Potential Development and Recharge of Ground Water in Mill Creek Valley, Butler and Hamilton Counties, Ohio, Based on Analog Model Analysis

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1893

Prepared in cooperation with the Ohio Department of Natural Resources Division of Water

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By RICHARD E. FIDLER

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A theoretical study of artificial recharge through injection wells in a glacial outwash aquifer

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POTENTIAL DEVELOPMENT AND RECHARGE OF GROUND WATER IN MILL CREEK VALLEY, BUTLER AND HAMILTON COUNTIES, OHIO, BASED ON ANALOG MODEL ANALYSIS

By RICHARD E. FIDLER

ABSTRACT

Mill Creek valley is part of the greater Cincinnati industrial area in southwestern Ohio. In 1964, nearly 30 percent of the water supply in the study area of about 27 square miles was obtained from wells in the glacial-outwash aquifer underlying the valley. Ground-water demand has increased steadily since the late 1800's, and excessive pumpage during the years of World War II caused water levels to decline to critical levels. Natural recharge to the aquifer, from precipitation, is about 8.5 mgd (million gallons per day). In 1964, the total water use was about 30 mgd, of which 8.1 mgd was obtained from wells in Mill Creek valley, and the remainder was imported from outside the basin. With rapid industrial expansion and population growth, demand for ground water is continuing to increase. By the year 2000 ground-water pumpage is expected to exceed 25 mgd.

At a public hearing before the Ohio Water Commission in 1961, artificial recharge of the aquifer through injection wells was proposed as a possible solution to the Mill Creek valley water-supply problem. The present study attempts to determine the feasibility of injection-well recharge systems in the Mill Creek valley.

Although basically simple, the hydrologic system in Mill Creek valley is complex in detail and is difficult to evaluate using conventional quantitative methods. Because of this complexity, an electric analog model was used to test specific development plans.

Three hypothetical pumping plans were developed by projecting past pumpage data to the years 1980 and 2000. Various combinations of injection wells were tested on the model under different hypothetical conditions of pumpage. Based on analog model analysis, from three to eight injection wells, with an approximate input of 2 mgd each, would reverse the trend in declining ground-water levels and provide adequate water to meet anticipated future demands.

INTRODUCTION

PURPOSE AND SCOPE

Practically every type of industry is represented in the Mill Creek valley in southwestern Ohio. A survey conducted by the Ohio Division of Water in 1955 reported 459 manufacturing plants in the basin. The most concentrated industrial activity is between Ivorydale and Rialto, the area of this investigation. Expanding industrial activity and population growth have imposed heavy demands for water on the sand and gravel aquifer underlying the heavily industrialized Mill Creek valley. This has resulted over the years in the lowering of water levels and a reduction of well yields as the quantity of water pumped exceeds natural replenishment.

Numerous investigations, beginning in the middle 1930's, have resulted in various proposals for development projects designed to reverse the trend in declining ground-water levels. The Southwestern Ohio Water Co. developed a ground-water system in the Great Miami River valley in 1952. This facility is the most significant of the development projects and the only one that has been built. Water from this source has since been brought by pipeline to the Mill Creek valley industrial complex. This project has relieved the trend in declining water levels in parts of the valley, although it appears to be only an interim solution to the problem.

In 1961, local interests again became concerned about the future of the Mill Creek valley water supply and realized that additional planning would be required to assure an adequate water supply for anticipated future municipal and industrial growth. On March 24, 1961, a public hearing was held before the Ohio Water Commission at Evendale, Ohio, concerning the overuse of ground-water supplies in the Mill Creek valley. The Commission recommended "that the Division of Water in cooperation with local interests determine the annual rate of water withdrawal from and recharge to the Mill Creek valley aquifer; and suggest means by which artificial recharge can be accomplished" (Ohio Water Commission, 1961). In 1963, the Ohio Division of Water submitted its report to the Ohio Water Commission. The report (Kaser, 1963) gave an estimate of the withdrawal and natural recharge rates, and included a proposal for artificially recharging the aquifer through injection wells. Because of the interest engendered by Kaser's report, a cooperative investigation was made, utilizing the U.S. Geological Survey's electric analog modeling facilities in Phoenix, Ariz.

The purpose of the study was to ascertain, by use of an electric analog model, whether artificial recharge of the aquifer in Mill

Creek valley through injection wells was a feasible solution to the problems of declining water levels and providing sufficient water for industrial and population growth. Moreover, better knowledge of the response of the aquifer system to the continuation of present pumpage and to future increases in pumpage was believed essential. The results provide guidelines which will permit selection of an artificial recharge plan to fit local requirements.

COOPERATION AND ACKNOWLEDGMENTS

The Ohio Division of Water was represented in this investigation by C. V. Youngquist, chief. The electric analog model and analysis were made by personnel of the U.S. Geological Survey Analog Model Unit in Phoenix, Ariz., working under the supervision of E. P. Patten, Jr., research hydrologist. S. M. Longwill, hydrologist, and M. L. Field, technician, were directly responsible for construction and analysis of the model, based on hydrogeologic data assembled by the author.

The author wishes to express his appreciation to Paul Kaser, S. M. Longwill, and S. E. Norris for their guidance and suggestions given throughout the investigation and in preparation of this report. The author thanks J. C. Krolczyk and J. N. Pennell of the Ohio Division of Water for assistance with the illustrations and personnel of the many industries and municipalities who freely gave information.

PREVIOUS INVESTIGATIONS

Prior to 1936, before the ground-water situation became a matter of general concern in the Mill Creek valley, published information about the aquifer was limited to general descriptions such as those prepared by Fuller and Clapp (1912) and Fenneman (1916). In 1936, the U.S. Geological Survey, in cooperation with the respective Boards of County Commissioners, made a preliminary study of the ground-water resources in Butler and Hamilton Counties, and in 1938, the county commissioners requested a more detailed investigation, which was made by Klaer and Thompson (1948).

The engineering firm of Shoecraft, Drury, and McNamee (1942) investigated the Mill Creek valley water-supply problem in 1942 on behalf of the Ohio Water Supply Board. Also, in 1942, Klaer and Kazmann (1943) reviewed the situation in the Mill Creek valley and made a quantitative study in the Great Miami River valley near Hamilton, which led to development of a well field by the Federal Works Agency. Water from the wells, which subsequently were sold to the city of Hamilton, was used during the war years by the Wright Aeronautical plant near Evendale, in the Mill Creek valley. This system, in which water was brought into Mill Creek valley by pipeline, was the forerunner to that of the present Southwestern Ohio Water Co. In 1946 the U.S. Geological Survey cooperated with the Ohio Water Resources Board, successor to the Ohio Water Supply Board, in studying data collected subsequent to the earlier studies (Bernhagen and Schaefer, 1947). The report by Kaser (1963) regarding the feasibility of recharging the aquifer in Mill Creek valley artificially has been mentioned.

Brief discussions of ground-water conditions in the Mill Creek valley at various times are also contained in a series of U.S. Geological Survey Water-Supply Papers entitled, "Water levels and artesian pressures in observation wells in the United States, Northeastern States, 1938–55," and "Ground-water levels in the United States, Northeastern States, 1956–62," and in various Ohio Department of Natural Resources reports. (See Harstine, 1965; Rudnick, 1959, 1960, 1962; and Ohio Division of Water, 1964.)

A few site studies have been made by consultants for private companies and municipalities, and the results have been made available to public agencies.

DESCRIPTION OF THE AREA

Mill Creek rises in Liberty Township near the village of Princeton in southern Butler County and flows generally south 28.1 miles through Hamilton County to a confluence with the Ohio River at Cincinnati. Mill Creek drains approximately 166 square miles.

That part of Mill Creek valley discussed in this report covers an area of 27 square miles. From the village of Rialto on the north, the study area extends about 12 miles south to Ivorydale and Bond Hill. The valley ranges in width from 1.5 to 2.5 miles and averages 2.25 miles. The Mill Creek valley is bounded on the east and west by the bedrock walls of the ancestral valley (fig. 1).

Mill Creek valley is generally broad and flat and is bounded by gently rolling glacial and alluvial terraces and steep, deeply dissected rock walls. The valley elevation along Mill Creek is 590 feet above mean sea level near Rialto and 490 feet above mean sea level at Ivorydale; the average gradient is about 8 feet per mile between these points. The entire reach of Mill Creek, 28.1 miles, has a gradient of 12 feet per mile. The valley walls, consisting of sedimentary deposits of limestone and calcareous shale of Ordovician age, rise from 200 to 400 feet above the general

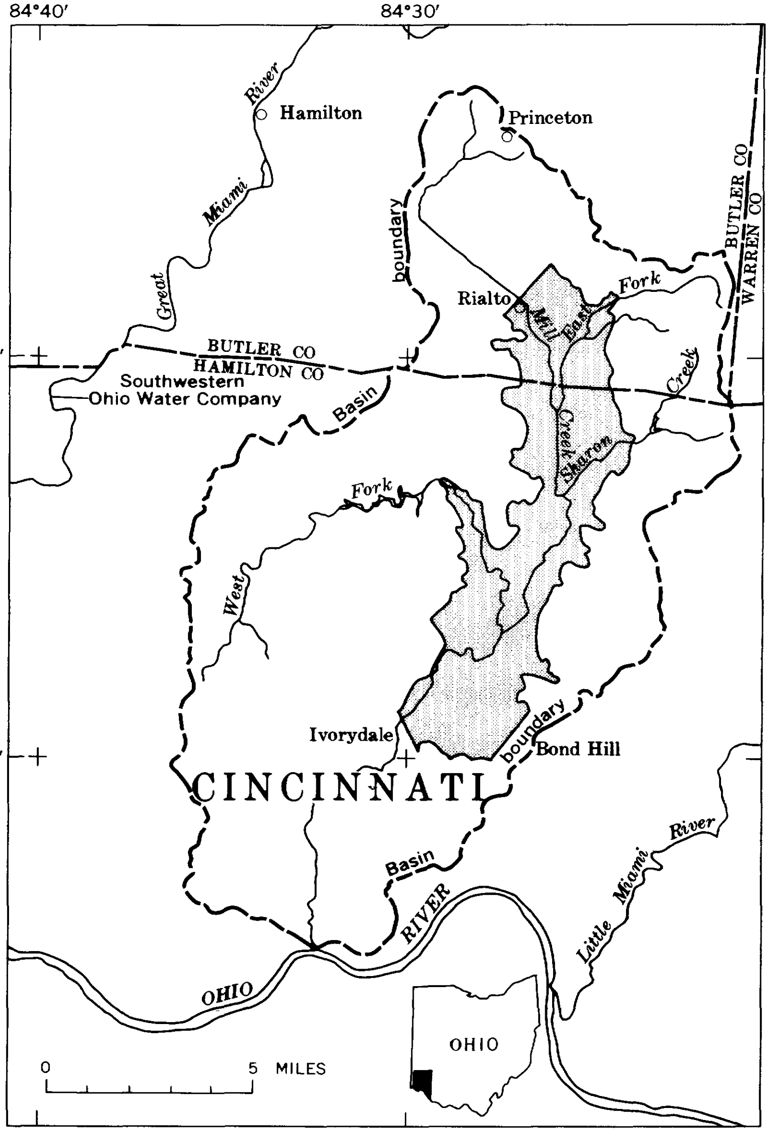

FIGURE 1.—Mill Creek basin showing location of the report area (shaded).

level of the valley surface, or from 700 to 900 feet above mean sea level.

Mill Creek is small compared with the large valley in which it flows. In the north the main channel is little more than a ditch and is dry much of the time. Near Crescentville (fig. 3), Mill

Creek is joined by East Fork, and at Evendale by Sharon Creek; from there it flows through Reading, Lockland, and Arlington Heights. In this area Mill Creek has an average width of about 20 feet and a depth of 0.5 foot, measured during a period of low flow of about 10 cfs (cubic feet per second). At the south edge of Arlington Heights, West Fork joins Mill Creek, and the average width and depth of Mill Creek increase to about 30 feet and 1 foot, respectively, measured during a flow of about 10 to 15 cfs.

THE HYDROLOGIC SYSTEM

Although the hydrologic system in Mill Creek valley is basically simple, it is complex in detail. The sand and gravel aquifer is nonhomogenous and has irregular boundaries. In much of the area a glacial till layer separates the aquifer horizontally and significantly reduces natural recharge. Ground-water pumpage varies seasonally, and the annual rainfall is irregular. Because of the irregularity and nonhomogeneity of the aquifer, a quantitative analysis was made using the electrical analog model.

The wide, deep preglacial valley beneath Mill Creek contains permeable glacial-outwash sand and gravel interbedded with layers of clay and till. The valley provides a natural underground reservoir from which large quantities of good quality water can be obtained from wells. The outwash deposits range from 90 to nearly 200 feet in thickness and are thickest in the vicinity of Reading, Lockland, Wyoming, and Evendale. The geologic sections (pl. 1) show the variation in the thickness and character of the glacial deposits.

From Evendale to the north limit of the study area, the sand and gravel deposits are essentially continuous above the bedrock, except for irregular lenses of clay. In the central and southern parts of the valley, the outwash is divided horizontally by a fairly continuous layer of relatively impermeable clay into an upper and lower aquifer, of which the lower is the principal source of ground water.

Natural recharge to the aquifer system is principally from precipitation. In the northern part of the area part of the precipitation percolates into the outwash deposits, moves slowly southward, and enters the lower aquifer in the vicinity of Evendale. Most precipitation south of Evendale does not infiltrate to wells because of the overlying clay layer. Although precipitation is reasonably well distributed seasonally in this area, its distribution throughout the year is also important relative to the amount of recharge entering the aquifer. The average annual precipitation at the Hamilton Water Works, north of the study area, is 38.81 inches based on the period 1931–60 (U.S. Weather Bureau, 1964). According to L. T. Pierce, formerly State Climatologist, of the U.S. Weather Bureau (oral commun. 1964), of the total average annual precipitation, evapotranspiration accounts for about 25 inches, runoff about 8 inches, and ground-water recharge about 6 inches. Infiltration is greatest during periods of heavy precipitation (normally during the first 6 months of the year) when high stream flow or flooding usually occurs. The effect on the water table is illustrated by the hydrograph of well BU–9 (fig. 7), in the northern part of the area, near Crescentville. Well BU–9 is not influenced appreciably by pumping. The following table shows the average monthly precipitation recorded at the Hamilton Water Works station:

	Inches		Inches
January	3.63	July	3.82
February	2.64	August	2.68
March	3.65	September	3.37
April	3.61	October	2.22
May	3.72	November	2.76
June	4.06	December	2.65

Several quantitative estimates of natural recharge to the aquifer in Mill Creek valley have been made. In 1940 Klaer and Thompson (1948) estimated the natural recharge as 13 mgd (million gallons per day). Bernhagen and Schaefer (1947) estimated the recharge in 1943 as 10.7 mgd. In the present study the natural recharge is estimated as 8.5 mgd. The differences in estimates have resulted largely because more data have become available, including a progressively longer period of water-level and pumpage records. Part of the discrepancy between the first and last estimates is due to the reduction of exposed surface area, which has resulted in greater runoff and less infiltration to the aquifer. In all probability, natural recharge will be further reduced as suburban and industrial development continues northward in Mill Creek Valley.

OVERDEVELOPMENT OF THE AQUIFER

Ground water, combined with available manpower, transportation, and markets, promoted the industrialization of the Mill Creek valley. The ground water requires very little treatment for municipal use and is adequate for many industrial applications without treatment. The uniformly low temperature, about 13° C, makes it ideally suited for use in the processing of steel and in other cooling applications.

The demand for ground water has been increasing steadily since industrial development began in the valley in the late 1800's. By the turn of the century, all wells in the Ivorydale area were yielding an average of 1 mgd, and elsewhere in the valley about 0.5 mgd was being pumped for domestic use. As other industries moved into the area, the resulting industrial growth brought commercial and residential expansion, which also required water.

World War I provided impetus for new plants and factories, especially in the southern and central parts of the valley. In the period 1900–19, average ground-water pumpage for municipal and industrial use was 4.6 mgd; the greatest increase in pumpage occurred during the war years of 1914–18.

From 1920 to 1942, water use was more than double that of the preceding period, 1900–19. Average pumpage of nearly 10 mgd during this period caused a serious decline in water levels in some areas. Following three drought periods, in 1930, 1934, and 1936, water levels in areas of heavy pumpage declined to the point that well yields were reduced by nearly 50 percent. By 1936 many people in the Mill Creek valley had become aware that there apparently inexhaustible water supply was in danger. The situation was made worse during World War II when new plants were built for war production. Again, there was a large increase in water requirements. In 1942, record ground-water pumpage of 17.5 mgd was reached. From 1942 to 1952, ground-water pumpage in Mill Creek valley averaged 14.38 mgd, and much of the increase over the preceding period, 1920–41, occurred in the Lockland, Reading, and Evendale areas.

After World War II it was generally recognized that a water problem existed in the Mill Creek valley. In many locations water levels were extremely low and well yields had been drastically reduced; some wells had been abandoned. Many of the larger ground-water users were forced to purchase water from municipal systems at a cost higher than that of pumping their own wells. Aware that something had to be done to supplement the ground-water supply, representatives of 11 water-using industries in Mill Creek valley pooled resources and formed the Southwestern Ohio Water Co. In 1952 a ground-water system was developed in the so-called Big Bend area of the Great Miami River valley, about 10 miles south of Hamilton, and water was piped approximately 12 miles to the Mill Creek valley industrial complex. Between 1952 and 1965, the Southwestern Ohio Water Co. supplied an average of 13.5 mgd to its industrial consumers in the Mill Creek valley. As a result, from 1952 to 1965 ground-water pumpage in Mill Creek valley was reduced from 14.38 mgd in the period 1942 to 1952 to an average of only 8.11 mgd. Some industries that had been purchasing water from the city of Cincinnati began buying it from the Southwestern Ohio Water Co.

The importation of water from outside the Mill Creek valley arrested the decline in water levels in parts of the valley, at least temporarily, but such importation was not deemed the final solution to the Mill Creek water-supply problem. Ground-water pumpage in the Mill Creek valley once averaged as much as 17.5 mgd, and there is no reason to believe that pumpage might not exceed 20 mgd in the relatively near future. Recent industrial growth in Mill Creek valley has been extended north beyond Evendale to areas that are not close to the distribution system of the Southwestern Ohio Water Co. nor to existing municipal systems. With the current rapid industrial expansion and population increase the demand for ground water will continue to grow.

The water supplied by the Southwestern Ohio Water Co. permitted the industrial ground-water users in the Carthage and Ivorydale areas to essentially discontinue ground-water pumpage. Water levels in these areas rose about 2 feet per year during the 13-year period 1952–64. Water levels continued to decline, though at a lesser rate, in the Reading, Lockland, and Evendale areas. The general recovery of water levels will permit further industrial expansion and the development of new industry in Mill Creek valley until ground-water pumpage increases again to a critical point.

ARTIFICIAL RECHARGE AS A SOLUTION

Because of the growing demand for water and the limited natural recharge available to sustain a high rate of withdrawal, it has been proposed that a practical solution to the problem of overdraft in Mill Creek valley might be to develop a method of recharging the aquifer artificially. Several methods have been used successfully in the United States and Europe for artificially recharging glacial-outwash aquifers. Whether a given method is practical depends on hydrologic, environmental, and economic factors.

The two methods generally used for artificial recharge are (1) construction of reservoirs, ponds, lagoons, ditches, and pits to allow direct infiltration of water from the surface to the aquifer, or the spreading a thin sheet of water over a large land area and permitting the water to percolate through the surficial material into the aquifer; and (2) injection of water directly into the aquifer through wells.

In Mill Creek valley, direct infiltration or spreading methods do not appear feasible for several reasons:

1. Land acquisition costs are prohibitive in the areas where it would be most useful.
2. A clay layer separates the major aquifer from the surface in more than half the area. It is doubtful that enough water would enter the aquifer through this clay layer to make the method effective.
3. Excessive sealing of the bottoms of infiltration basins would likely occur, as the soils in the Mill Creek valley contain considerable silt.

If we use the same criteria, the injection-well method of artificial recharge does appear feasible and warrants consideration because:

1. Land area required is relatively small, and recharge wells could be placed at precise locations where the effects on the aquifer would be most beneficial.
2. The clay layer separating much of the aquifer from the surface would not be a problem because injection wells would penetrate through the clay directly into the major aquifer.
3. Silt or suspended material could readily be removed before injection of recharge water into the aquifer.

Theoretically, water could be put into an aquifer through injection wells at the same rate at which it can be withdrawn under a given head differential. However, certain criteria must be followed for a successful artificial-recharge program. Injection wells must be as near as possible to areas of heavy pumping, yet far enough away to allow the recharge water to mix with the water already in the aquifer. Wells must be located where the depth to water is great and a thick permeable section exists above the water level for storage. Because of the users' preference for relatively cold water, the recharge water should be as cold as the ground water (13° C). The recharge water also should be free of silt or suspended material so that the efficiency of the wells could be maintained. The chemical quality of the injected water must be compatible with that of the natural ground water so that no undesirable precipitates form which could clog wells or the pore spaces within the aquifer.

Three possible surface sources of recharge water have been considered: the Great Miami River, the Little Miami River, and Mill Creek. The U.S Geological Survey has operated a gaging station on Mill Creek at Carthage since 1947. On the basis of discharge data for the water years 1947 through 1962, Kaser (1963) calculated that a sufficient yield could be obtained from Mill Creek to provide 2,920 million gallons of recharge water per year. He proposed that a low-head dam and pumping station be constructed on Mill Creek just below the mouth of West Fork, in the vicinity of Carthage. This dam and station would be designed to pass 10 cfs continuously for dilution of wastes entering the stream below the dam, and to permit pickup of discharge between 10 cfs and 41 cfs (20 mgd) of which an average of 2,920 million gallons per year would be available for recharge water. The 2,920 million gallons per year would provide 10.8 mgd of recharge water in a 270-day period, or 8 mgd for a 365-day period. A treatment plant of 20-mgd capacity constructed in the same area would provide clarification, settlement, chlorination, and rapid sand filtration of the water prior to injection through wells.

The quantity of flow and the water temperature were such that operation of the dam and treatment plant would be most profitable in the 270-day period October through June. Studies of the surface-water temperature showed that during these months the average temperature is 8° C as compared with the average ground-water temperature of 13° C. The lower temperature of the recharge water would eventually lower the temperature of the ground water and, thus, improve its usefulness for industrial cooling processes.

If more recharge water is needed, it will have to be obtained outside the Mill Creek valley. Water from the Little Miami River could be brought about 7.5 miles by pipeline to the proposed recharge plant at Carthage. A recharge facility as proposed by Kaser (1963) could be operated 270 days per year at its full 20-mgd capacity, for a total of 5,400 million gallons, using water from the Little Miami River. Thus, 14.8 mgd of recharge water would be available year round and, when added to the natural recharge, would permit a total ground-water withdrawal of about 23 mgd. As an alternative source, water at about the desired temperature (13° C) probably could be obtained from the city of Cincinnati in the winter, offpeak months.

The analog model study was made to test the validity of Kaser's empirical findings and to determine how much recharge water would be required and where it should be introduced into the aquifer to be most beneficial.

ANALOG MODEL ANALYSIS

ELECTRIC ANALOG MODEL DEFINED

An electric analog model is a small-scale laboratory replica of a real hydrologic system. The model operates on the principle that the flow of electricity through a network of resistors and capacitors is analogous to the flow of water through an aquifer. Much of the early work in ground-water hydrology was based on equations derived from those used in the study of electricity. Transmissibility, simulated by the effect of electrical resistors in the model, is a measure of the rate of movement of water through an aquifer under a given hydraulic gradient and is inversely proportional to the resistance to flow resulting from the physical character of the aquifer. The storage coefficient, simulated by capacitors in an analog model, is essentially a measure of the percentage of the total aquifer occupied by water. Changes in head, or water level, are simulated by changes in voltage impressed on the model. Thus, in the analog model, the parameters of the aquifer are simulated electrically.

The primary advantage offered by the electric analog model method of analysis is that no matter how complex the aquifer system, boundary conditions, pumping interference, and variation in recharge can be integrated in a manner that is almost impossible to achieve by any other method. The number of combinations of conditions which can be tested is almost unlimited. The time required to make such tests by conventional quantitative methods would be prohibitive. The analog is no better than the data used to construct it.

Assembly of the physical equipment used in the analog model study began with a map showing the limits of the study area, the position of the valley walls, streams, and other sources of recharge, the hydraulic coefficients of transmissibility and storage. The base map was prepared from topographic maps, and both the map and the model were ruled in a grid for ease in working from one to the other.

The model network was constructed on masonite pegboard (fig. 2), with the holes spaced 1 inch apart. The holes serve as junction points and correspond to the intersections of the grid lines on the

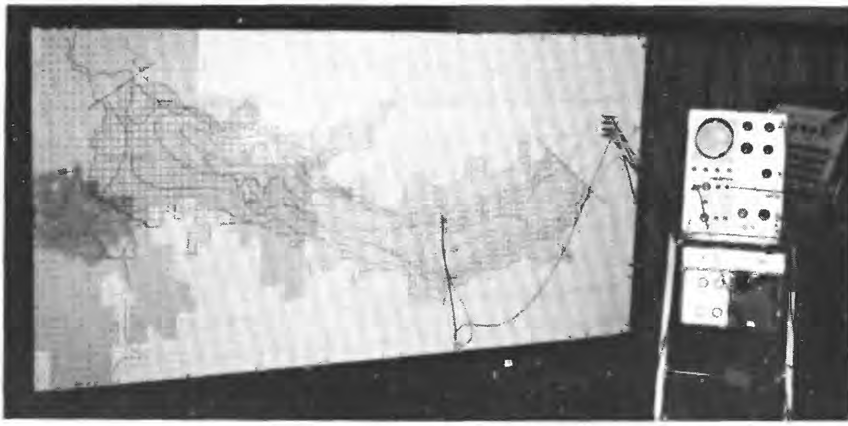

FIGURE 2.—Electric analog model as set up for the analysis of Mill Creek valley.

base map. Resistors and capacitors are wired on the front and back of the board, respectively, and are scaled according to the field-determined values of the coefficients of transmissibility and storage.

Electrical function generators are used to simulate pumpage and (or) recharge. Programing of the model is highly flexible and either pumpage or recharge can be pulsed into any junction for any period of time. The flexibility permits many combinations of well spacing and pumping rates to be tested. An oscilloscope provides visual observation of the results of the analysis. The graph on the oscilloscope screen was made to read in feet of water-level change vertically and in years horizonally. (See oscillograms, pl.2.) Both of these scales are adjustable.

MODELING THE HYDROLOGIC SYSTEM

The first step in modeling the hydrologic system is to assemble all available information related to the area of investigation. The coefficient of transmissibility of the sand and gravel deposits has been determined at several places within the Mill Creek valley by means of aquifer tests. A map showing lines of equal transmissibility (fig. 3) was prepared using data collected from these tests. The coefficient of transmissibility as shown on the map ranges from 100,000 to more than 300,000 gpd per ft (gallons per day per foot). The assumed value of the coefficient of storage, based on results of aquifer tests, is 0.20, a value typical for glacial-outwash aquifers in Ohio.

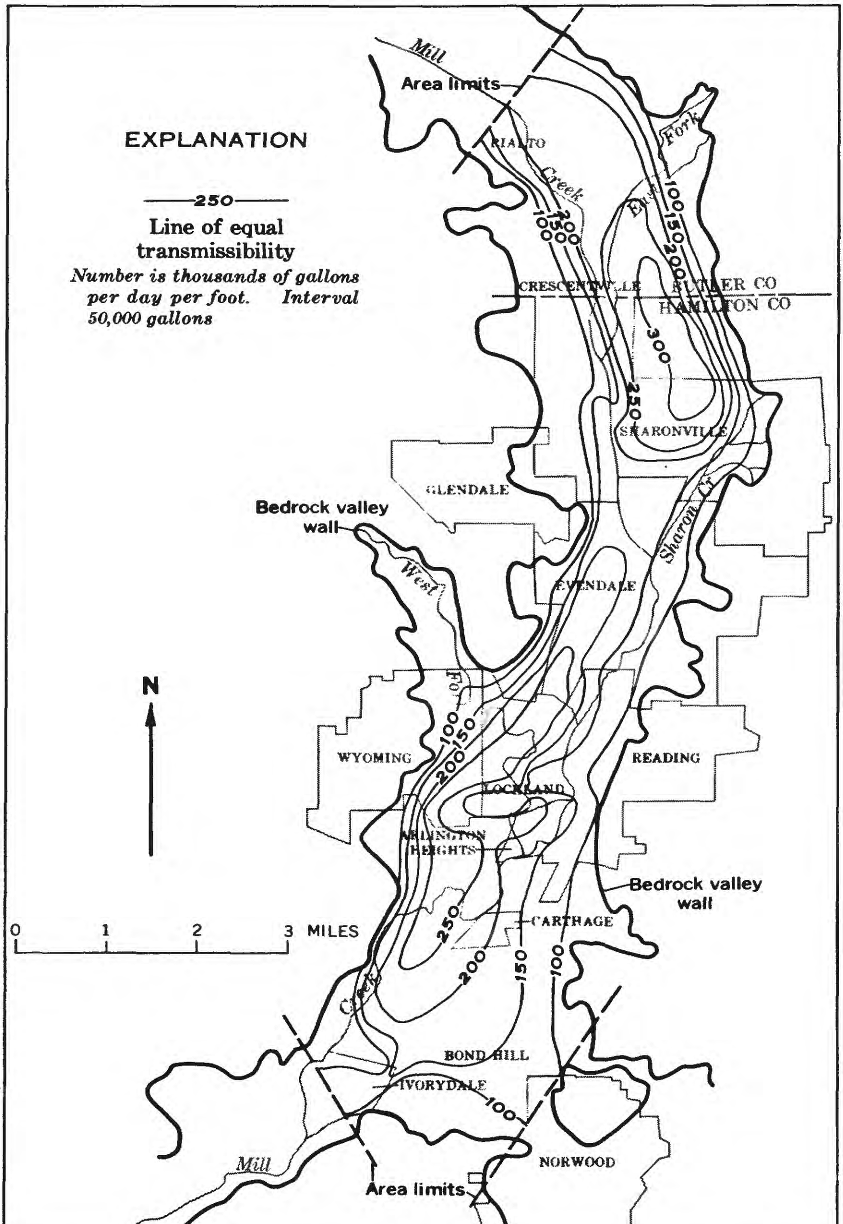

FIGURE 3.—Coefficient of transmissibility contours.

Under steady-state conditions, ground-water inflow to an aquifer will approximately equal outflow, and the water table will remain relatively stable. The generalized water levels (fig. 4) existing prior to the beginning of significant pumping in 1890 represent steady-state conditions. It was assumed that prior to development, the water table was everywhere only a few feet below the land surface.

Major water-level changes have occurred within the aquifer in Mill Creek valley as a result of pumping. Significant withdrawal of ground water began about 1890. As it is essential to know how much ground water has been pumped in the past in order to evaluate the future effects of pumping, data were collected from 51 ground-water users whose pumpage averaged more than 0.01 mgd from 1939 to 1965. Of the 51 users, 10 pump over 1 mgd, or have done so in the past 25 years; 29 pump over 0.1 mgd; and 12 pump less than 0.1 mgd. Thirty-seven users are industrial and five are municipal. In areas of concentrated development, several of the smaller users are grouped together so that a total of 32 current pumping centers are shown on the map (fig. 5). Two other pumping centers, numbers 33 and 34, represent locations of anticipated future pumping.

For convenience in programing the analog model, the pumpage data are related to five arbitrary time periods: 1890–99, 1900–19, 1920–41, 1942–51, and 1952–64. An average daily pumping rate for each of these periods (table 1) was computed for the 32 pumping centers, and the total pumping is shown graphically in figure 6.

Data for the preparation of regional contour maps were not available until 1939 when the U.S. Geological Survey, began obtaining measurements on about 50 observation wells. The number of observation wells was gradually reduced, and in 1964 there were only seven continuous water-level recorders in operation within the study area. Hydrographs of the seven wells are shown in figure 7, and the locations of the wells are shown in figure 5.

Most of the hydrographs show a net decline from the beginning of record until 1952, when the Southwestern Ohio Water Co. began furnishing water to several of the large water users. The effect on water levels resulting from cessation of local pumping is most apparent in wells H–8 at Wyoming, H–9 at Lockland, H–10 at Carthage, and H–11 at Ivorydale. Water levels rose significantly in all these wells. Wells H–7 at Evendale and H–6 at Glendale continued to show a decline, owing to increased pumping due to the northward expansion of industrial activity.

Well BU–9 at Crescentville, outside the area of heaviest pump-

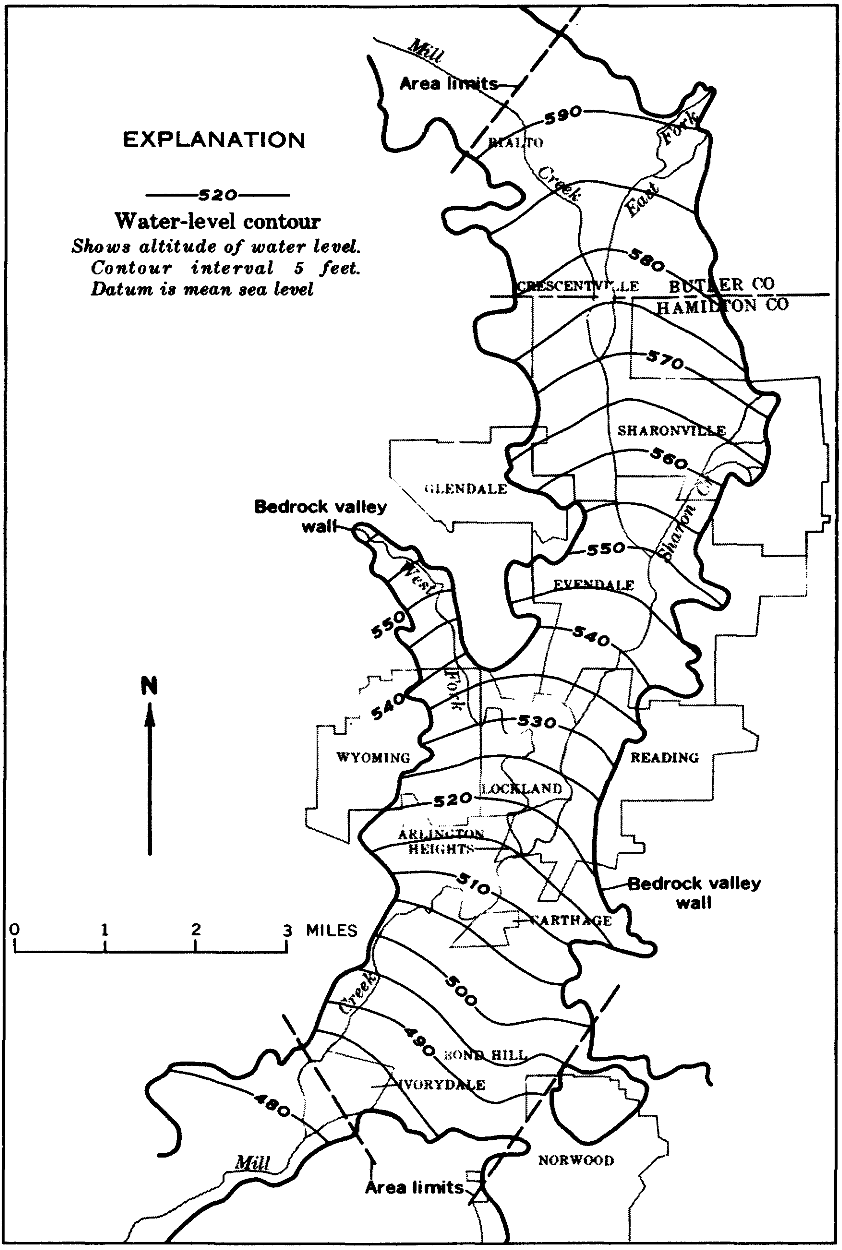

FIGURE 4.—Water-level contours as they were assumed to exist prior to the beginning of significant pumping in 1890.

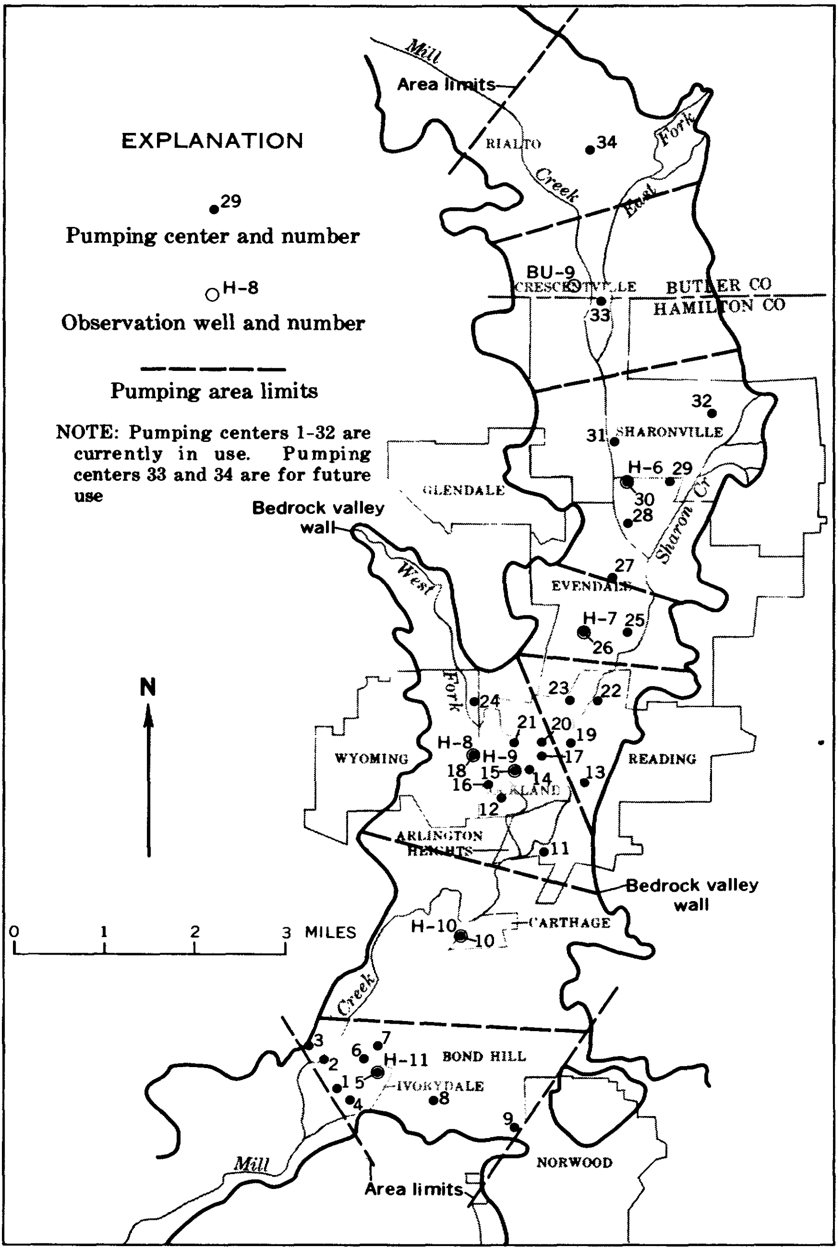

FIGURE 5.—Location of 34 ground-water pumping centers, seven observation wells, and eight ground-water pumping areas.

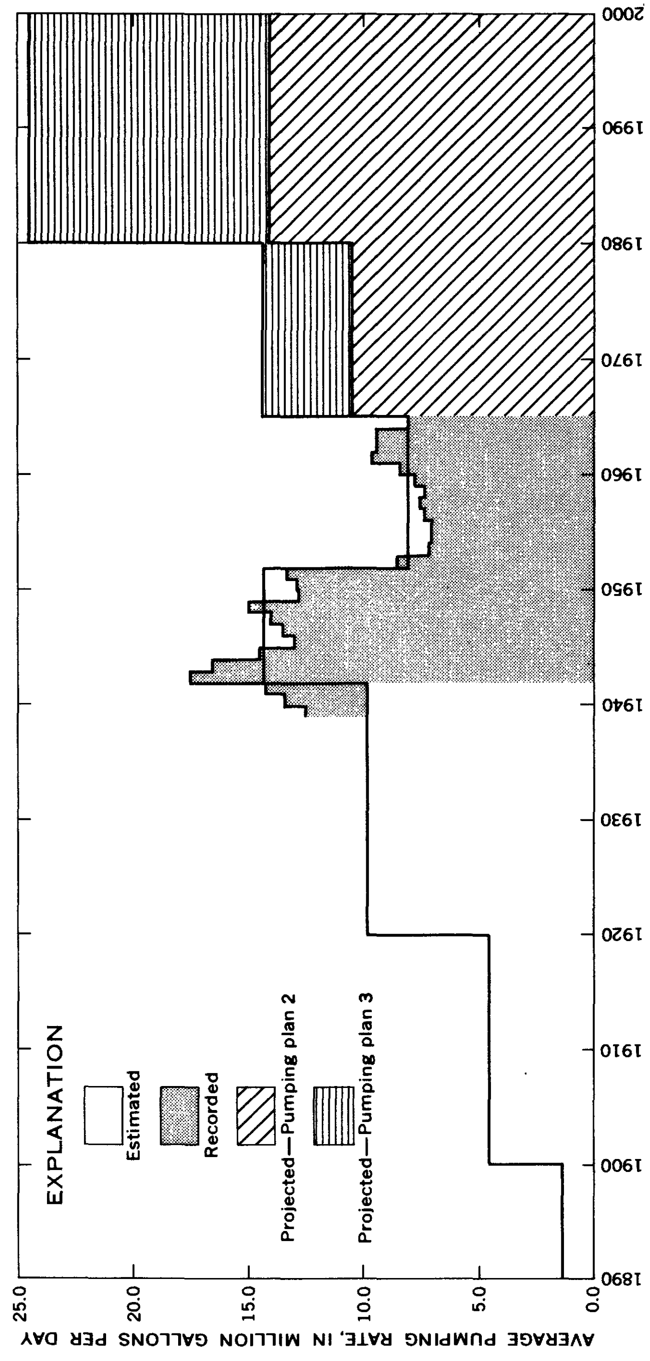

FIGURE 6.—Total average rate of ground-water pumpage at 34 ground-water pumping centers for the period 1890 to 2000.

TABLE 1.—*Average ground-water pumpage, in million gallons per day, at 32 pumping centers for the period 1890–1964*

Pumping centers (fig. 5)	1890–99	1900–19	1920–41	1942–51	1952–64
1	0.75	1.50	2.00	1.04	0.10
2	....	.10	.50	.65	.05
3	....	.30	.20	.33	.17
4	....	.07	.10	.10	.05
5	....	....	.04	.08	.04
6	....	.20	.50	.59	.07
7	....	....	.01	.08	.10
8	....	.01	.05	.05	....
9	....	.05	.10	.15	.01
10	0.25	.25	1.00	2.29	.43
11	....	....	.03	.04	....
12	....	.50	1.50	1.91	.59
13	....	.30	.08	.12	....
14	....	.10	.35	.50	.11
15	....	.50	1.00	1.05	.03
16	....	.03	.10	.13	....
17	....	.05	.15	.22	.10
18	0.50	.50	.70	.98	.75
19	....	.10	.25	.72	1.57
20	....	....	.30	.13	.13
21	....	....	....	.16	.83
22	....	.01	.04	.05	.04
23	....	....	.20	.99	.75
24	....	.15	.30	.52	....
25	....	....	....	....	1.12
26	....	....	.01	.56	.44
27	....	.01	.05	.07	.02
28	....	.20	.30	.41	.21
29	....	.07	.15	.24	.03
30	....	.14	.18	.22	.28
31	....	....	....	....	.05
32	....	....	....	....	.04
Total	1.50	4.60	9.92	14.38	8.11

ing, shows a cyclic fluctuation in water level ranging from 10 to 20 feet per year. Highest levels normally occur during the first half of each year.

North-south profiles of the water levels in Mill Creek valley (fig. 8) show the position of the water table or piezometric surface in selected years. The profiles for the four years 1890, 1944, 1951, and 1964 show significant changes. The water-level profile in 1890 represents the approximate static level prior to any significant pumping in the valley. The water levels in 1944 show the effects resulting from heavy pumping during World War II. The

1951 water-level profile represents conditions after the war, prior to the importation of water by the Southwestern Ohio Water Co. The 1964 water-level profile shows the effect of the reduction in

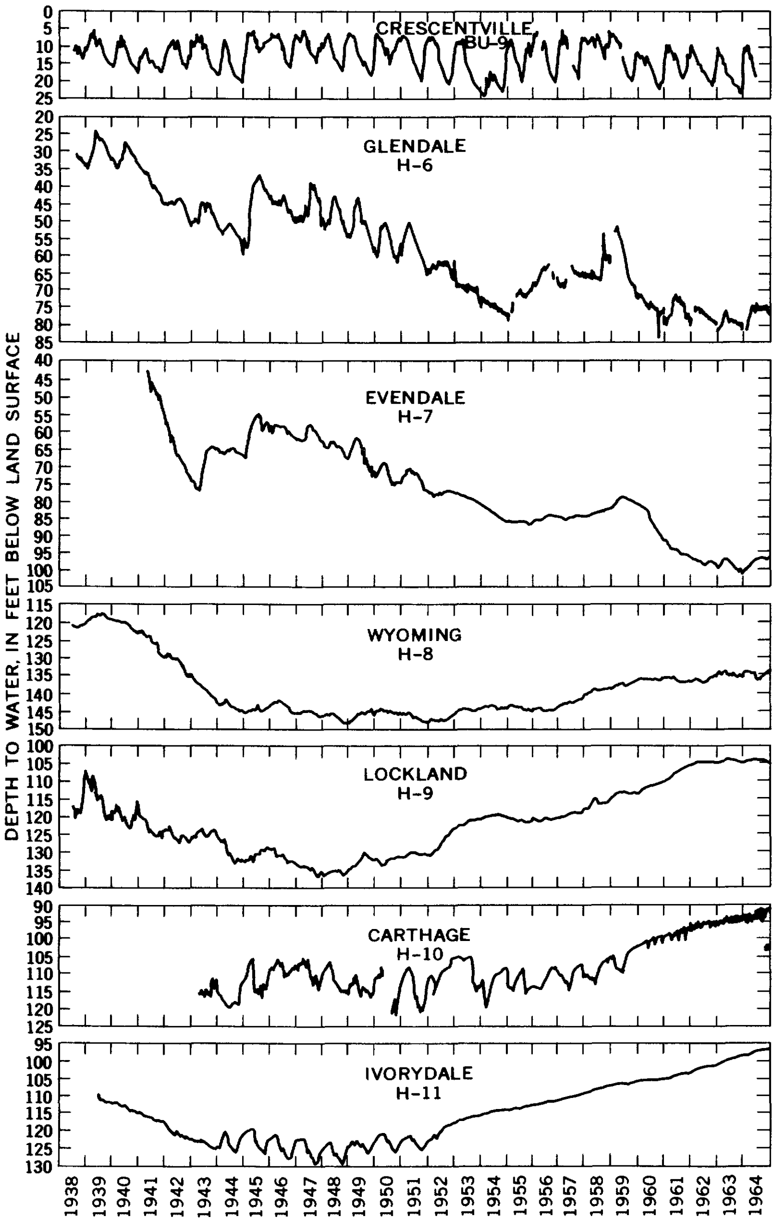

FIGURE 7.—Water-level trends in seven observation wells.

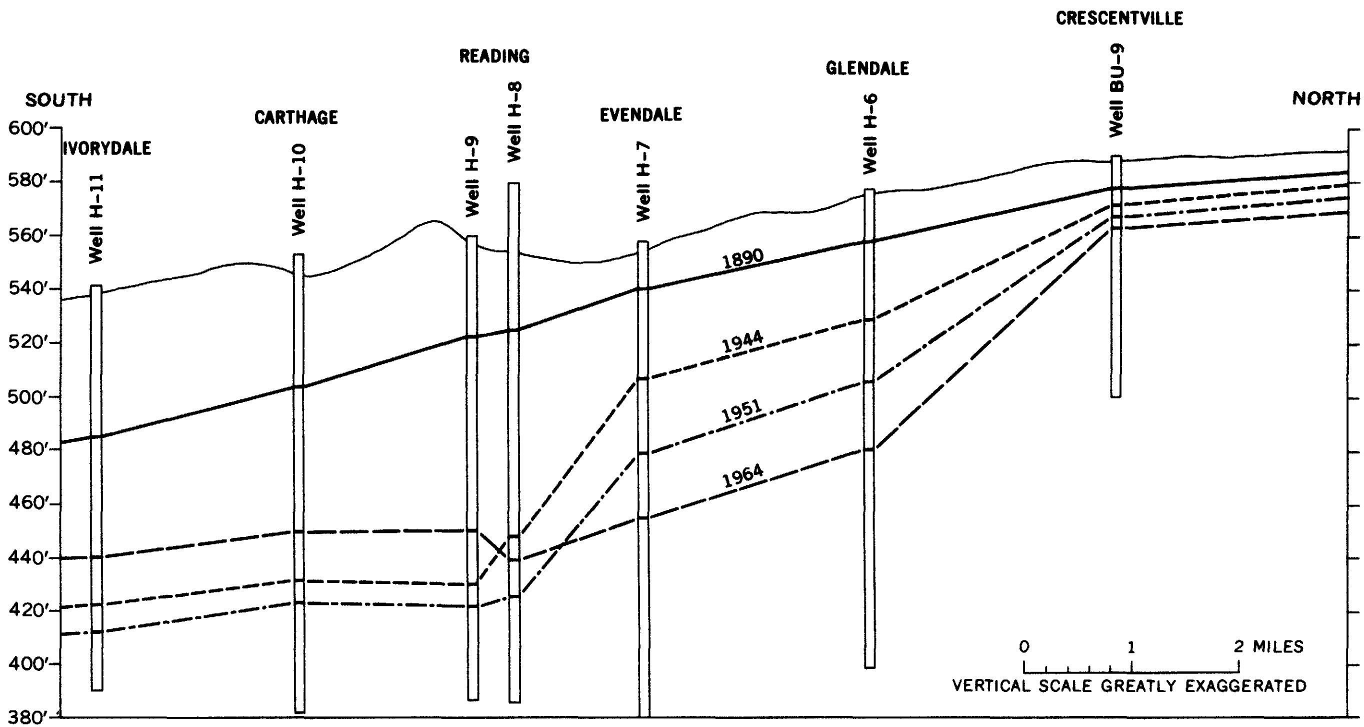

FIGURE 8.—Generalized profiles of ground-water levels showing lowest water levels for 1890, 1944, 1951, and 1964. Datum is mean sea level.

local pumpage that occurred after the establishment of the Southwestern Ohio Water Co. The center of greatest drawdown is moving northward in the valley. This is attributable to the importation

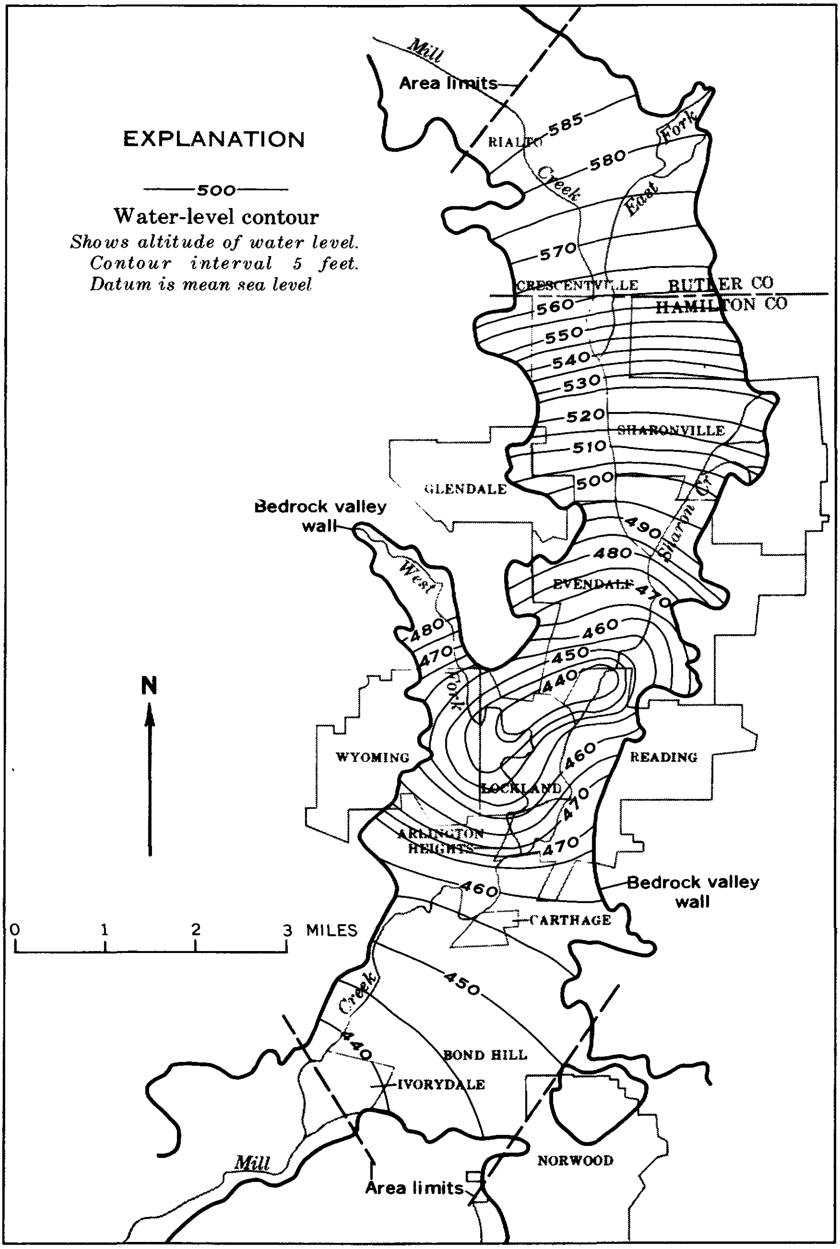

FIGURE 9.—Water-level contours as they existed at the end of 1964.

of water by the Southwestern Ohio Water Co. and the increase in ground-water pumpage in the central part of the valley.

On the basis of seven hydrographs and the records from other

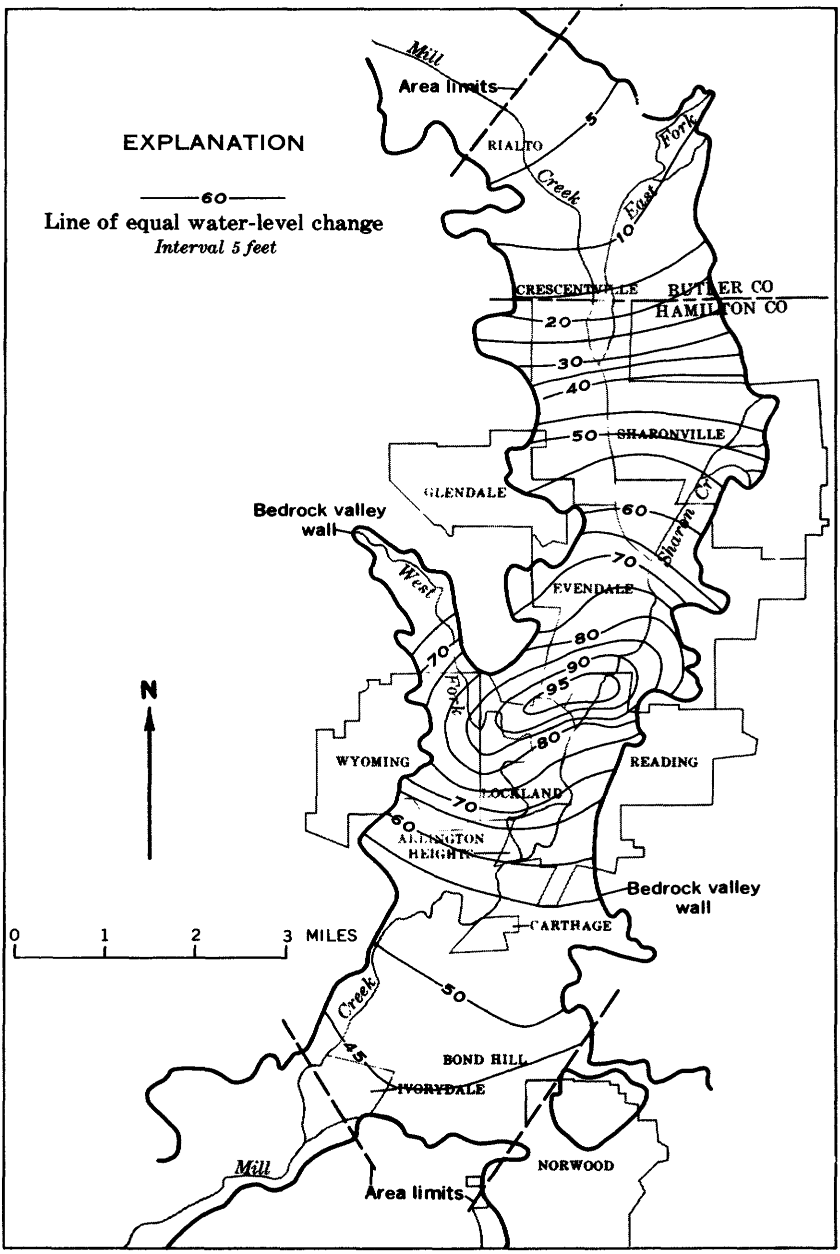

FIGURE 10.—Water-level change caused by pumping, 1890–1964.

wells measured periodically, a water-level contour map was prepared for 1964 (fig. 9). Elevations shown in figure 9 were subtracted from the water-level elevations in figure 4, which represent conditions prior to ground-water development. The differences in water levels were plotted on a base map and contoured to produce a map showing changes in water levels between 1890 and 1964 (fig. 10).

Six natural recharge and discharge boundaries, shown in figure 11, were used in designing the analog model. Boundaries A and D represent the shale and limestone formations along both sides of the valley. Most wells drilled in the bedrock yielded less than 5 gpm (gallons per minute) ; therefore, it can be assumed that the bedrock contributes very little water to the aquifer. As water levels were lowered, however, relatively more water was drawn from the shale and limestone formations.

Discharge boundaries B and C, at Ivorydale and Bond Hill, respectively, have become recharge boundaries resulting from ground-water development and the reversal of natural gradients. Under natural conditions, ground water flowed across these hypothetical boundaries and eventually discharged into the Ohio River. With development of the area, water levels were lowered by pumping, and a cone of depression was created that induced ground-water flow toward the wells.

Boundary F represents the natural inflow to the aquifer across the north limit of the area. Boundary E represents the surface area from Evendale to Rialto and represents induced infiltration from Mill Creek and recharge resulting from precipitation falling directly on the surface and infiltrating through the unconsolidated deposits to the water table. Lowering of water levels in this part of the area where the confining clay beds are absent has reduced natural losses from evapotranspiration.

Induced infiltration from Mill Creek is difficult to assess. In the reach between Evendale and Rialto, the creek is nearly dry most of the year. South of Evendale the creek contains water, but infiltration is inhibited by clay layers beneath the streambed. For these reasons Mill Creek was not considered as a separate boundary.

PROGRAMING AND VERIFYING THE ANALOG MODEL

After the analog model was constructed, a test was made to determine whether the values of transmissibility and storage that were built into the model were representative. Adjustments were made where necessary so that when changes in pumping and recharge were programed into the model the resultant water-level changes, read out at each junction and plotted on a base map, agreed with the map of observed water-level change (fig. 10).

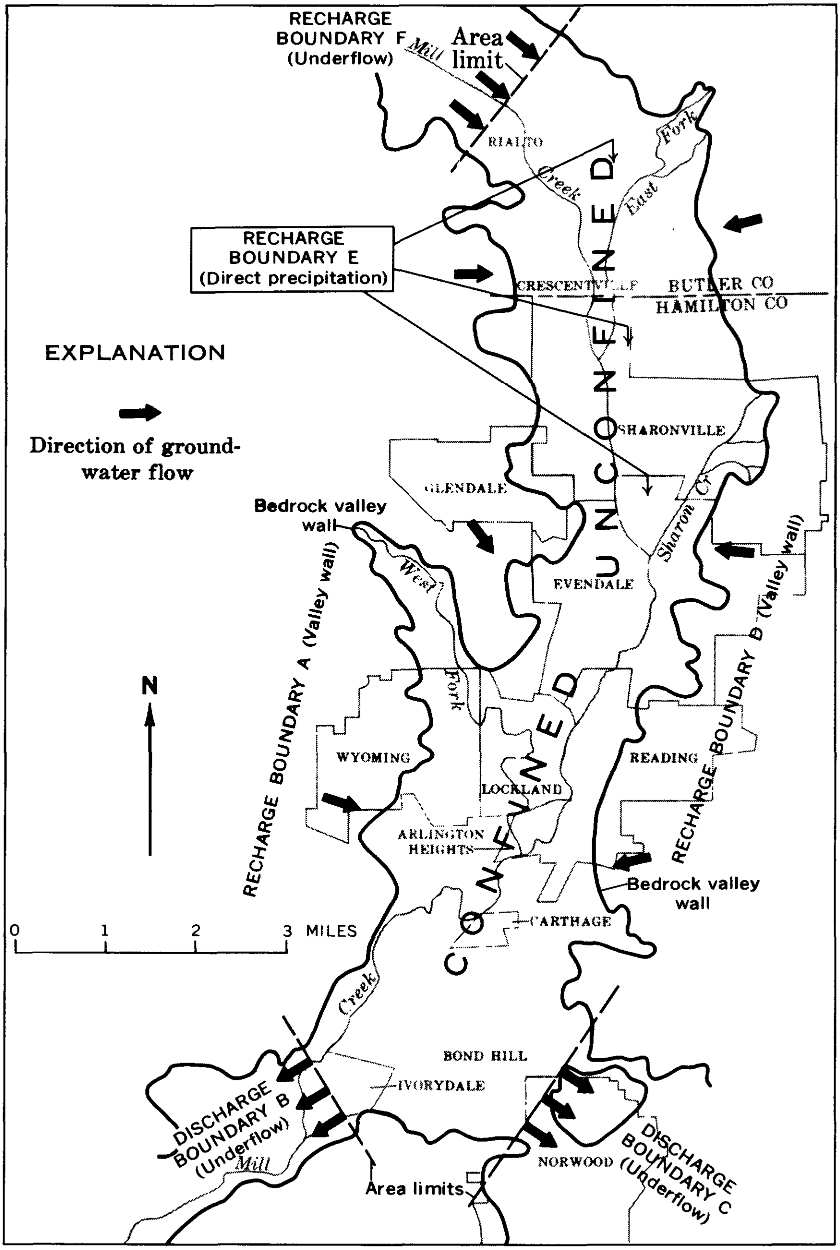

FIGURE 11.—Location of six natural recharge and discharge boundaries.

Before proceeding with the analog model analysis, it was arbitrarily decided that lowering of ground-water levels in the model, in the most heavily pumped area, should not exceed the lowering shown for 1952–64 on the map (fig. 10), which was based on actual field data. The following table shows the arbitrary limits of the water-level changes set for the observation well locations. Well BU–9 at Crescentville shows a change of only about 20 feet; however, the change at that location could probably be increased to 40 feet because the map was based upon data collected prior to significant pumping in the Crescentville area.

Well	*Location*	*Maximum allowable change in water level (feet)*
BU–9	Crescentville	40
H–6	Glendale	50
H–7	Evendale	80
H–8	Wyoming	80
H–9	Lockland	80
H–10	Carthage	50
H–11	Ivorydale	40

From the model a series of four water-level change maps was prepared which illustrates the simulated effects of pumping on the aquifer resulting from industrial development from 1890 to 1965. The first map (pl. 2A), for the year 1920, shows the water-level changes resulting from an average pumping rate of 1.5 mgd programed into the model for the period 1890–99 and 4.6 mgd for the period 1900–19. The maximum water-level change of 25 feet indicates that no apparent water problem existed during the period.

Plate 2B, for 1942, shows the effects resulting from an increase in the average pumping rate to 9.92 mgd for the period 1920–41. Plate 2C, for 1952, shows the effects of increasing the average rate to 14.38 mgd for the period 1942–51. Most of the increase occurred in the central and southern parts of the valley, where water levels were lowered considerably.

From 1952 to 1965, ground-water pumpage was reduced to an average of 8.11 mgd owing to importation of water by the Southwestern Ohio Water Co. Most of this imported water went to industries in areas where water levels were extremely low, as in the Ivorydale, Carthage, Lockland, and Wyoming areas. Pumpage in these four areas was reduced about 8.07 mgd. An increase of about

1.5 mgd occurred in the Reading and Evendale areas, however. Plate 2D, for 1965, shows the effects of these changes in pumpage distribution.

For each change map prepared from the analog model, oscillograms are shown representing water levels at five locations in the valley (pl. 2). The oscillograms show the changes in water levels from 1890 to 1965. Oscillogram 1 shows the water-level change in the vicinity of Crescentville; 2, Evendale; 3, Reading; 4, Lockland; and 5, Carthage. Location of the five sites is shown on each change map. The water level near Reading, oscillogram 3, shows a greater change than that at any other of the selected locations. Similar oscillograms, observed on the oscilloscope at each junction point, were used as a basis for the preparation of the change maps. By selection of specific values, change maps could have been drawn for any desired time interval.

PREDICTIONS OF FUTURE WATER LEVELS BASED ON PROJECTIONS OF PUMPING

PROJECTIONS OF PUMPING RATES

To predict future water levels in the Mill Creek valley, pumping rates were arbitrarily projected to the year 2000. Three hypothetical pumping programs were considered, involving six arbitrarily designated areas of past and present pumping, and two areas in which significant pumping is expected to begin in the future. These pumping areas, shown in figure 5, are identified as (1) Ivorydale, (2) Carthage, (3) Lockland-Wyoming, (4) Reading, (5) Evendale, (6) Glendale-Sharonville, (7) Crescentville, and (8) Rialto. Table 2 shows the projected average daily pumping rates for these areas. Estimates of future pumpage in two areas, Crescentville and Rialto, are based on information from local planning groups. Pumpage records and estimates for all areas are shown graphically in figure 12.

PUMPING PLAN 1

Pumping plan 1 is based on the conservative assumption that pumping will continue to the year 2000 at the rate of 8.11 mgd, the same as in the period 1952–64 (table 2). Under this hypothetical program, pumpage in the southern part of the valley (Ivorydale and Carthage) will be less than at present, and that in the central part of the valley (Lockland-Wyoming, Reading, and Evendale) will be greater. Pumping in the Glendale-Sharonville

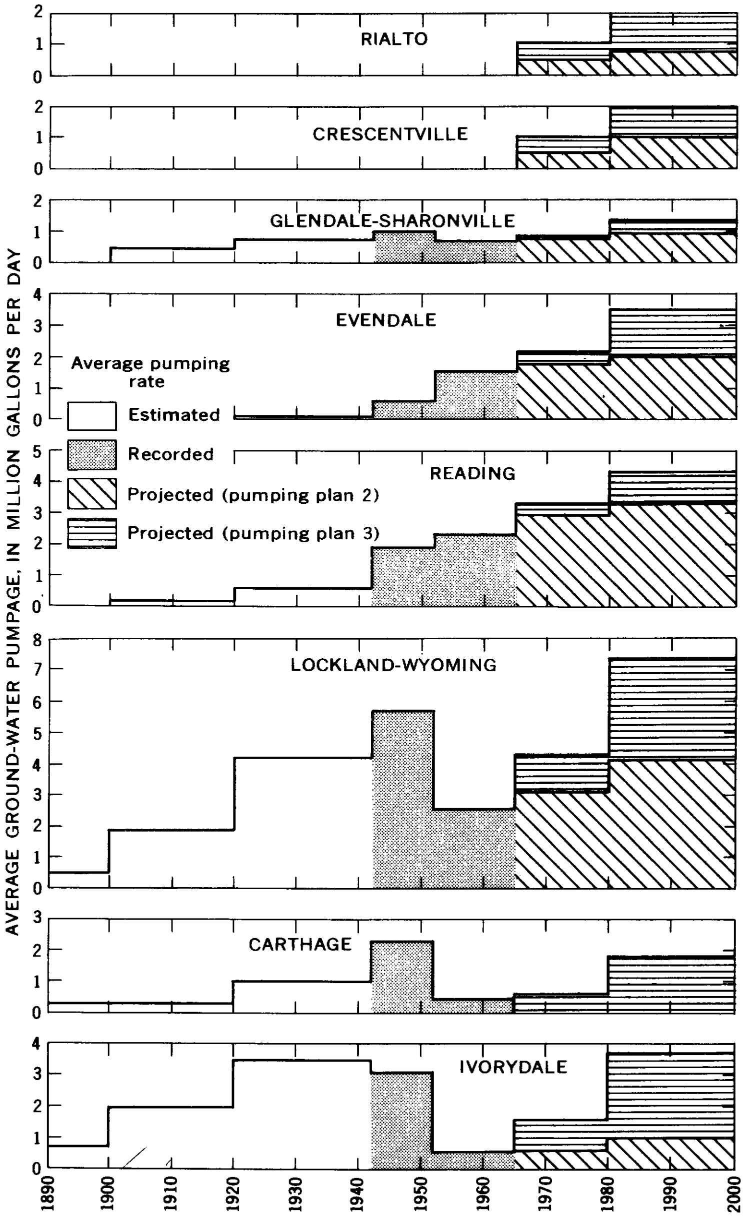

FIGURE 12.—Average pumping rates for eight major ground-water pumping areas.

TABLE 2.—*Projected average ground-water pumpage, in million gallons per day, from 1965 to 2000*

Pumping centers	Pumping plan 1 1965–99	Pumping plan 2 1965–79	Pumping plan 2 1980–99	Pumping plan 3 1965–79	Pumping plan 3 1980–99
Ivorydale:					
1	0.10	0.40	0.90	0.75	1.75
2	.05	----	----	.20	.60
3	.17	.03	----	.14	.27
4	.05	.05	.05	.08	.16
5	.04	.04	.04	.05	.09
6	.07	.05	----	.20	.50
7	.10	.03	----	.10	.13
8	----	----	----	.03	.08
9	.01	----	----	.04	.12
Total	.59	.60	.99	1.59	3.70
Carthage: 10	.43	----	----	.60	1.80
Lockland-Wyoming:					
11	----	----	----	.02	.05
12	.59	.50	.50	1.00	1.95
14	.11	----	----	.15	.55
15	.03	----	----	.50	1.45
16	----	----	----	.04	.15
17	.10	.15	.20	.14	.23
18	.75	1.05	1.40	.95	1.10
20	.13	.25	.45	.15	.15
21	.83	1.15	1.60	1.10	1.10
24	----	----	----	.25	.65
Total	2.54	3.10	4.15	4.30	7.38
Reading:					
13	----	----	----	.04	.11
19	1.57	2.65	3.75	2.10	2.10
22	.04	----	----	.02	.06
23	.75	.65	.60	.80	1.05
Total	2.36	3.30	4.35	2.96	3.32
Evendale:					
25	1.12	1.22	1.32	1.10	1.55
26	.44	.54	.64	1.05	1.95
Total	1.56	1.76	1.96	2.15	3.50
Glendale-Sharonville:					
27	.02	.02	.02	.05	.10
28	.21	.21	.21	.15	.50
29	.03	.01	.01	.08	.21
30	.28	.33	.40	.33	.33
31	.05	.10	.10	.10	.10
32	.04	.10	.19	.10	.11
Total	.63	.78	.94	.81	1.35
Crescentville:					
33	----	.50	1.00	1.00	2.00
Rialto:					
34	----	.50	.75	1.00	1.50
Total, all locations	8.11	10.54	14.14	14.41	24.55

area will not change appreciably under pumping plan 1, and there will be no pumping in the Crescentville and Rialto areas.

Pumpage of 8.11 mgd, for the period 1965–99, was pulsed into the analog model at 27 pumping centers. As the maximum natural recharge programed into the model was 8.5 mgd, the change in water levels in the aquifer generally was slight. It was reasonable to assume that 8.11 mgd could be withdrawn from the aquifer for an indefinite time without causing serious water-level decline in any part of the valley.

PUMPING PLAN 2

Pumping plan 2 is based on the assumption that trends in pumping rates observed in 1960–64 will continue to 2000; that is, pumping rates will continue to decline in the southern part of the valley and to increase in the south-central and central parts of the valley. This projection also takes into account the strong probability that industrial expansion in the northern part of the valley will cause an increase in pumpage in a previously undeveloped area. The projected pumping rates for the entire valley are 10.54 mgd for the period 1965–79, and 14.14 mgd for the period 1980–99. These values (table 2) were pulsed into the model at the 34 pumping centers shown in figure 5.

The projected pumping rate of 10.54 mgd for the period 1965–79 represents an increase of 2.43 mgd over the 1952–64 period. The most significant increase is forecast for the Lockland-Wyoming, Reading, Crescentville, and Rialto areas. For Lockland-Wyoming and Reading, the assumed increase is 1.5 mgd, and for Crescentville and Rialto, 0.5 mgd each. In the vicinity of Carthage, the projected pumpage is nil.

The change map (pl. 3*A*) shows the hypothetical effects on water levels resulting from pumping plan 2 for the first part of the period 1965–79. Water-level changes generally are within the arbitrary limits, and are significant only in the Reading area, where they exceed 95 feet.

The hypothetical pumping rate of 14.14 mgd for the second part of the period 1980–99 represents an increase of 6.03 mgd over the 1952–64 period and 3.6 mgd over the 1965–79 period. The projected pumping rate, considering the area as a whole, is about the same as that of the 1942–51 period. The greatest projected increase in pumping, compared with 1952–64, is in the Lockland-Wyoming, Reading, Crescentville, and Rialto areas. In the Lockland-Wyoming and Reading areas, the projected increase is 3.6 mgd, and at Crescentville and Rialto, 1.75 mgd.

These four areas alone account for nearly all the 6.03 mgd increase.

The water-level change map (pl. 3*B*) for 1980–99 shows a drastic lowering of water levels, which is most pronounced in the central part of the valley. Only at Ivorydale, Crescentville, and Rialto are the changes in water levels within the arbitrary limits. The maximum change, 131 feet, occurred in the Reading area, indicating a potential depth to water there of about 155 feet, lower than that observed during World War II.

Oscillograms from the model, representing the five key sites in pumping plan 2, are shown on plate 3. The first part of each oscillogram shows the changes in water levels from 1890 to 1965, and the other part represents the hypothetical changes resulting from recharge plans A and B.

PUMPING PLAN 3

Pumping plan 3 was made on the assumption that present ground-water users would pump at maximum rates of record by the year 2000. Also, it was assumed that pumping would begin and significantly increase in the northern part of the valley. The projected pumping rates for the area as a whole are 14.41 mgd for the period 1965–79 and 24.55 mgd for the period 1980–99. Table 2 lists the values programed at each of the 34 pumping centers shown in figure 5.

The projected pumping rate of 14.41 mgd for the period 1965–79 represents an increase of 6.3 mgd over the 1952–64 period. Increases in pumpage are programed for all eight pumping areas. Plate 4*A* shows the simulated effects on water levels caused by the hypothetical pumping for the 1965–79 period. In all probability, pumping in the central part of the valley will decline by 1980. Only at Ivorydale, Crescentville, and Rialto are water levels expected to stay within the limits set.

From 1980 to 2000, the projected pumping rate is estimated at 24.55 mgd, an increase of 10.14 mgd over the 1965–79 period and of 16.44 mgd over the 1952–64 period. Pumping at these rates would significantly lower water levels over the entire area, as shown on plate 4*B*. The change of 160 feet indicated by the model for the central part of the valley would be impossible under real pumping conditions, as water levels would be below the base of the aquifer.

Oscillograms from the model, representing five critical sites, are shown on plate 4. It is apparent from the change maps and oscillograms that hypothetical pumping rates approaching 25 mgd cannot be sustained under natural conditions.

SIMULATED ARTIFICIAL RECHARGE

Several methods of artificially recharging glacial-outwash aquifers have been used successfully. In the Mill Creek valley study, only the injection-well method was examined because other common methods, such as water spreading, require the use of large land areas which are not readily available in this heavily populated area.

The analog model was used to determine the practicability of the injection-well method of artificial recharge in the Mill Creek valley. A trial-and-error method was used to find the most desirable locations for recharge wells where the least amount of recharge water could have the greatest effect on the water levels. The wiring required for placing injection wells in the model is simple and easily changed, permitting virtually an unlimited number of recharge combinations to be tested.

The more water pumped from an aquifer, the greater will be the natural recharge which will enter the aquifer in response to lowered ground-water levels and increased gradients. Conversely, the more artificial recharge that is put into the aquifer, the less will be the natural recharge. This situation limits the quantity of artificial recharge that is practical for a given aquifer.

To avoid complications, several criteria were established to simplify the testing procedures. First, the maximum input at each injection-well site was set at 2 mgd, a rate based on knowledge of the hydraulic properties of the aquifer. Second, the minimum spacing of the injection wells was 1,600 feet, or 0.25 mile. The electrical junction points on the model represent 800-feet spacing, and no wells were placed closer together than two junction points. Finally, a maximum water-level change of 60 feet was set as a criterion for determining when enough recharge water had been introduced into the system to raise the water levels to a practical level. The 60-foot change criterion cannot be applied to the entire valley, as locally the aquifer is not thick enough for 60 feet of change to occur. On the model, the recharge water was introduced near the areas of greatest pumpage, where the net change in water levels has generally exceeded 60 feet.

Values of the recharge rate were estimated using the above criteria and pulsed into the model at selected junction points or simulated wells. If the water-level changes were above or below the limits set, adjustments were made by either relocating the injection wells or varying the quantity of water being introduced.

Different combinations of recharge wells and injection rates were superposed on and tested for each the hypothetical pumping plans except for pumping plan 1. Pumping plan 1 did not warrant further examination, as water levels would not be further lowered if pumpage were to remain constant until the year 2000.

For pumping plan 2, two recharge plans were tested and are designated as recharge plans A and B. In recharge plan A, water at a constant rate was introduced into the system for the 35-year period 1965–99. It was assumed for recharge plan B that an artificial recharge program would not be undertaken immediately. Water was introduced into the system at a constant rate beginning in 1980 and continuing to 2000. By using both plans a comparison can be made showing the effects of waiting until a water crisis actually occurs in Mill Creek valley versus the results of a program designed to keep pace with the increasing demand.

RECHARGE PLAN A

In recharge plan A, for the period 1965–79, the projected pumping rate is 10.54 mgd and the maximum natural recharge is estimated as 8.5 mgd. Thus, a hypothetical deficit of 2.04 mgd exists, which must be replaced for ground-water levels to rise to their observed position in 1964 (fig. 10). More than 2.04 mgd was pulsed into the model, however, to raise levels above those of 1964 and to bring the net water-level changes to within the 60-foot limit. No attempt was made in the model simulation to raise water levels to their original prepumping position.

Three injection wells, each recharging at the rate of 2 mgd, were located near the center of heaviest pumping. Response of the model showed that a recharge rate of 6 mgd would raise groundwater levels to the desired position. The injection well locations and the simulated effects of artificial recharge are shown on the 1965–79 change map (pl. 3*C*). Recharge across the six natural boundaries (fig. 11) totals 5 mgd on (pl. 3*C*), or 4 mgd less than that postulated for the condition where no artificial recharge has been injected (pl. 3*A*). Because the maximum natural recharge available to the aquifer under near minimum ground-water levels is 8.5 mgd, much natural recharge is rejected by maintaining water levels within the 60-foot change limit.

Postulated recharge for the period 1965–79, based on pumping plan 2 and recharge plan A is 11 mgd—5 mgd from natural recharge and 6 mgd from artificial recharge. If the assumed pumping rate of 10.54 mgd is continued beyond 1980, water levels will rise and gradients will be reduced so that only 4.54 mgd will enter the aquifer from natural recharge instead of 5 mgd, and the system will be in equilibrium. Under the stated conditions, the average daily pumpage could be increased from 10.54 to a maximum of 14.5 mgd without causing the water levels to decline below the levels observed in 1964 (fig. 10). By using the higher pumping rate, more of the estimated total potential of 8.5 mgd natural recharge would become available.

The projected average pumping rate for the period 1980–99 is 14.14 mgd under pumping plan 2. A constant artificial recharge rate of 6 mgd was simulated for this period. The effects on water levels are shown on plate 3*D*. The natural recharge from the six boundaries totals 5.5 mgd, the natural recharge plus the artificial recharge of 6 mgd give a 11.5 mgd total recharge. Thus, a deficit of 2.64 mgd exists for the period. However, if pumping at the projected rate were continued beyond the year 2000, water levels would decline until the lower gradients would permit natural recharge to increase to 8.14 mgd and eventually bring the system into equilibrium. As the net result, water levels in the year 2000 would be slightly higher than those observed in 1952–64 (fig. 10).

RECHARGE PLAN B

Recharge plan B was based on the premise that an artificial recharge program would not be initiated until a critical lowering of water levels occurs in Mill Creek valley. The same projected pumping rates as were considered in recharge plan A were pulsed into the model for the periods 1965–79 and 1980–99. No artificial recharge was introduced until 1980, after an assumed decline in water levels resulting from increased pumping. Six million gallons per day was injected into the system beginning in 1980 and continuing to 2000. The simulated effects on water levels are shown on the change map for the period 1980–99 (pl. 3*E*). Natural recharge from the six boundaries for the period 1980–99 is 6.5 mgd, resulting from the relatively steep gradients. Total recharge to the aquifer is 12.5 mgd by 2000. If the postulated pumping and artificial recharge rates were continued beyond 2000, water levels would eventually be lowered until the system was in equilibrium.

Oscillograms representing ground-water levels at the five key sites (pl. 3) show a comparison of the water-level response to variations in artificial recharge. Change maps were prepared from values read out at the end of each period, 1979 and 1999, and do not reflect intermediate conditions. Although the change maps generally indicate that the objectives have been met, conditions often are worse than indicated at times preceding the end of the period. This condition is most evident for recharge plan B, under which artificial recharge is not introduced into the system until 1980 and water levels decline seriously prior to that time.

RECHARGE PLANS C AND D

Recharge plans C and D were designed for pumping plan 3. In recharge plan C, eight simulated injection wells were located on the model in areas of greatest withdrawal. For the period 1965–79, 1 mgd was pulsed constantly through each of the eight simulated injection wells to represent a total recharge of 8 mgd. For the period 1980–99, 2 mgd was pulsed into the model through each of the eight wells to represent a total recharge of 16 mgd. The hypothetical pumping rates were 14.41 mgd for the first period, and 24.55 mgd for the second. The injection-well locations and the simulated effects of artificial recharge are shown on plates *4C* and *4D*.

Injection of 8 mgd into the aquifer plus the natural recharge of 8.5 mgd would sustain a maximum pumping rate of 16.5 mgd without taking additional water from aquifer storage. Thus, for an average pumping rate of 14.41 mgd, water levels would be maintained above the 1952–64 levels. For the second period, an artificial recharge rate of 16 mgd would allow withdrawal of 24.5 mgd.

For recharge plan D, water at a constant rate of 16 mgd was injected into the aquifer commencing in 1980 and continuing to 2000 (pl. *E*). The five oscillograms on plate 3 show the changes in water levels resulting from both recharge plans.

SUMMARY AND CONCLUSIONS

Industries in the Mill Creek valley depend on an adequate ground-water supply to sustain their economic growth. Ground-water demand has been increasing steadily since 1890. During World War II, water levels declined to the point where many industries were forced to reduce pumpage or abandon wells. The Southwestern Ohio Water Co., formed in 1952, pipes ground water from the Great Miami River valley to several of the larger ground-water users in the Mill Creek valley. As a result of this diversion, water levels have risen locally in what formerly were problem areas. Although important locally in insuring an adequate water supply for member industries, importation of water by the Southwestern Ohio Water Co. is not considered a final solution to the problem of providing an adequate water supply generally in the Mill Creek valley.

A comprehensive plan for developing the ground-water resources in Mill Creek valley is as yet unformulated. Planning groups predict enormous industrial and building expansion for this area, which will require large quantities of water. In 1964, ground-water pumpage from the sand and gravel aquifer was about 8.1 mgd, and the pumpage demand is expected to exceed 25 mgd by 2000.

In this study three hypothetical pumping plans were developed by projecting past pumpage data to 1980 and 2000 and were programed into the electric analog model. Analysis for pumping plan 1 showed that if ground-water pumpage demand were to remain at about 8.5 mgd to 2000, no significant water problems would exist. Pumping plans 2 and 3 were based on expected large future increases in demand. For pumping plan 2, the projected average pumping rates are 10.54 mgd for the period 1965–79 and 14.14 mgd for the period 1980–99. For pumping plan 3, the projected average pumping rates are 14.41 mgd for the period 1965–79 and 24.55 mgd for the period 1980–99. Analysis showed that for either plan water levels would decline to critical levels, and the demand could not be met.

Artificial recharge through various combinations of injection wells was tested on the analog model under the hypothetical conditions of pumpage. Under pumping plan 2, analysis showed that three injection wells providing about 2 mgd each to the aquifer would maintain water levels at an efficient level. For pumping plan 3, eight injection wells providing about 1 mgd each until 1980 and about 2 mgd each from 1980 to 2000 would be required. Based on electric analog model analysis, each artificial recharge plan tested showed that water levels would be nearly the same as those levels observed at the end of 1964.

The results of the analog model analysis provide guidelines for assessing the value of artificial recharge as a solution to the problem of local overdevelopment. Perhaps none of the artificial recharge plans studied here will be put into effect. It may be that none of the proposed plans represent the best solution. However, there seems little doubt, on the basis of this study, that artificial recharge through injection wells can provide for additional ground-water use up to about 25 mgd. Sufficient surface water for artificially recharging the aquifer in Mill Creek valley is available from Mill Creek and Little Miami River.

Industrial and residential growth is rapidly expanding in the Mill Creek valley, and data collection on a systematic basis should be continued. Local pumpers should keep a close watch on water levels in the vicinity of their own properties. This is especially important for the recharge area north of Evendale, where much industrial growth is expected. As ground-water pumpage increases, additional studies will be needed for measurement and evaluation of any significant changes in the hydrologic system.

More engineering work be required to design and develop an injection-well system and a recharge program in the Mill Creek valley on a practical basis. Engineering and economic feasibility will largely determine the character of any recharge project.

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