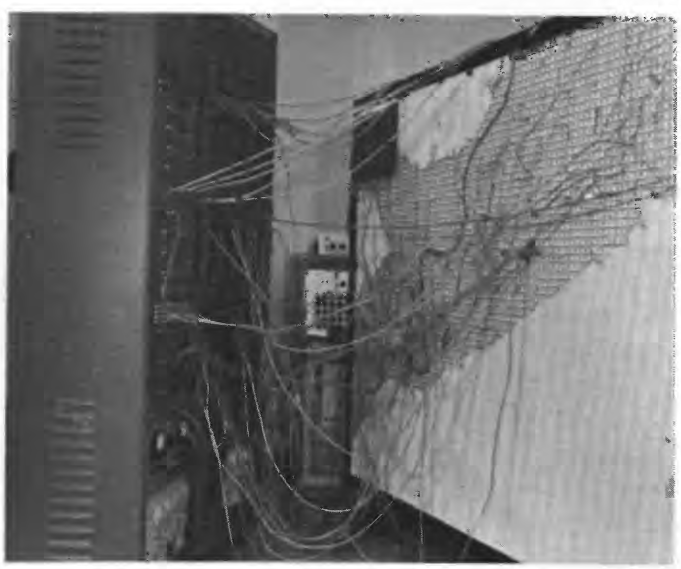

FIGURE 12.—Eastern part of the study area as set up for analysis on the analog model and the diode bank which simulates on the model the effect of ground-water recharge.

to be 250 feet. If using these dimensions and the scale factor of 10^{10} gpd=1 ampere is used, this rate is equivalent to 325,000 gpd (0.51 cfs) per acre of streambed. In all runs but 7 and 8 (table 2), the stream recharge rate is limited to this amount, which is in virtual agreement with the previously cited field determinations. In runs 7 and 8 a maximum stream recharge rate of 490,000 gpd (0.76 cfs) per acre is programed. This is the same rate as was calculated by Smith from the Cincinnati pumping test.

INDUCED RECHARGE FROM BOUNDARIES

The boundaries of the modeled area can be considered in two distinct categories: first, the bedrock valley walls, which form the boundary over most of the area, and second, the arbitrary model limits and tributary buried valleys, as indicated in figure 3. The transmissibility of the latter areas approaches that of the aquifer itself and is considerably higher than the transmissibility of the bedrock. Therefore considerably more water can be expected to recharge the aquifer from these tributaries and extensions of the aquifer than from the bedrock.

Recharge from the boundaries is simulated by current pulsed into the model net through several variable resistors, each connected through a bus-bar wire to a segment of the boundary. The resistors are set to the resistance value which permits sufficient current to effect duplication of the regional drawdown distribution in 1962 (fig. 8) to enter the model. This rate is equivalent to an average inflow of 13 gpd per lineal foot along bedrock boundaries and 68 gpd per lineal foot along arbitrary model limits and tributary buried valleys. The rate of induced, or increased, recharge from bedrock of 13 gpd per lineal foot is believed to be consistent with the previously cited estimates (p. C11) of Walton and Scudder and of Dove, which range from 30 to 38 gpd per lineal foot, as the 13 gpd per lineal foot represents the change in the leakage rate caused by pumping. These resistance rates are held constant through all model runs so that increased drawdown at the boundaries causes increased recharge. Total recharge from the boundaries for each run is shown in table 1.

ASSUMPTIONS MADE IN THE ANALYSIS

Any model, physical or mathematical, of a hydrologic system can, at best, be only a close approximation of the system. The primary reason for the use of electric analog simulation of the system is that this method can give a closer approximation of the system than can most other methods. The electric analog is capable of dealing with a greater number of variables than numerical analysis can consider. Nevertheless, some simplifying assumptions are necessary. The present analysis is based on the following five assumptions:

1. All flow within the aquifer is two dimensional (no vertical flow component); recharge from the boundaries is one dimensional.
2. The aquifer is isotropic and is homogeneous within the boundaries indicated for the various values of the transmissibility and storage coefficients.
3. All wells fully penetrate the aquifer; the stream is modeled as having partial hydraulic connection with the aquifer.
4. The hydrologic system is in equilibrium at the start of pumping.
5. The coefficients of transmissibility and storage do not vary with time.

All these assumptions are partly at variance with actual field conditions, but errors in the analysis caused by violation of the first four assumptions are largely of local extent and will not introduce any serious errors in the regional potential distribution. Only violation of the fifth assumption can produce serious error in the present analysis.

The fifth assumption states that the coefficients of transmissibility and storage do not vary with time—that is, the model makes no allowance for dewatering and the consequent reduction of the transmissibility due to thinning of the aquifer. Nor does the model allow for the possibility that in the eastern part of the area modeled (fig. 3), where semiconfinement exists, drawdown below the base of the confining layer might effect a change to water-table conditions and a resultant increase of the coefficient of storage. The latter possibility does not pertain to the present analysis, for drawdowns in this part of the area do not exceed a few feet, and nowhere do they even approach the base of the confining layer, which is about 100 feet deep.

Dewatering, on the other hand, poses a problem which must be evaluated. The acquifer in most of the Fairfield–New Baltimore area is unconfined. Therefore, drawdowns caused by pumping invariably result in some dewatering of the aquifer and the resultant reduction of aquifer transmissibility. As a matter of practical consequence, however, the error introduced by dewatering probability does not become serious until 20 to 25 percent of the aquifer's saturated thickness has been dewatered. Therefore, the present model can be used to evaluate drawdowns of as much as 35 feet without introducing serious errors into the analysis. If the drawdown indicated by the model is more than 35 feet, then the actual drawdown at that point would be greater than the indicated drawdown. In none of the model runs (table 1) are drawdowns of 35 feet or more predicted.

VERIFICATION OF THE ANALOG MODEL

Now that the elements of the hydrologic system and the techniques used in their simulation have been described, the next step in the analysis is to verify the accuracy of the model by attempting to duplicate on the model the hydrologic conditions shown in figure 8. This is done by simulating the effects of pumping during the period 1952–62 on the model and measuring the model's response to this simulated pumping.

RUN 1: DRAWDOWN CAUSED BY PUMPING, 1952–62

Pumping is programed on the model as two square-wave pulses which correspond to the two periods of pumping described under the heading "Pumping History." The first pulse, which represents the period 1952–56 includes pumping of 10 mgd (15.5 cfs) at collector S–1 of the Southwestern Ohio Water Co. The second pulse, representing 1956–62, includes pumping at both collectors of the Southwestern Ohio Water Co., at three wells of the Hamilton South well field, and at the Fairfield Water Works. Pumping of 1 mgd (1.55 cfs) at the U.S. Atomic Energy Commission plant continues through both pulses. Recharge by induced stream infiltration is programed at a maximum rate of 325,000 gpd (0.51 cfs) per acre of streambed. Actual recharge for this run totals 16.8 mgd from the Great Miami River and 5.2 mgd from the boundaries. Figure 13 shows that the drawdowns resulting from analysis of the analog model are in general agreement with the results interpreted from field observations. Near the Hamilton South well field, however, the model indicates 2–3 feet more drawdown than was observed in the field. This discrepancy may be due to imperfect records or erroneous interpretation of drawdown in the well field rather than to errors in the simulation of the hydrologic system. Nonetheless, the discrepancy is not considered to be serious enough to render the model invalid. The general configurations of the cones of depression as observed from field measurements and as duplicated by the analog model are very similar. A minor exception is that the cone around the Atomic Energy Commission well field (A–2) is overestimated on the map based on field data, but this error is of little consequence to the regional drawdown configuration.

Although the regional drawdown caused by present pumping is not excessive, the cone of depression has a rather flat configuration and has spread throughout nearly all the modeled area. Such flatness of the cone is a characteristic effect of pumping in a highly transmissive aquifer, such as the one presently under consideration.

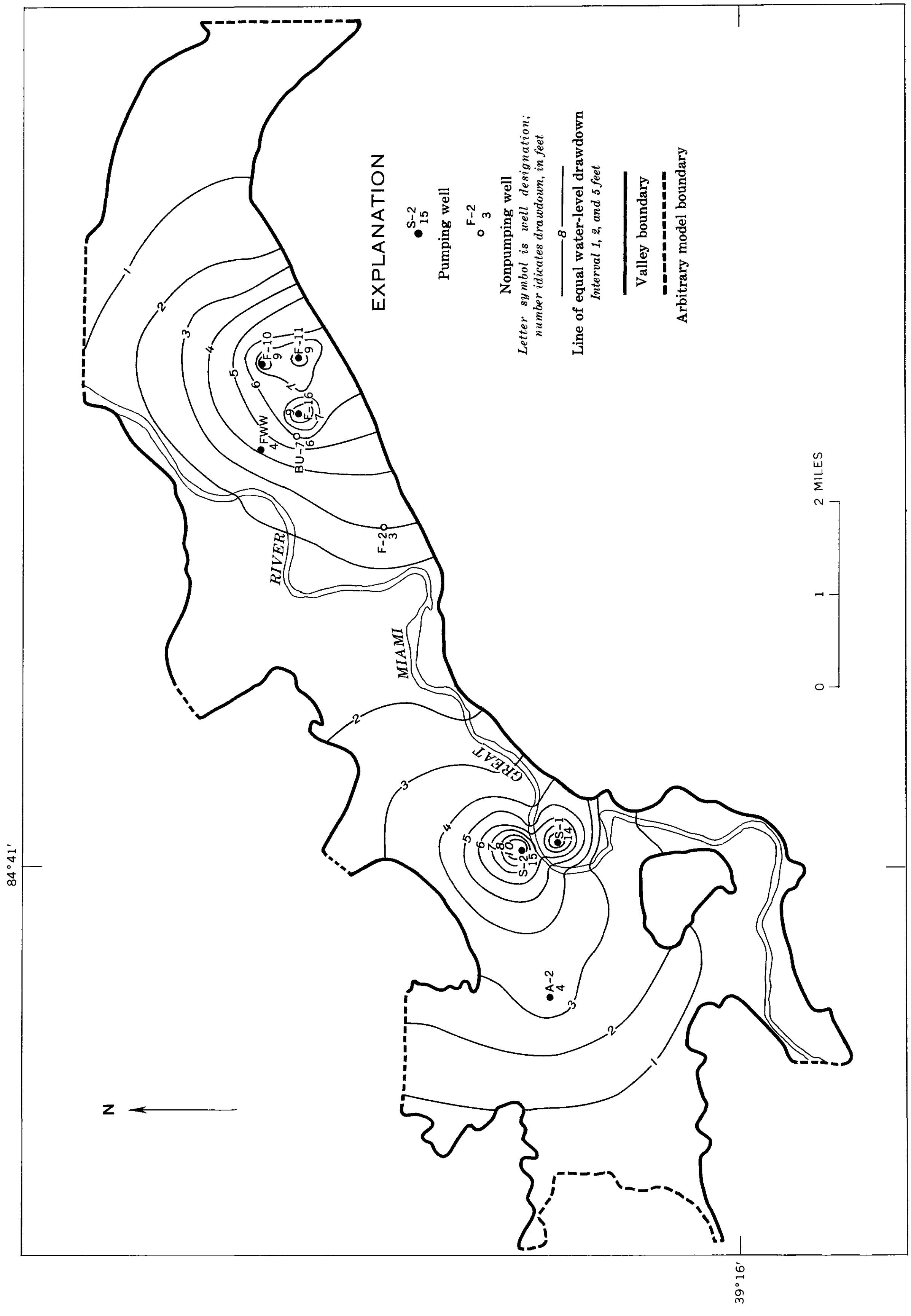

FIGURE 13.—Drawdowns caused by pumping for the period 1952–62, based on analog-model analysis.

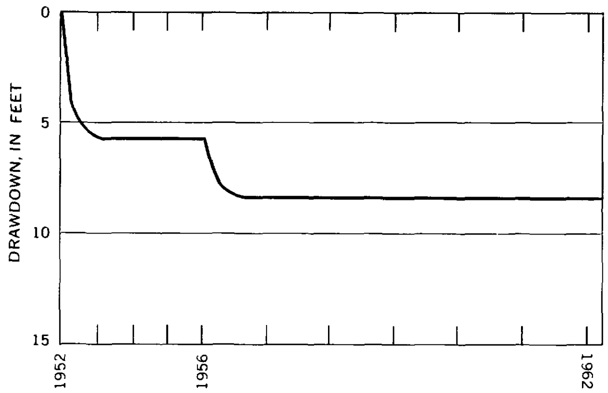

Figure 14.—Time-voltage oscillogram represents a time-drawdown graph for the pumping period 1952–62. Flatness of curve shows equilibrium has been achieved.

Figure 14 shows the trace of a characteristic time-voltage oscillogram taken during run 1 of the model. This trace represents a time-drawdown curve for the pumping period 1952–62. The curve flattens long before the end of the period of pumping, indicating that equilibrium has been achieved and that the cone of depression has ceased spreading.

The match of field drawdowns and model drawdowns is good, but such a match in itself does not constitute complete verification of the model. Total verification would require matching the time-drawdown data observed in the field with that obtained from the model. Unfortunately, in the present analysis the field data are not sufficiently conclusive to permit such a match. A match of the observed drawdown, then, is only an approximation of verification, but it is the best that can be made from the available data. This approximate verification, however, is sufficient to form a basis for use of the model to predict drawdowns as a result of future changes in the pumping regimen, as proposed by the city of Cincinnati.

PREDICTED EFFECT OF FUTURE PUMPING

The purpose of this analysis is to predict the effect on existing well fields in the Fairfield–New Baltimore area of future pumping proposed by the Cincinnati Water Works Department. Nine runs of the analog model were selected for discussion in the present report. The first run verifies the model; the other eight runs predict the effects of future pumping. Table 1 briefly summarizes the results of all nine runs.

The predicted drawdowns resulting from the analog model analysis represent what would actually occur as a result of the modeled conditions described earlier in the report. The model was built and analyzed on the basis of the author's interpretation of basic hydrologic data. Although the author believes that his interpretations are the best which can be made on the basis of data available, these interpretations should by no means be considered as the only ones possible. Therefore the drawdowns given in the following analysis should likewise be regarded as the results of an interpretation rather than as dogma, and they in no way preclude other interpretations.

CONDITIONS GOVERNING THE ANALYSIS

Certain conditions which prevail in all or several of the model's runs are stated here to avoid needless repetition in the discussions of the individual runs. In all runs, future pumping is superimposed on the 1956–62 pulse, which is continued through the pumping period of each run. Cincinnati proposes to pump 40 mgd (62 cfs) during the summer months and 10 mgd (15.5 cfs) during the remainder of the year from the new well field. Although the present plan does not call for pumping at the higher rate for extended periods of time or even continuously, this possibility must be considered. Future growth of the area will undoubtedly increase the demand for water, and the new well field may eventually be forced to operate at its full rated capacity much or all of the time. For this reason the approach followed in the present analysis is, first, in runs 2, 3, 4, and 6, to determine the effect of continuous pumping by Cincinnati at 40 mgd (62 cfs) for a 10-year period and, second, in runs 5 and 7, to determine the extent this drawdown distribution is modified by pumping at 10 mgd (15.5 cfs). Finally, in runs 8 and 9, a longer range view of the hydrologic system is taken with Cincinnati pumping for a 20-year period and all existing well fields pumping at double their present rates for the last 10 years of the period.

Recharge by induced stream infiltration is limited to a maximum rate of 325,000 gpd (0.51 cfs) per acre of streambed in all runs but 6 and 7, in which the recharge is limited to 490,000 gpd (0.76 cfs) per acre. Leakage from the boundaries functions in direct proportion with the drawdown at the boundaries. The actual amounts of recharge obtained from the stream and from the boundaries in each run are given in table 1.

In the following discussions of each run of the analysis and in table 1, the terms "net drawdown" and "interference" are synonymous, referring to that component of the total drawdown at a given location which is the result of pumping at the Cincinnati well field. The drawdown-contour maps used to illustrate this discussion are drawn with contour intervals of 1, 2, and 5 feet, the interval used depending on the steepness of the hydraulic gradient. Some contours are omitted in the immediate vicinity of pumping wells, where an attempt to follow a consistent contour interval would result in clutter. At these places, only the drawdown at the pumping well is indicated on the map. At the proposed Cincinnati well field, drawdowns at the two end wells and the well with the maximum drawdown are indicated.

The drawdowns indicated at pumping wells on the drawdown maps and in table 1 represent only that component of the drawdown due to characteristics of the aquifer. Additional drawdown will result from characteristics of the well itself. At the time the present analysis was made, no means of simulating these pumped-well characteristics had been developed. Since this study was completed, however, Prickett (1967) developed techniques for simulating these characteristics.

Well characteristics whose effects will result in additional drawdown in pumped wells can be classified into three categories: 1) effects of different effective well radius; 2) effects of partial penetration of the pumped well; and 3) effects of well loss due to turbulent flow. Following is an example of the corrections for effective well radius and partial penetration which would apply to a "typical" well in the Fairfield–New Baltimore area. (Well loss is not considered in this example, as it is highly variable, depending on the well's construction and degree of development.) The hypothetical well in this example is in a gravel aquifer with $T=400{,}000$ gpd per ft and a saturated thickness of 150 feet. The well radius is 18 in. (a 3 ft diameter), and the screen length is 50 feet (one-third of the saturated thickness). The pumping rate is 2,000 gpm, or about 2.8 mgd. The drawdown indicated by the model at this pumped-well junction might range from 5 to 10 feet, depending on the recharge rate.

Prickett (1967, p. 39–41) concludes that the effective radius of a pumped well on a typical two-dimensional analog model is 0.208 times the resistor-junction spacing. For the present model, with a junction spacing of 400 feet, the effective radius of this well would be about 83 feet. Thus the drawdown at a pumped-well junction indicated by the model actually represents the drawdown in the aquifer at a point 83 feet from the center of the well. No vertical well in the report area actually has so large a radius, although the effective radii of the two horizontal collectors would be very close to this figure. Prickett (written commun. 1967) has calculated that the actual drawdown in an 18-inch radius well would exceed the drawdown indicated by the model by 4.6 feet. If the analyses of the model were to be rerun, these corrections could be programed by inserting an appropriate resistor into the circuit between the pulse generator and the pumped well junction (Prickett, 1967, p. 41–42).

In addition to this correction for well radius, the correction for partial penetration would indicate 6.1 feet of drawdown (Prickett, written commun., 1967).

TABLE 1.—*Summary of analog-model analysis*

[Run 1 represents verification; runs 2–9, prediction. 1952–62 pumping rates doubled for 1972–82 in runs 8 and 9]

Run	Text figure	Period of pumping	Cincinnati well field			Drawdown (feet)										Maximum potential stream infiltration rate (mgd per acre)	Total pumpage (mgd)	Total recharge (mgd)	
			Pumping rate (mgd)	Period	Well spacing	Center Hamilton well field		Observation well Bu-7		Hamilton well F-2		Center Cincinnati well field		Southwestern Ohio Water Co. S-2				From stream	From boundaries
						Total	Net	Total	Net	Total	Net	Total	Net	Total	Net				
1	13	1952–62	....	1952–62	....	9	......	6	......	3	......	1	......	15	......	0.325	22	16.8	5.2
2	15	1952–72	40	1962–72	400 ft in east-west line	10	1	7	1	8	5	34	33	16	1	.325	62	49.3	12.7
3	16	1952–72	40	1962–72	800 ft along north bank of river	11	2	8	2	10	7	26	25	16	1	.325	62	49.3	12.7
4	17	1952–72	40	1962–72	700 ft along south bank of river	11	2	8	2	12	9	30	29	16	1	.325	62	45.2	16.8
5	18	1952–72	10	1962–72	do	9	0	6	0	4	1	7	6	15	0	.325	32	27.4	4.6
6	19	1952–72	40	1962–72	do	10	1	8	2	8	5	25	24	15	0	.490	62	55.8	6.2
7	20	1952–72	10	1962–72	do	9	0	6	0	4	1	7	6	15	0	.490	32	26.0	6.0
8	21	1952–82	40	1962–82	do	18	0	12	0	13	10	32	30	32	2	.325	84	73.6	10.4
9	22	1952–82	10	1962–82	do	16	0	10	0	6	0	8	6	30	0	.325	54	45.0	9.0

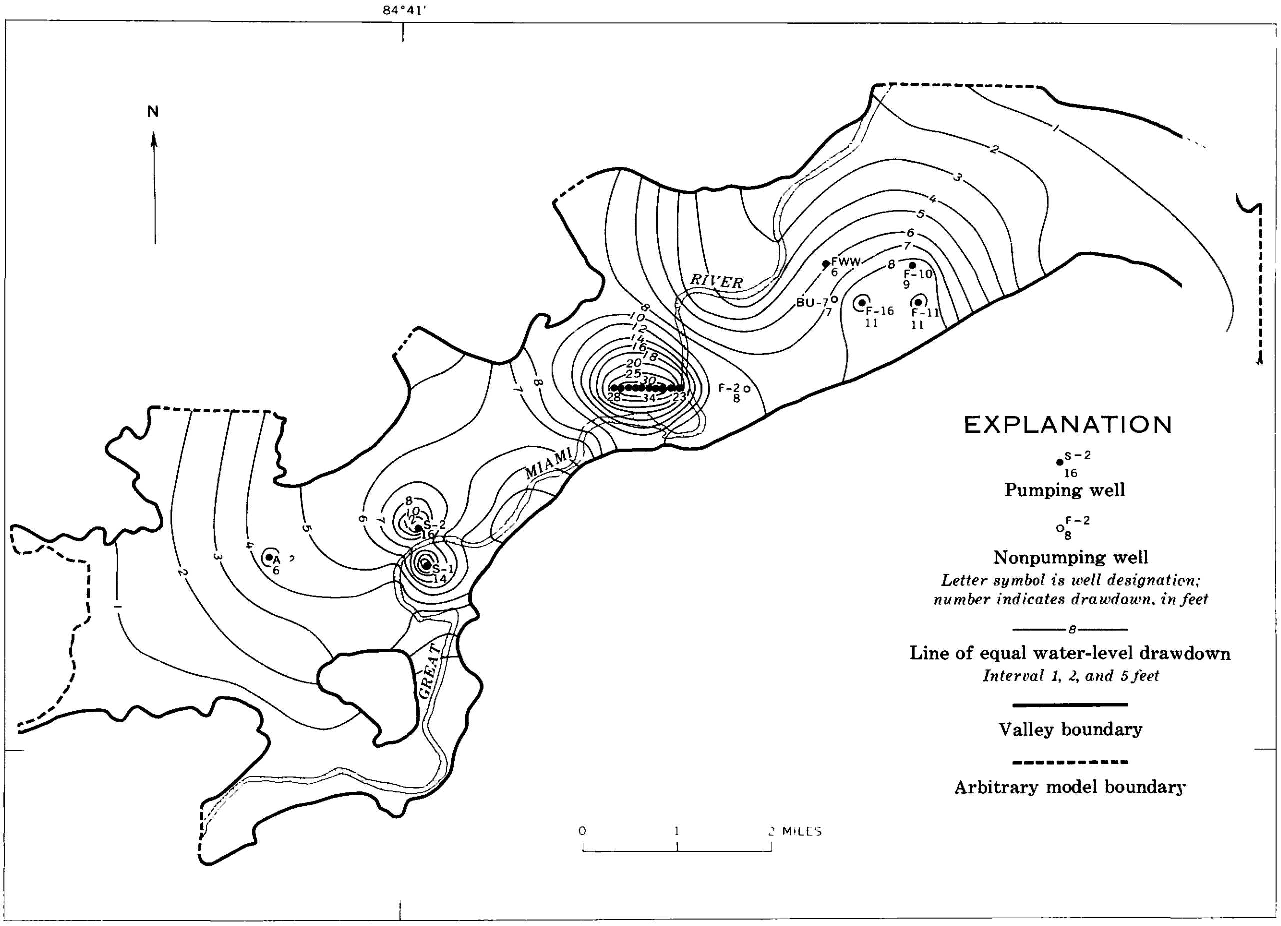

FIGURE 15.—Drawdown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 40 mgd from 10 wells in a straight line north of the river, 1962–72.

EFFECT OF PUMPING PROPOSED BY CINCINNATI

RUN 2: CINCINNATI PUMPING 40 MGD, 1962-72, FROM 10 WELLS IN LINE

Cincinnati's proposal for a well field in the Fairfield area provides three alternate plans of well spacing. The first plan calls for 10 wells spaced 400 feet apart in a straight east-west line near the site of the 1962 aquifer test. Figure 15 is a water-level drawdown map showing the result of Cincinnati's pumping 40 mgd (62 cfs) from this well pattern for the period 1962–72. In this plan, as in the other two, the proposed well field is approximately midway between the Hamilton and Southwestern Ohio Water Co. well fields, a location which should keep interference at the two fields to a minimum.

Pumping 40 mgd (62 cfs) from wells in this pattern creates a fairly steep cone of depression around the Cincinnati well field and has some effect, however slight, on water levels in the entire modeled area. The cone flattens out about 4,000 feet from Cincinnati's wells. Comparison of figure 15 and figure 13 shows that the cone of depression spreads slightly farther in all directions as a result of Cincinnati's pumping. Drawdowns at the Cincinnati wells range from 23 to 34 feet. Interference at the center of the Hamilton South well field is 1 foot, and at the Hamilton well F–2, 5 feet. Interference at the Southwestern Ohio Water Co. well field is 1 foot. Thus, the only adverse effect on existing well fields of Cincinnati's pumping 40 mgd (62 cfs) continuously for a 10-year period would be a slight increase in pumping lifts.

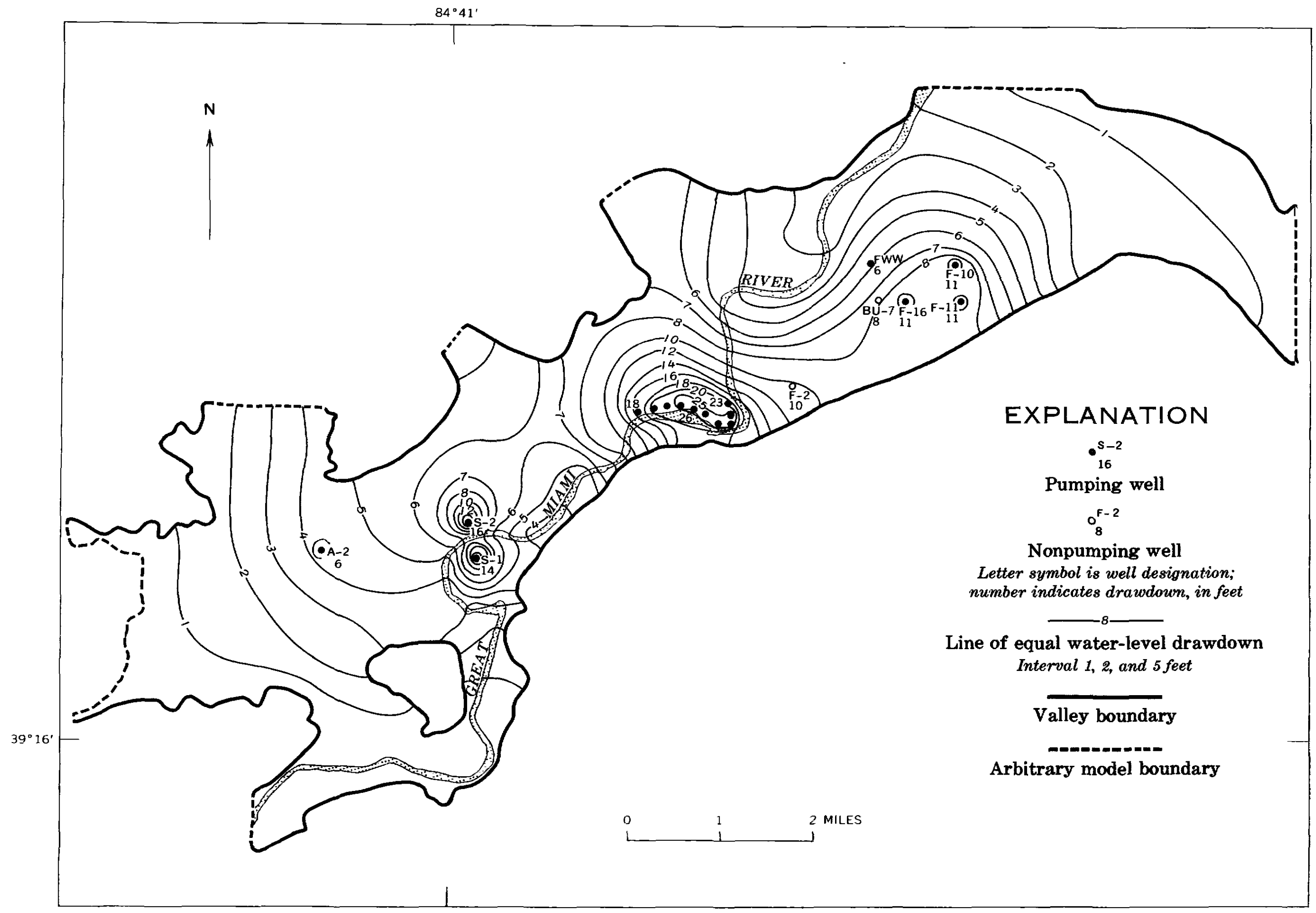

FIGURE 16.—Drawdown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 40 mgd from 10 wells along north bank of the river, 1962–72.

RUN 3: CINCINNATI PUMPING 40 MGD 1962–72, FROM 10 WELLS ALONG NORTH BANK OF THE GREAT MIAMI RIVER

The second plan being considered by Cincinnati for its new well field calls for 10 wells spaced about 800 feet apart along the north bank of the Great Miami River (fig. 16). This plan, too, places the well field midway between the Hamilton and Southwestern Ohio well fields. Figure 16 is the water-level drawdown map showing the results of this run. The greater well spacing and the proximity to the river result in less drawdown at the Cincinnati well field. Drawdown at the pumping wells ranges from 18 to 26 feet. However, under this plan the Cincinnati wells are closer to the south wall of the valley and considerably closer to Hamilton's well F–2, so that slightly more interference at the Hamilton South well field. Interference at the center of the Hamilton field is 2 feet, and at well F–2 7 feet. At the Southwestern Ohio well field interference is 1 foot, the same as in run 2. The second plan appears to be more advantageous to Cincinnati than the first owing to the lower pumping lift. The slightly greater drawdown at the Hamilton South well field should hardly prove to be detrimental.

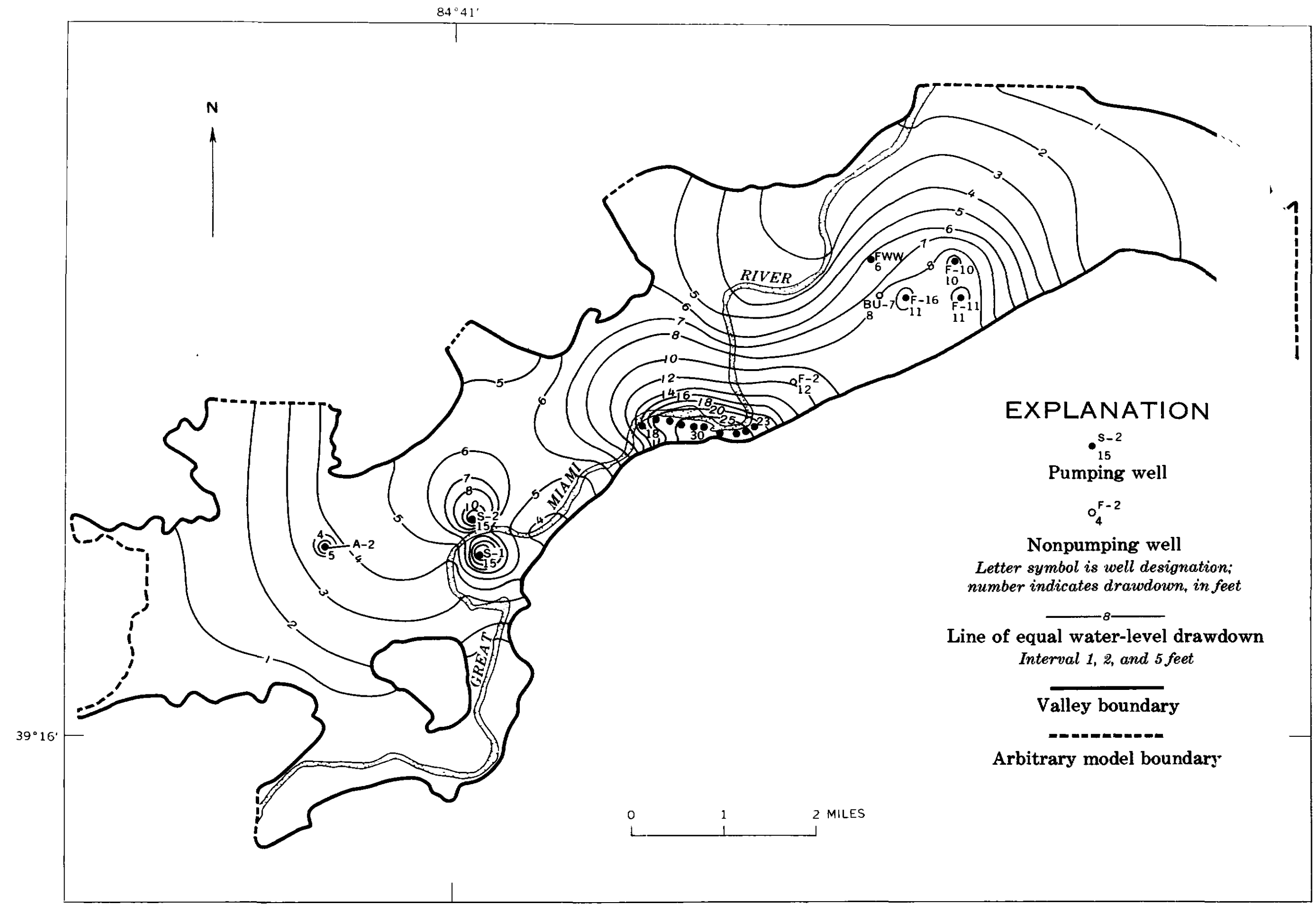

FIGURE 17.—Drawdown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 40 mgd from 10 wells along south bank of the river, 1962–72.

RUN 4: CINCINNATI PUMPING 40 MGD, 1962–72, FROM 10 WELLS ALONG SOUTH BANK OF THE GREAT MIAMI RIVER

The third of Cincinnati's alternate plans—the one being followed at least in the initial stages of development—calls for 10 wells spaced approximately 700 feet apart along the south bank of the Great Miami River (fig. 17). Hydrologically, this plan appears to be the least favorable of the three considered, for the wells are within a few hundred feet of the bedrock valley wall. Economically, however, the third plan is very attractive. The land-acquisition and pipeline-construction costs to Cincinnati can be materially reduced if the well field is on the south side of the river, as all areas to be served are south of the proposed well field.

Although this plan may at first appear to be unfavorable, the regional drawdown distribution resulting from pumping 40 mgd (62 cfs) from wells in this pattern differs only slightly from the drawdowns resulting from pumping wells at the two apparently more favorable well spacings (fig. 17). Drawdown at the Cincinnati well field itself is somewhat higher, ranging from 18 to 30 feet. Interference at the center of the Hamilton South well field and at the Southwestern Ohio Water Co. well field is 2 feet and 1 foot, respectively, the same as in run 3. Interference at Hamilton well F–2 is 9 feet.

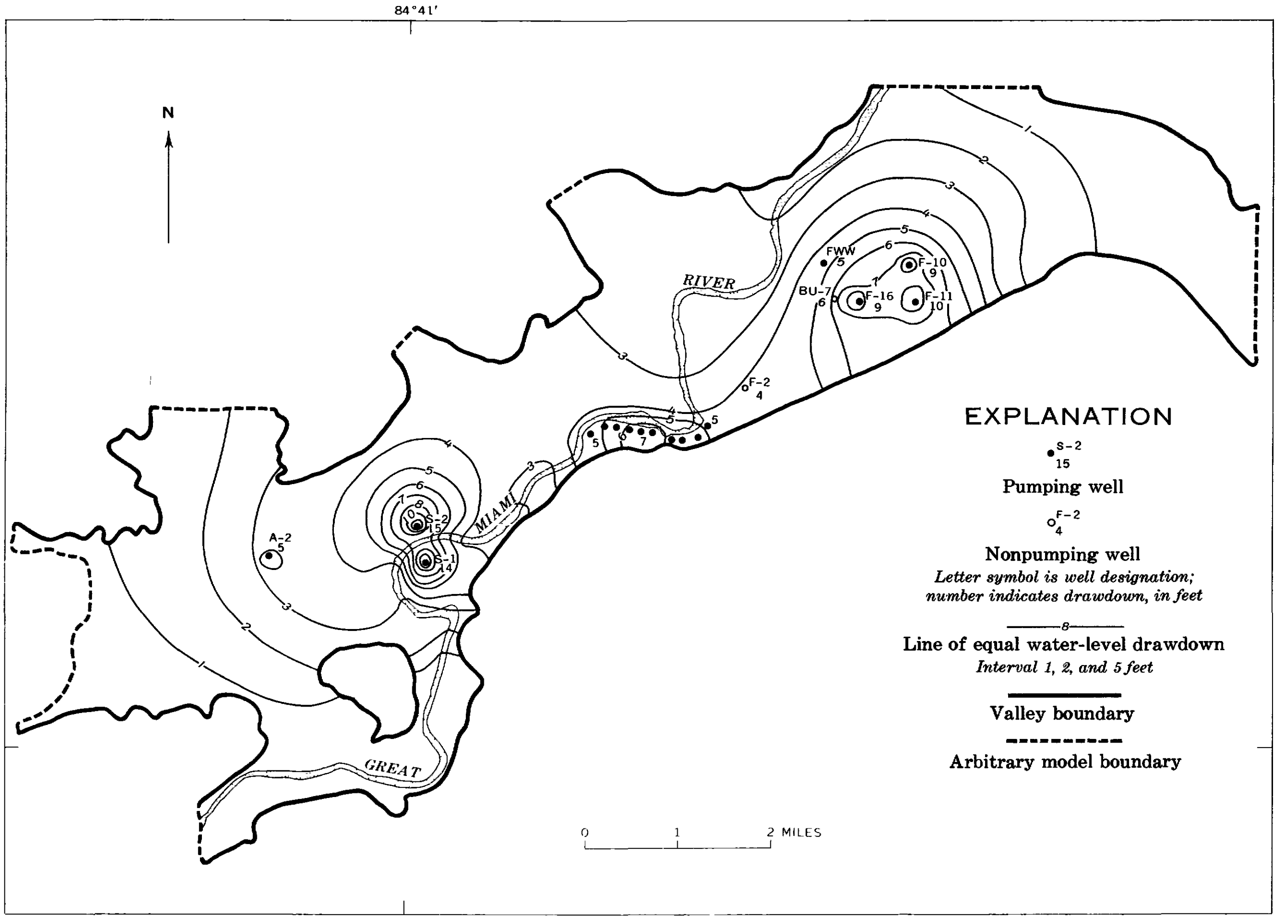

FIGURE 18.—Drawdown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 10 mgd from 10 wells along south bank of the river, 1962–72.

RUN 5: CINCINNATI PUMPING 10 MGD, 1962–72

Cincinnati's stated intention is to pump 40 mgd (62 cfs) during the summer months and 10 mgd (15.5 cfs) during the rest of the year. So far, the present analysis has assumed pumping by Cincinnati at a continuous rate of 40 mgd (62 cfs). In run 5 the effects of pumping at the rate of 10 mgd (15.5 cfs) from 10 wells spaced approximately 700 feet apart along the south bank of the Great Miami River are examined. Figure 18 is the water-level drawdown map resulting from this analysis. Even a casual glance reveals that the overall effect of Cincinnati's pumping at this lower rate is slight. Interference at the center of the Hamilton South well field and at the Southwestern Ohio Water Co. well field is negligible. At Hamilton well F–2 the interference is only 1 foot. Drawdown at the Cincinnati well field ranges from 5 to 7 feet.

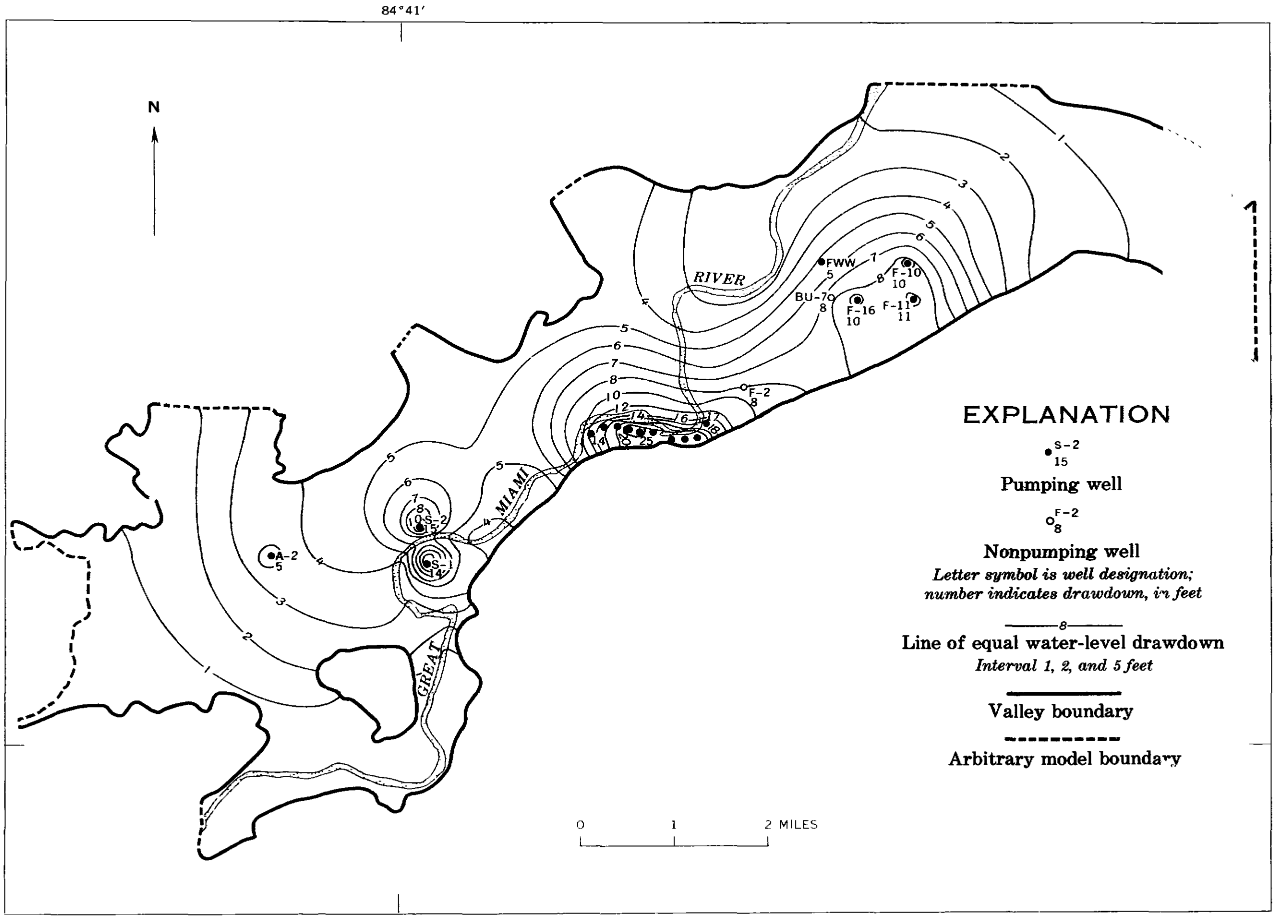

FIGURE 19.—Drawdown, with assumed maximum stream recharge of 499,000 gpd per acre and Cincinnati pumping 40 mgd from 10 wells along south bank of the river, 1962–72.

RUN 6: CINCINNATI PUMPING 40 MGD, 1962–72, WITH POTENTIAL STREAM RECHARGE OF 490,000 GPD PER ACRE

In run 6 the effects of Cincinnati's pumping 40 mgd (62 cfs) from 10 wells along the south bank of the river for the 10-year period 1962–72, are analyzed. The programed maximum potential stream recharge rate is 490,000 gpd (0.76 cfs) per acre, or about 50 percent greater than that programed in runs 1 through 5; this rate is essentially the same as that determined by R. C. Smith (written commun. to the Cincinnati Water Works Dept., 1962) from the 1962 Cincinnati aquifer test. Although the recharge rate is half again as great as the lower rate, it nevertheless is still representative of low streamflow.

Figure 19 is the water-level drawdown map showing the results from run 6. A comparison of this map with figure 17 indicates that the greatest effect of increasing induced stream recharge is in the immediate vicinity of the proposed Cincinnati well field and that elsewhere the effect is slight. Drawdowns at the Cincinnati well field range from 14 to 25 feet, or 4 to 5 feet less than those resulting from pumping at the lower recharge rate. Interference at Hamilton well F–2 is 5 feet, or 4 feet less than run 4. Interference at the center of the Hamilton South well field is 1 foot, or 1 foot less than in run 4. At the Southwestern Ohio Water Co. well field, interference is negligible, whereas it is 1 foot in run 4.

Total recharge from the Great Miami River (table 1) in this run is 55.8 mgd (86.5 cfs), compared with 45.2 mgd (70 cfs) in run 4.

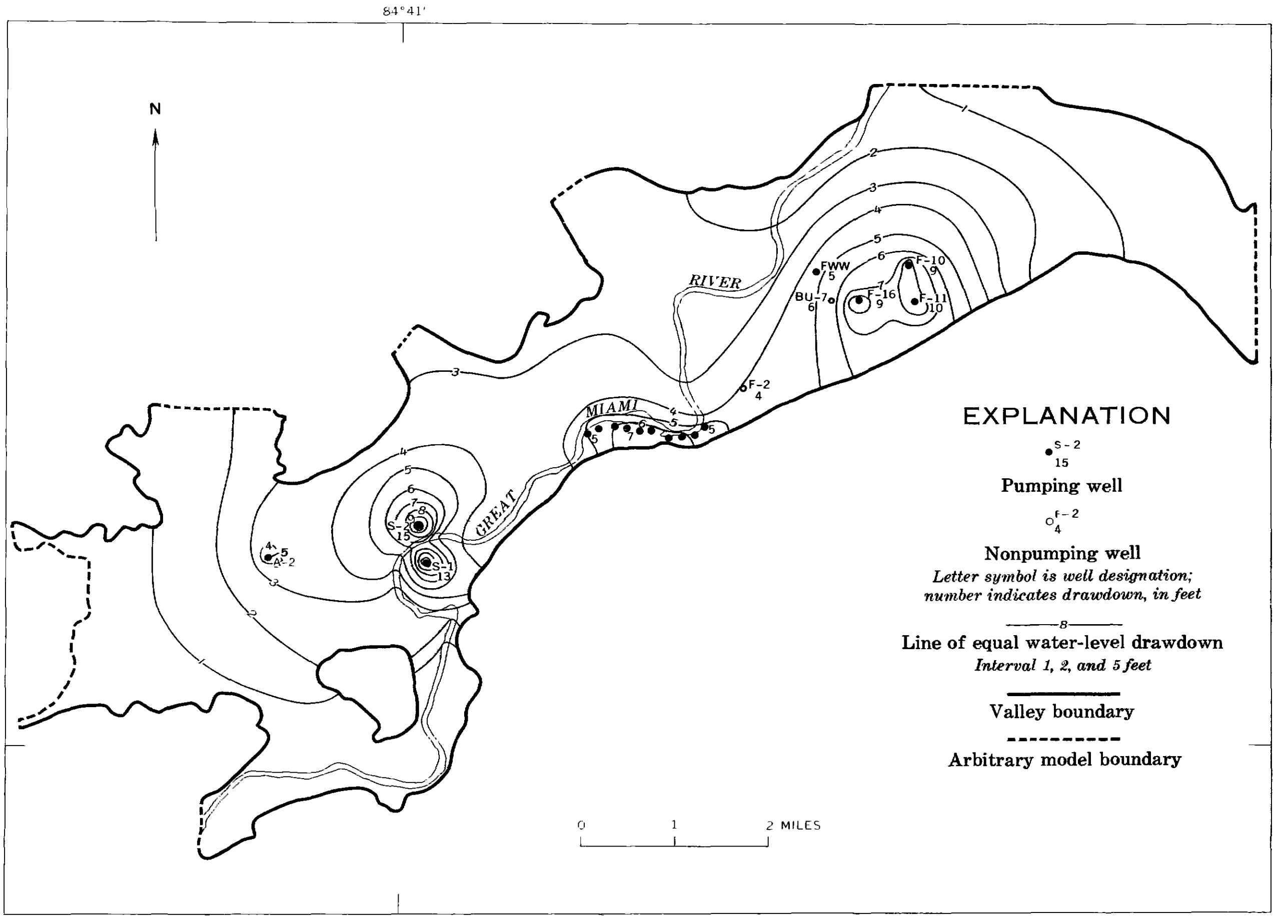

FIGURE 20.—Drawdown, with assumed maximum stream recharge of 490,000 gpd per acre and Cincinnati pumping 10 mgd from 10 wells along south bank of the river, 1962–72.

RUN 7: CINCINNATI PUMPING 10 MGD, 1962-72, WITH POTENTIAL STREAM RECHARGE OF 490,000 GPD PER ACRE

Run 7 is an analysis of the effect of Cincinnati's pumping 10 mgd (15.5 cfs) from 10 wells along the south bank of the river for the 10-year period 1962–72 with the increased maximum potential rate of stream recharge of 490,000 gpd (0.76 cfs) per acre. The resulting water-level drawdown map (fig. 20) shows that for this lower pumping rate, increasing recharge will have little effect on drawdowns. Figure 20 is virtually identical with figure 18, the drawdown map resulting from Run 5, in which Cincinnati is pumping 10 mgd (15.5 cfs) and recharge is limited to 325,000 gpd (0.51 cfs) per acre of streambed. The drawdowns at all the key locations (table 1) are identical.

It is apparent from this lack of influence of increased recharge that increasing the maximum possible recharge rate will affect drawdowns only where the pumping rate is high enough to create a fairly steep cone of depression. A more detailed analysis of this relationship is beyond the scope of the present investigation, but the relationship is deserving of further study.

EFFECT ON THE SYSTEM OF DOUBLING PRESENT PUMPING RATES IN ADDITION TO THE PROPOSED PUMPING BY CINCINNATI

Analysis of runs 2 through 7 indicates that the hydrologic system in the Fairfield-New Baltimore area should be able to sustain pumping of 40 mgd (62 cfs) by the proposed Cincinnati well field provided the pumping rates at all existing well fields remain unchanged. It is most unlikely, however, that the present rates will long remain unchanged. The lower Great Miami River valley is in the heart of a rapidly expanding industrial area. The demand for water is certain to increase in the

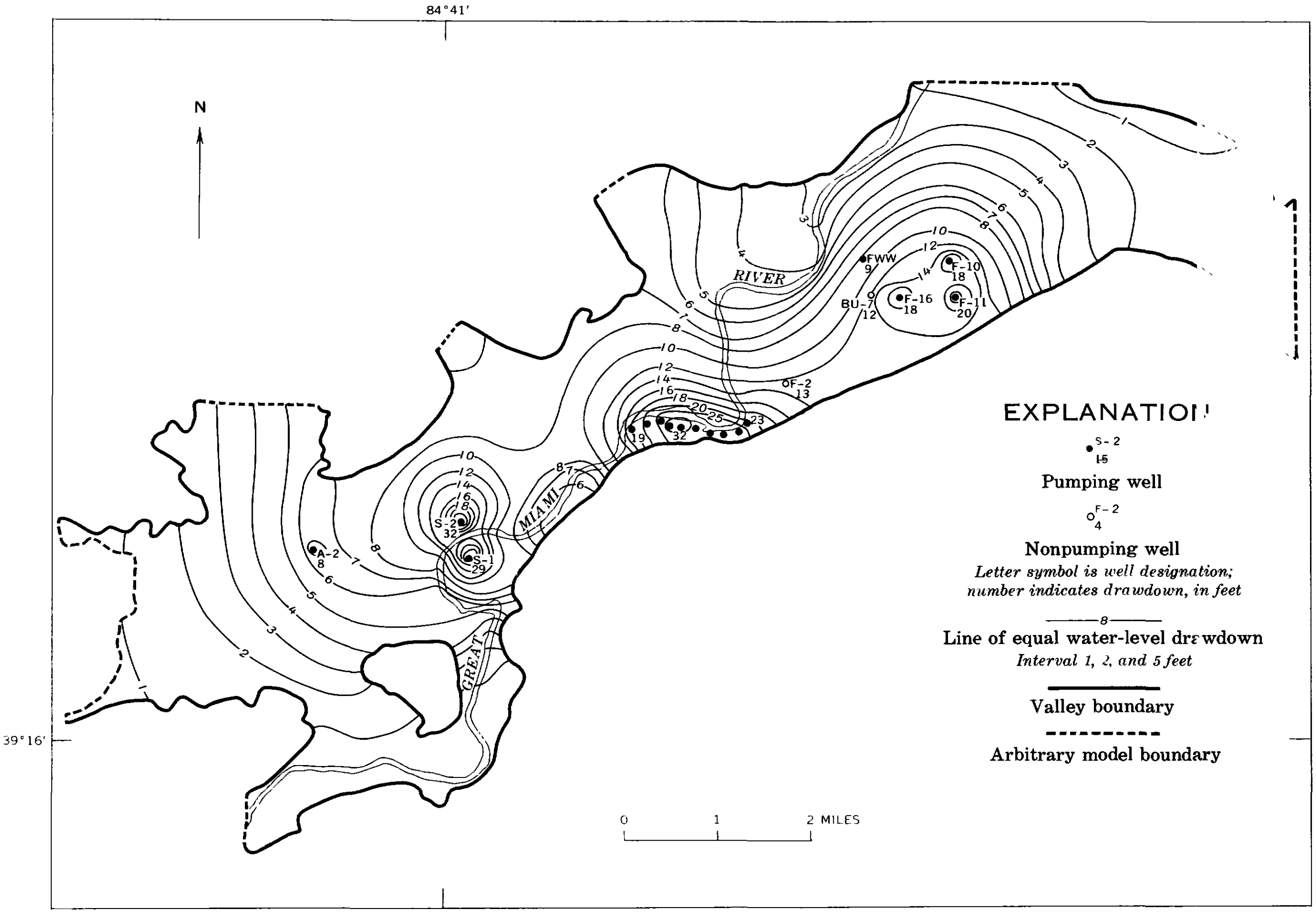

FIGURE 21.—Drawndown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 40 mgd from 10 wells along south bank of the river, 1962–82; pumping a total of 44 mgd from all other well fields, 1972–82.

future. A complete appraisal of the capacity of the hydrologic system in this area requires that the long-term effects of pumping at rates higher than the present ones be examined. This is the purpose of runs 8 and 9. These last two runs cover a 30-year period of pumping from 1952 to 1982. The present pumping rates of all existing installations are maintained for the period 1952–72 and are doubled for the period 1972–82. Doubling of present rates plus development of the proposed Cincinnati well field to its full capacity of 40 mgd (62 cfs) results in a combined withdrawal from the area of 84 mgd (131 cfs) for the period 1972–82. Pumping from the proposed Cincinnati well field on the south bank of the river is programed in run 8 at the rate of 40 mgd (62 cfs) and in run 9 at 10 mgd (15.5 cfs).

RUN 8: CINCINNATI PUMPING 40 MGD, 1962–82; ALL OTHER PUMPING RATES DOUBLED, 1972–82

In run 8 the Cincinnati well field is programed at the pumping rate of 40 mgd (62 cfs) for the period 1962–82. Pumping at the Hamilton, Southwestern Ohio, Fairfield, and Atomic Energy Commission well fields is continued at the 1962 rates of 22 mgd through 1972 and is doubled to 44 mgd for the period 1972–82. Therefore, the combined pumpage for the period 1972–82 is 84 mgd. Figure 21 is the resulting water-level drawdown map. Doubling of the 1962 pumping rates has the expected result of doubling the drawdowns at the pumping wells, so that the total drawdown at the center of the Hamilton South well field is now 18 feet and at the Southwestern Ohio Water Co. well field, 32 feet. The overall cone of depression in the area is spread farther than in any previous run. The 1-foot drawdown contour is virtually at the extremities of the modeled area. Drawdown at the Cincinnati well field ranges from 19 to 32 feet, or about 2 feet more than in run 4.

The interference at the Hamilton and Southwestern Ohio wells caused by pumping at the Cincinnati well field is difficult to distinguish from the drawdown due to the increased pumping rate at the wells themselves. No apparent interference can be detected at the center of the Hamilton South well field. Based on comparison

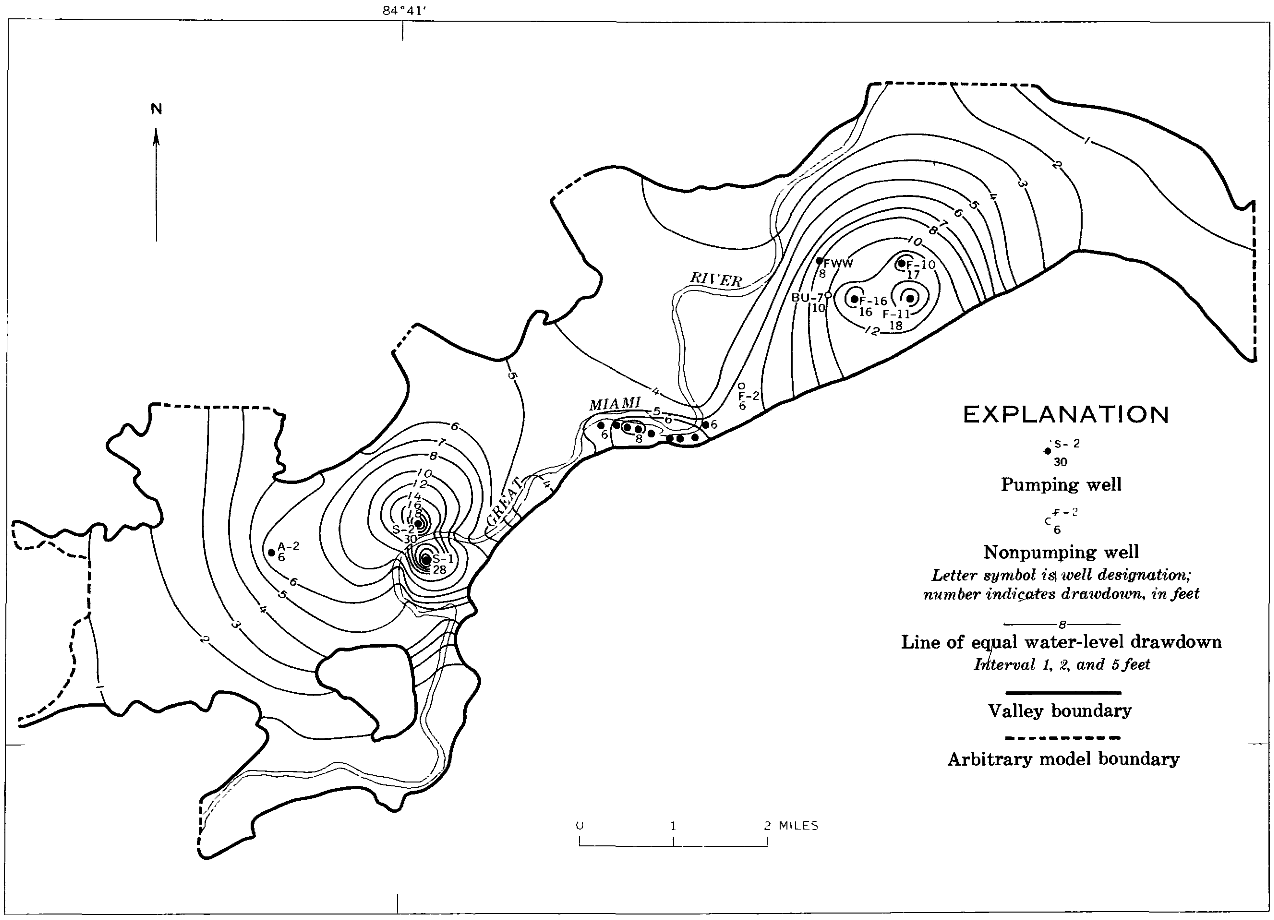

FIGURE 22.—Drawdown, with assumed maximum stream recharge of 325,000 gpd per acre and Cincinnati pumping 10 mgd from 10 wells along south bank of the river, 1962–82; pumping a total of 44 mgd from all other well fields, 1972–82.

with run 4 (table 1), however, as much as 2 feet of the total drawdown there might be the result of Cincinnati's pumping. Interference at Hamilton well F-2 is 10 feet and at the Southwestern Ohio Water Co. well field, 2 feet. These last two figures may be slightly high, as some of the drawdown may be due to pumping other than Cincinnati's.

RUN 9: CINCINNATI PUMPING 10 MGD, 1962–82; ALL OTHER PUMPING RATES DOUBLED, 1972–82

Run 9 is programed in the same manner as run 8 except that the pumping rate at the Cincinnati well field is 10 mgd (15.5 cfs) rather than 40 mgd (62 cfs). Figure 22 is the resulting water-level drawdown map. Cincinnati's pumping has a negligible effect on the Hamilton and Southwestern Ohio well fields, as has already been shown by runs 5 and 7, but the doubled pumping rates at these well fields cause about 1 foot of interference in the Cincinnati well field.

CAPACITY OF THE HYDROLOGIC SYSTEM TO SUSTAIN INCREASED PUMPING

The hydrologic system in the Fairfield–New Baltimore area has been shown, under the modeled conditions, to be able to sustain pumping of 40 mgd (62 cfs) at the proposed Cincinnati well field for a 10-year period under prolonged conditions of low streamflow. In runs 8 and 9, pumping at double the present rates is imposed on the system in addition to the proposed withdrawals from the Cincinnati well field. Can the hydrologic system sustain this total withdrawal of 84 mgd (131 cfs) indefinitely? Figure 23 shows the trace of three typical time-voltage oscillograms representing the time-drawdown curves for run 8 at the sites indicated. Just as that in figure 14, these oscillograms have flattened out long before the end of the pumping period, showing that equilibrium has been attained. Therefore, under the programed conditions, the pumping rates of run 8 could be

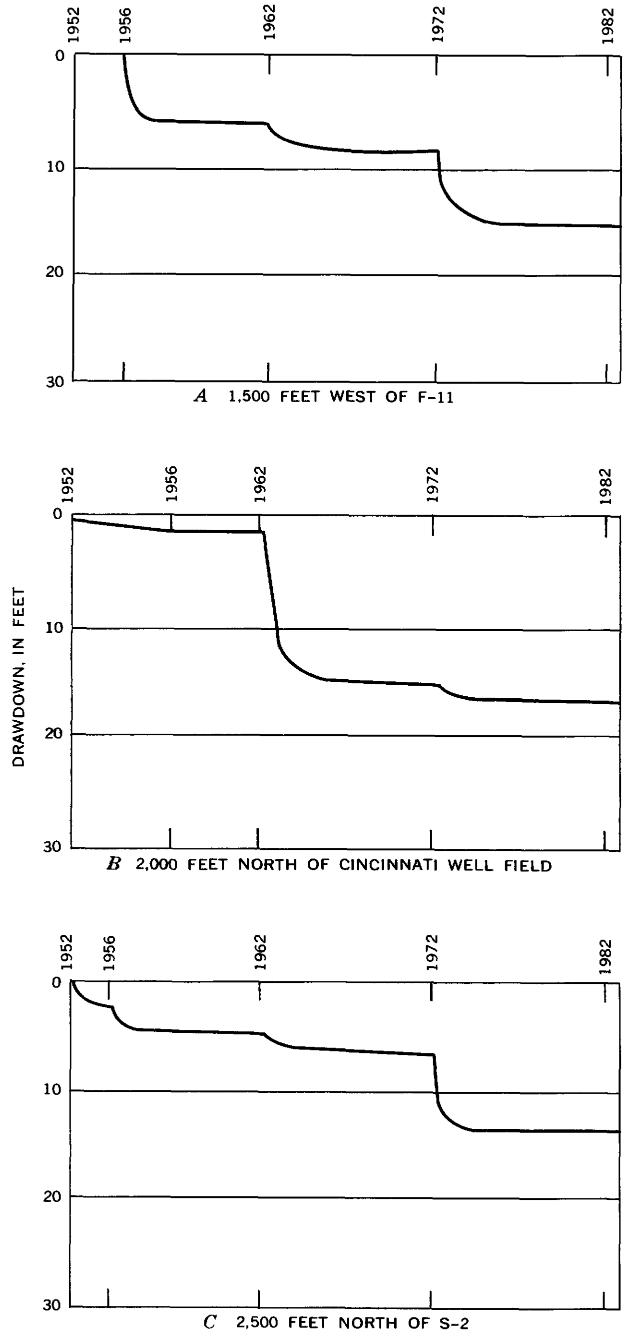

FIGURE 23.—Time-voltage oscillograms representing time-drawdown curves for the period of 1952–82 under conditions of run 8 at sites indicated.

continued beyond the 1972–82, pumping period without any further expansion of the cone of depression.

Further supporting evidence for the attainment of equilibrium can be found in the measurements of pumpage and recharge (table 1). In all runs the total recharge is seen to equal the total pumpage. Thus the aquifer is not being dewatered and can be considered in a state of equilibrium.

SUMMARY

VALIDITY OF ANALYSIS

Any model of a complex hydrologic system is certain to raise a skeptical reaction from some observers, as it must necessarily deal with a multitude of variables. An error in the simulation of any one of the variables could raise questions concerning the validity of the analysis. The results of the analysis can be no better than the reliability of the data on which the analysis is based. Before conclusions are reached, it would be well to take a final critical look at these variables to identify the most likely sources of error and to emphasize the limitations of the present analysis. The principal variables involved in the analysis, in order of decreasing reliability of definition, are—

1. Boundaries of the area;
2. Pumping history;
3. Configuration of the water table;
4. Coefficient of transmissibility;
5. Coefficient of storage;
6. Rate of recharge by induced stream infiltration; and
7. Rate of recharge from boundaries.

The first four variables are considered to be reliably defined and simulated. Control on the bedrock valley walls and on the tributaries, which form the boundaries of the area, is excellent; the pumping history has been thoroughly documented. Enough observation wells exist to permit mapping of the water table with a reasonable degree of accuracy. The coefficient of transmissibility (T) has been determined from four aquifer tests of good reliability and estimated from eight others of fair reliability; the results from all these tests are consistent. The thickness and lithology of the aquifer are well known from drillers' logs of wells and from seismic-refraction data.

The coefficient of storage (S) of the sand-and-gravel aquifer has never been definitively determined from an aquifer test in the modeled area. Water occurs under unconfined conditions in most of the area, however, and the storage coefficient of an unconfined aquifer is generally about 0.2. In the parts of the area where the aquifer is known to be semiconfined, values of the storage coefficient consistent with semiconfinement—that is, from 0.02 to 0.1—are used in the analysis. The figure of 0.2 for the majority of the area is considered to be valid, its validity being partly borne out by the close agreement between drawdowns determined from the model analysis and those actually measured in the field. The field time-drawdown data are too inconclusive to permit full verification of the storage coefficient, however. The smaller values of S in the marginal areas involve more speculation but are nevertheless considered to be of the right order of magnitude. Owing to the slight extent and marginal location of these areas, any error in the determination of S would have virtually no effect on the significant conclusions of the analysis.

The last remaining variables are the rates of induced recharge to the aquifer by induced stream infiltration and by leakage from the boundaries. It is in these critical quantities that the greatest uncertainty in the analysis exists.

The rate of recharge by induced stream infiltration is perhaps the most critical single factor in the present analysis. Only this great potential of replenishment permits the aquifer to be pumped at a high rate for a long period of time without being dewatered.

Only two determinations of the infiltration rate (both made at low river stage) in the Fairfield–New Baltimore area form the basis of the stream recharge rates programed in the present analysis. The two determinations are consistent. Programing of stream recharge at rates similar to these determinations results in a drawdown distribution consistent with that observed in the field; thus the programed infiltration rates are probably representative of conditions of low streamflow. The author therefore considers these programed rates to be valid for the present analysis.

Pumping from a ground-water supply sustained by induced stream infiltration will, on the average, reduce streamflow by the amount pumped between the point of withdrawal and the point of sewage return. (See also Spieker, 1968a, b.) Little net loss of flow usually results, for the sewage is generally returned close to the point of water withdrawal. In the Fairfield–New Baltimore area, however, the reduction of streamflow is greater; the 13.8 mgd (21.3 cfs) presently being pumped by the Southwestern Ohio Water Co. and the 40 mgd (62 cfs) proposed to be pumped by Cincinnati would be transferred out of the Great Miami River basin and, hence, would be withdrawn from any possible recirculation in that basin. Accordingly, the average streamflow would probably be reduced by the amount withdrawn from the basin. Such pumping and interbasin transfer probably would not materially reduce the flow of the Great Miami River. Most of the loss of flow and recharge to the aquifer would occur during periods of high streamflow, when the loss would amount to a small percentage of the total discharge. Although some streamflow loss would occur during periods of low flow, much of the water would be drawn from storage at these times. Even the characteristic low flow of the river, which is 490 cfs, or 316 mgd, at Hamilton, is well in excess of the anticipated future pumpage. Reduction of streamflow caused by the proposed pumping increase would therefore probably not be sufficient to have adverse effects on continuing use of the ground-water resource.

The stream recharge rates in the present analysis represent prolonged conditions of low streamflow. The infiltration rate can vary greatly as a function of river stage, temperature, and condition of the streambed. Under conditions of higher streamflow than are programed in the present analysis the system undoubtedly could sustain higher pumping rates with less drawdown than is observed here. Much more research in the determination of stream infiltration rates under various conditions is needed. Only when this critical factor is fully understood will it be possible to appraise with accuracy the capacity of the hydrologic system to sustain pumping under a wide range of conditions.

The greatest unknown in the present analysis is the rate of induced recharge from the boundaries, which consist principally of bedrock valley walls. The rate of leakage from these bedrock valley walls has never been determined; it has only been estimated. The rates programed in the present analysis are consistent with previous estimates. Little more can be said regarding their reliability. Leakage rates of the present analysis, like the stream infiltration rates, result in a drawdown distribution similar to that observed in the field.

Although there may be errors in the estimates of rates of leakage from the boundaries, such errors are not likely to seriously affect the validity of the analysis. About 75 percent of all pumping is sustained by induced stream recharge (table 1); so leakage from boundaries accounts for a relatively small part of the total recharge. Thus, in the analysis an overestimate of the rate of leakage from the boundaries would indicate a slightly smaller drawdown over the entire area than would actually occur. This difference would be somewhat greater in the proposed Cincinnati well field, owing to the field's proximity to the bedrock valley wall.

Perhaps the best testimony to the validity of the present analysis is the excellent match between field conditions (fig. 8) and conditions as simulated by the model (fig. 13). The close agreement of these maps suggests that all the critical variables have been simulated with reasonable accuracy.

If Cincinnati proceeds with the development of its well field as proposed, the increased pumping will cause additional drawdown at wells Bu–7 and F–2 in the Hamilton South well field. A continuous record of the water level in Bu–7 is maintained (fig. 6), and the water level of F–2 can be measured. If the present analysis is a valid approximation of the hydrologic system, then the observed water-level changes in these wells should closely approximate the changes predicted by this analysis, as summarized in table 1. The actual response of the hydrologic system to future pumping conditions will reveal which, if any, of the variables in the present analysis have been inaccurately determined, and should aid materially in their correction in future analog-model analyses of this and similar areas.

CONCLUSIONS

Analysis of the hydrologic system in the Fairfield–New Baltimore area, Ohio, by electric analog model indicates that the system can easily sustain the proposed withdrawal of 40 mgd (62 cfs) by the city of Cincinnati under prolonged conditions of low streamflow. Furthermore, the system can sustain pumping at twice the average 1962 rate of discharge of 22 mgd (34.1 cfs) from all existing municipal and industrial well fields in addition to the proposed Cincinnati withdrawals. Table 1 summarizes the conditions governing each run of the analog model, together with the total and net drawdowns at several critical points in the area.

The last two runs (8 and 9) show that the system can sustain a withdrawal of at least 84 mgd (131 cfs), which is more than three times the present pumping rate. Although in the model analysis this rate of pumping was programed for the period 1972–82, this rate may not actually be reached until considerably later than 1982. To look that far into the future would be of little value in the present analysis, as too much uncertainty is involved. The significant result of this analysis is that the hydrologic system should be able to sustain any increases in pumping likely to occur in the next 20–30 years. The programed rate of 84 mgd (131 cfs), moreover, should not be regarded as the maximum possible sustained yield of the hydrologic system.

The present analysis is intended to predict the effects of future pumping under prolonged conditions of low streamflow, for these conditions will be the limiting factor in future ground-water development. Undoubtedly, during extended periods of moderate to high streamflow much larger quantities of water than those considered in the present analysis could be withdrawn. In the future, when more precise determinations of the stream infiltration rate for various conditions of streamflow may be available, it will be possible to determine by more detailed analog-model analysis the capacity of the hydrologic system under more varied conditions.

The present analysis of the long-term effects of future pumping in the Fairfield–New Baltimore area is but an initial study of the problem: it should not be regarded as the final or ultimate solution. The problems of 1962 may not necessarily be the problems of 1972 or 1982; also, the hydrologic data available in the future hopefully will be more complete. A distinct advantage of using the electric analog model is that it can be readily adapted to new problems or to additional data that may become available in the future. The model, once built, is permanently available for future reference. Thus, if the development of additional ground-water supplies in the area is proposed, or if new data make possible a more accurate definition of the hydrologic system, the analog model can be revised and analyzed to determine the effect of such changes on the system. The present analysis should be regarded as the beginning of a new phase of hydrologic study of the Fairfield–New Baltimore area and not as the study to end all studies.

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