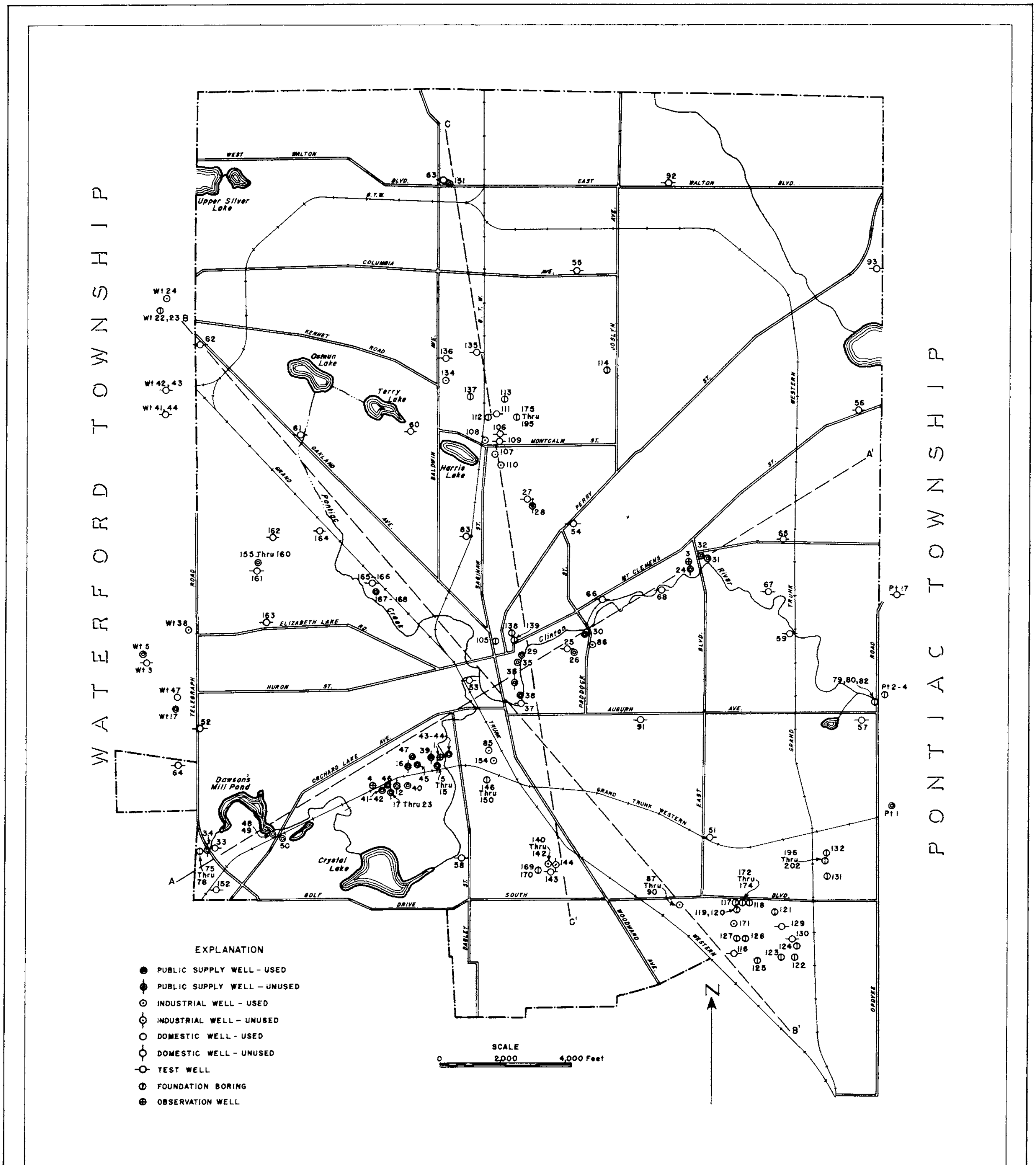

PLATE 3. MAP OF PONTIAC, MICHIGAN, SHOWING LOCATION OF WELLS, FOUNDATION BORINGS, AND GEOLOGIC CROSS SECTIONS

GROUND-WATER CONDITIONS IN PRINCIPAL AREAS OF DEVELOPMENT

Pontiac and environs

<u>Nature and extent of water-bearing formations</u>

Surficial outwash and alluvium

As shown by plate 1, the only extensive areas of permeable deposits mantling the surface of Pontiac and its environs are two small areas of outwash; one bordering the Clinton River in the southwestern part of the city and the other bordering Galloway Creek northeast of the city. Elsewhere the permeable surficial deposits are limited to the narrow bands of Recent alluvium which parallel the stream courses through Pontiac.

The locations of wells and foundation borings in Pontiac are shown by plate 3. Geologic sections A-A', B-B', and C-C' through Pontiac are shown by figures 17 to 19, inclusive, and are identified on the well location map of plate 3. The log of well PT 66 shows that as much as 36 feet of surficial sand and gravel are deposited locally adjacent to the Clinton River. Considerable difficulty arises in defining the extent of these permeable deposits, from test drilling records because of conflicting reports, as shown by the logs of wells PT 48, 49, and 50, which are shown on figure 17. These test holes were drilled within a stone's throw of each other, and in an area mapped as glacial outwash. Note that the log reported for well PT 49 records only clay from the surface to a depth of 50 feet; in contrast, the log of well PT 50 records only sand and gravel in the same zone. Conflicting with both reports and seemingly a happy compromise is the log of well PT 48, which records sand and gravel to a depth of 22 feet and the balance clay. Numerous other examples equally conflicting are shown by the graphic logs on figures 17 to 19, inclusive.

In part these discrepancies in logging the surficial deposits may be due to the fact that past emphasis on test drilling for ground water in the Pontiac area was placed on exploration of the buried outwash deposits and to a large extent the surficial deposits were looked upon only as an obstruction to be drilled through as rapidly as possible. Too often, exploratory drilling for ground-water development has been and continues to be pointed to drilling for water rather than to obtain the geologic information necessary to the best development of an adequate water supply. Consequently, the resultant pressure on the driller is often so great that obtaining geologic information must be sacrificed to make the daily footage of test hole dictated by contractual obligations. Unfortunately, such practices compromise the real objectives of a test-drilling program, which is to define accurately the nature and extent of the ground-water reservoirs and their associated deposits.

The log of well PT 29 suggests that the basal part of the surficial outwash may be connected locally to the buried outwash deposits which lie at greater depth, but all other well-log data refute this possibility and show consistently that the surficial outwash is separated from the buried outwash deposits by a relatively thick section of clay, gravelly clay, or hardpan.

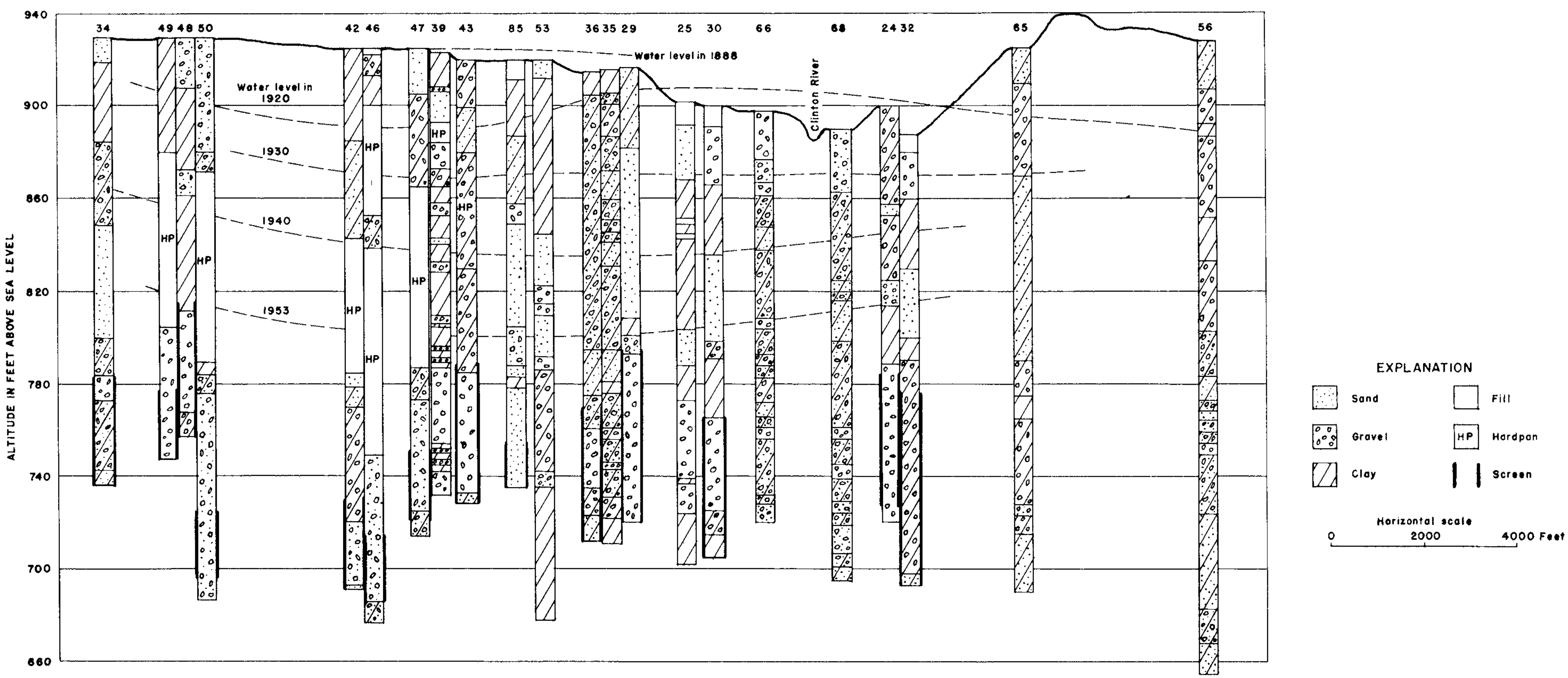

Figure 17. Geologic section and profile of piezometric surface along line A–A' shown on plate 3

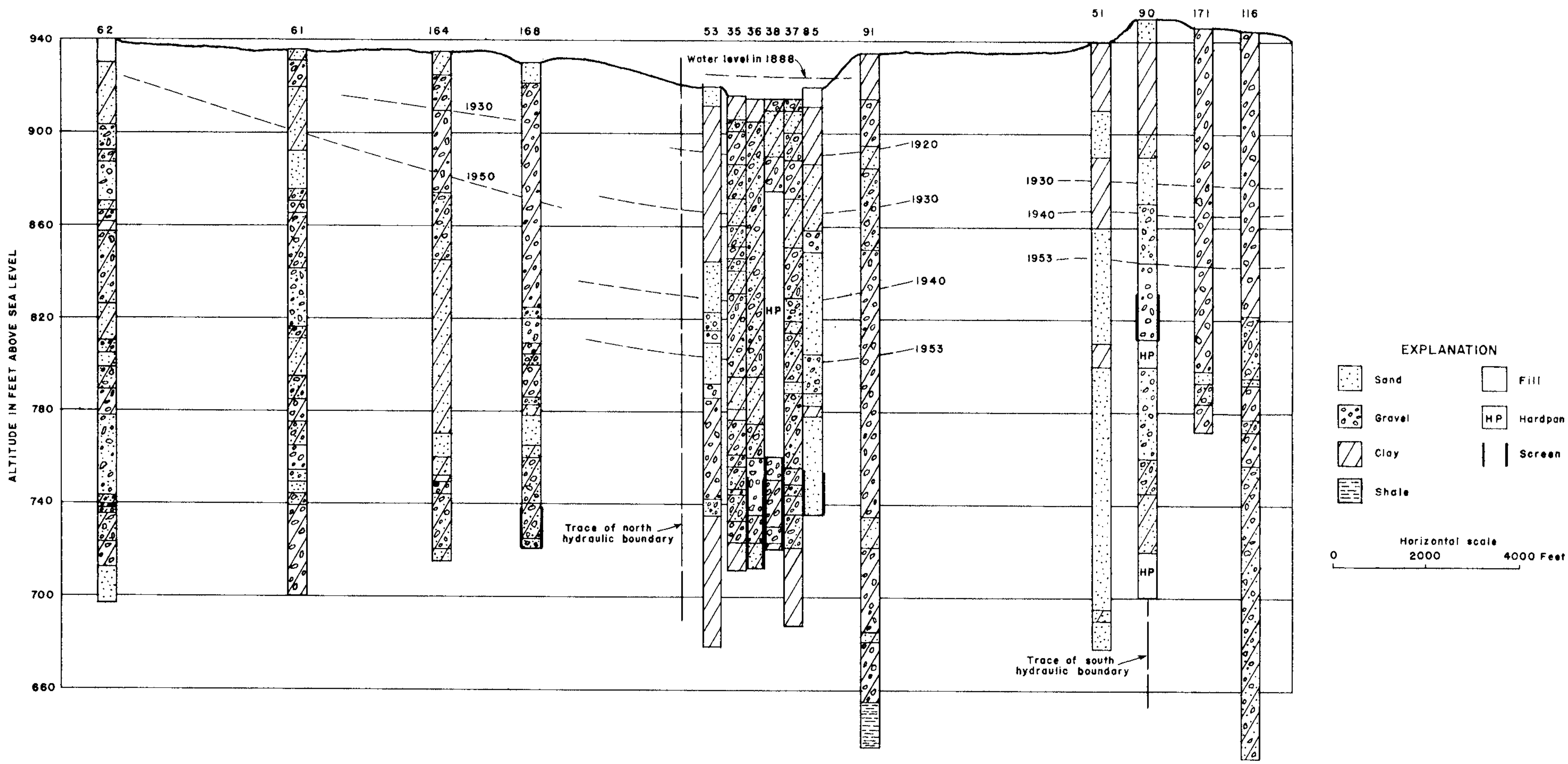

Figure 18. Geologic section and profile of piezometric surface along line B-B' shown on plate 3

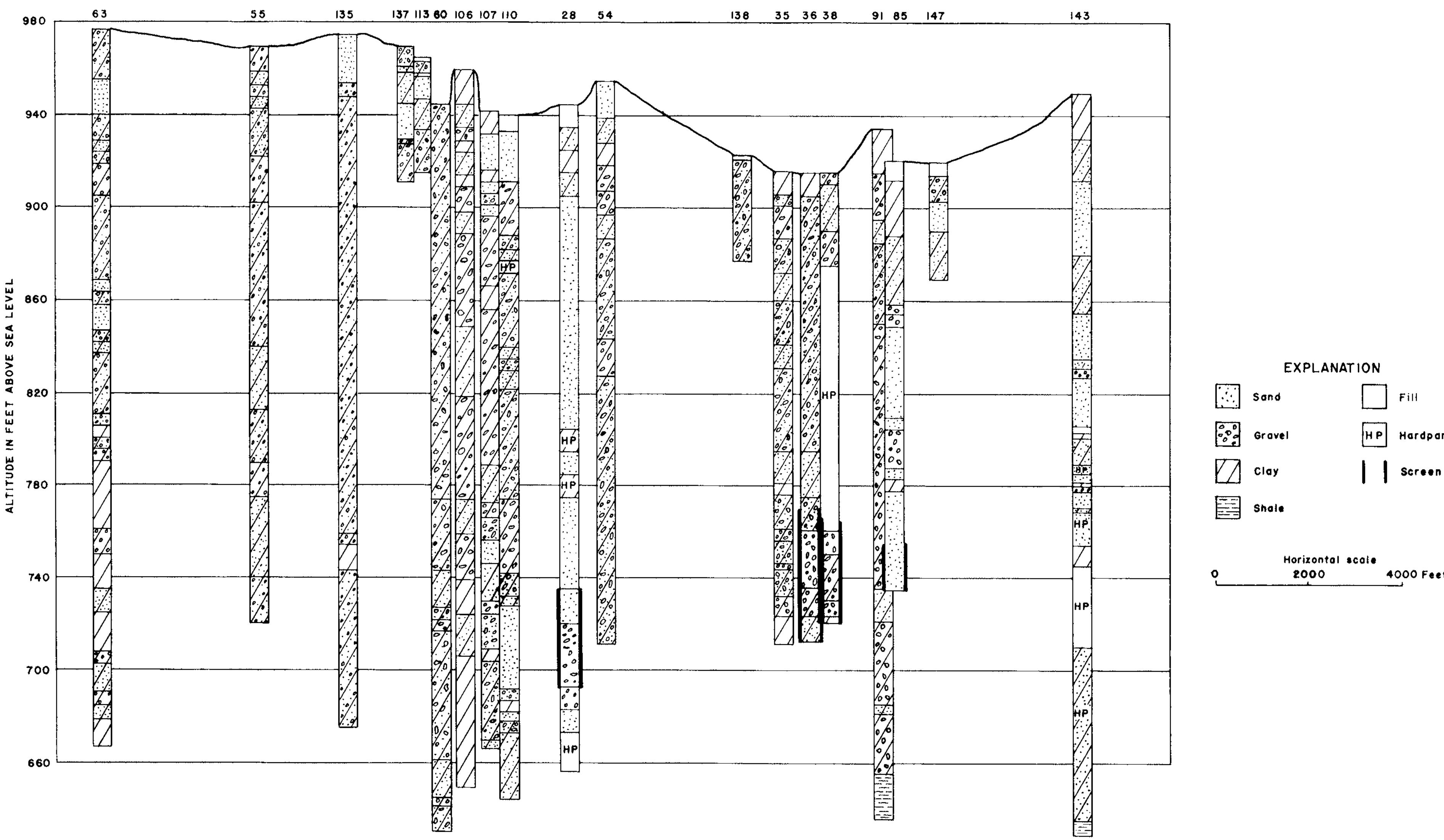

Figure 19. Geologic section along line C-C' shown on plate 3

Of considerable contrast is the log recorded for well PT 35, which adjoins well PT 29 and records clay, sandy clay, and gravelly clay throughout the section that was logged as sand in well PT 29. Equally contradictory, however, is the record that well PT 35 penetrated clayey gravel or gravelly clay throughout the zone in which adjacent wells are screened and are continuously withdrawing copious supplies of ground water. Although locally a permeable connection may occur between the surficial outwash and the buried outwash deposits, it seems that through the greater part of Pontiac a relatively thick section of clay, gravelly clay, or hardpan lies between them. The repeated contradictions between logs of adjacent wells rules out any effective correlation of these data across the sections of figures 17 to 19 inclusive.

For the most part, ground water in the surficial outwash is under water-table conditions and ground-water stages are at or slightly above the water surface of adjoining streams. In some places the surficial outwash deposits extend to depths as great as 36 feet below the average stage of the Clinton River. Wherever these permeable deposits are of appreciable thickness and are intersected by perennial streams, large ground-water supplies may be developed by induced infiltration.

West of Pontiac, in the areas of surficial outwash which surround the lakes, from several feet to more than 50 feet of sand and gravel are reported. Wherever the outwash is of appreciable thickness and is interconnected hydraulically to adjoining surface sources, copious supplies of ground water may be developed by induced infiltration. Adequate test drilling and aquifer pumping tests should precede any large ground-water development.

Buried outwash

A thick section of clay and gravelly clay underlies the surficial outwash and the morainal and till plain deposits throughout Pontiac. Some drillers refer to this section as hardpan. Along the Clinton River this hardpan reportedly ranges from 60 to more than 100 feet in thickness. Nearly everywhere the hardpan is recorded as clay, sandy clay, or gravelly clay. In contrast, however, the logs of wells PT 24, 25, 30, 32, 34, 53, and 85, shown on figure 17, record this hardpan section as clay, sandy clay, and gravelly clay that is interstratified with sand and gravel, clayey sand, and clayey gravel. These logs suggest that the hardpan section consists of a tripartite sequence beginning at the top with clay and gravelly clay, about 30 feet in thickness; overlying sand and some gravel about 40 feet or more in thickness; which is underlain by a basal member of clay and gravelly clay, about 20 feet in thickness. This tripartite sequence approximates the thickness and correlates with the position of the hardpan section recorded in the other logs. Well PT 90, shown on figure 18, is of interest in this regard because it was screened in the gravels that correspond in stratigraphic position to the intermediate and permeable zone of the tripartite sequence.

A resumé of early experience in the drilling and construction of wells in the Pontiac area, is pertinent to the interpretation of well-log data because it influenced local terminology as applied to well-log description. Perhaps the earliest large-scale development of ground water from the buried outwash deposits were the suction gang wells PT 1 and 5-16 inclusive, and air-lift wells PT 17-23, at the Walnut Street station of the municipal water supply. In the construction of these wells perforated pipe was set in the water-bearing formation in lieu of screens. The pattern of perforations consisted of 3/8-inch diameter holes drilled on 1-1/2 inch centers. A 3/8-inch opening corresponds to a number 375 slot screen and would permit the passage of any particle smaller than coarse gravel. Experience gained in the development of these earlier well stations directed subsequent exploratory drilling programs largely to the location of water-bearing formations of similar composition and particle size. Many of the later well developments for municipal supply were equipped with perforated pipe of similar construction.

Initial experience and success in locating zones of coarse gravel within the buried outwash developed local standards of acceptance for water-bearing formations that tended to rule out the medium and finer gravels, and particularly the coarse to medium sands or finer materials as aquifers. This experience background probably is a contributing factor in the lack of attention given to logging of sand or fine gravel. Perhaps equally or more important, the availability of the basal coarse gravels led to the consideration that the overlying beds of finer materials were of little importance as sources of water supply and were looked upon only as an obstacle to be drilled through as rapidly as possible. Probably, little effort was made in the earlier explorations to bail or clean the test hole while drilling through the hardpan section that overlies the buried outwash. If this were the practice, the high content of clay carried in the drilling fluid might effectively seal most water-bearing formations penetrated, excepting coarse to very coarse and clean gravel deposits.

The hardpan section of the drillers or the corresponding tripartite sequence of clay-sand-clay serves effectively as a confining bed to cap the ground water under artesian conditions in the basal gravels. In 1888, when the first group of wells was constructed for Pontiac at the Walnut Street station, ground-water levels in the buried outwash gravels rose to or slightly above land surface, or more than 920 feet above sea level. Thus, initially the piezometric surface in this ground-water reservoir stood at stages several feet above the level of nearby Crystal Lake and only a few feet below the level of the large chain of lakes west of Pontiac.

The buried outwash deposits range from 20 to more than 150 feet in thickness and underlie most of Pontiac (figs. 17-19) along a belt that is several thousand feet wide and is in general centered about line A-A' of plate 3. During the decade ending in 1929, test drilling by the municipal department of water supply sampled numerous sites within the limits of Pontiac and proved continuity of the coarser deposits of buried outwash from the Walnut Street station northeast along the Clinton River as far as East Boulevard, and southwest as far as Telegraph Road. On the basis of this exploratory program, it was concluded that the principal sites for further municipal ground-water development would be found along this southwest to northeast axis. Subsequent municipal well developments were located along this axis and were constructed with slotted pipe in lieu of screens. Most of the test holes at appreciable distances north or south of the Clinton River axis show considerably less gravel of the size found in the test holes on or near the axis. However, many outlying test holes show appreciable thicknesses of relatively coarse sand and fine gravel and in some outlying areas large-capacity wells have been developed by several industries.

Study of available drilling records, shows that the greater thickness and the coarser phases of the outwash deposits are along the Clinton River axis as originally defined by the municipal drilling program. To the north and northeast of the Clinton River axis, the buried outwash becomes thinner and grades progressively from sand and gravel through clayey sands and gravels, to sandy and gravelly clays. To the south of the Clinton River axis the buried outwash deposits continue with appreciable thickness but also grade progressively through finer materials to sandy and gravelly clays near the southeast corner of the city. Thus, the buried outwash is a channel of permeable deposition and probably marks the course of a glacial, interglacial, or perhaps a preglacial stream.

The log of test hole PT 91, (figs. 18 and 19) records Coldwater shale below the buried outwash at about 280 feet below land surface or 655 feet above mean sea level. This log also records about 70 feet of gravelly clay overlying the Coldwater shale. Several other logs shown on figures 17 to 19 inclusive report a zone of either gravelly clay, sandy clay, or clay hardpan at comparable altitudes.

The question arises whether some of the clays or hardpans reported in the basal part of the drift section include in part the shales or sandy shales of the Coldwater. It should be noted that the drillers' principal criterion in the recognition of bedrock is the resistance offered to drilling and his determination of the formation is not generally founded on lithologic examination. Some glacial deposits in this area are so indurated that they offer as much or more resitance to drilling than do the shales, sandy shales, or shaly sandstones of the Coldwater. Consequently, where the Coldwater underlies the glacial drift, its recognition on the basis of drilling resistance is difficult and in places presumably impossible, because some driller's logs have reported clays and gravelly clays in zones that are indisputably 100 feet or more within the Coldwater shales.

Coldwater shales

The shales, sandy shales, and shaly sandstones of the Coldwater formation underlie the glacial drift deposits throughout the Pontiac area. Few of the many well records reviewed for this area showed penetration of the Coldwater. None made specific note of the quantity or quality of water found. Brine was reported in test well PT 83 which penetrated the Coldwater shale, Sunbury shale, and the Berea sandstone. Only small quantities of water are obtained from wells tapping the Coldwater and at depth the waters are highly mineralized.

Where the Coldwater shale is overlain by thick deposits of permeable glacial drift, as in the Pontiac area, small to moderate quantities of potable water might be obtained by wells tapping the Coldwater at shallow depth. Joint systems may exist where the Coldwater is comprised of resistant sandy shales, shaly sandstones, or shaly limestones. Where such joint systems are at the contact with the drift mantle ground water from the

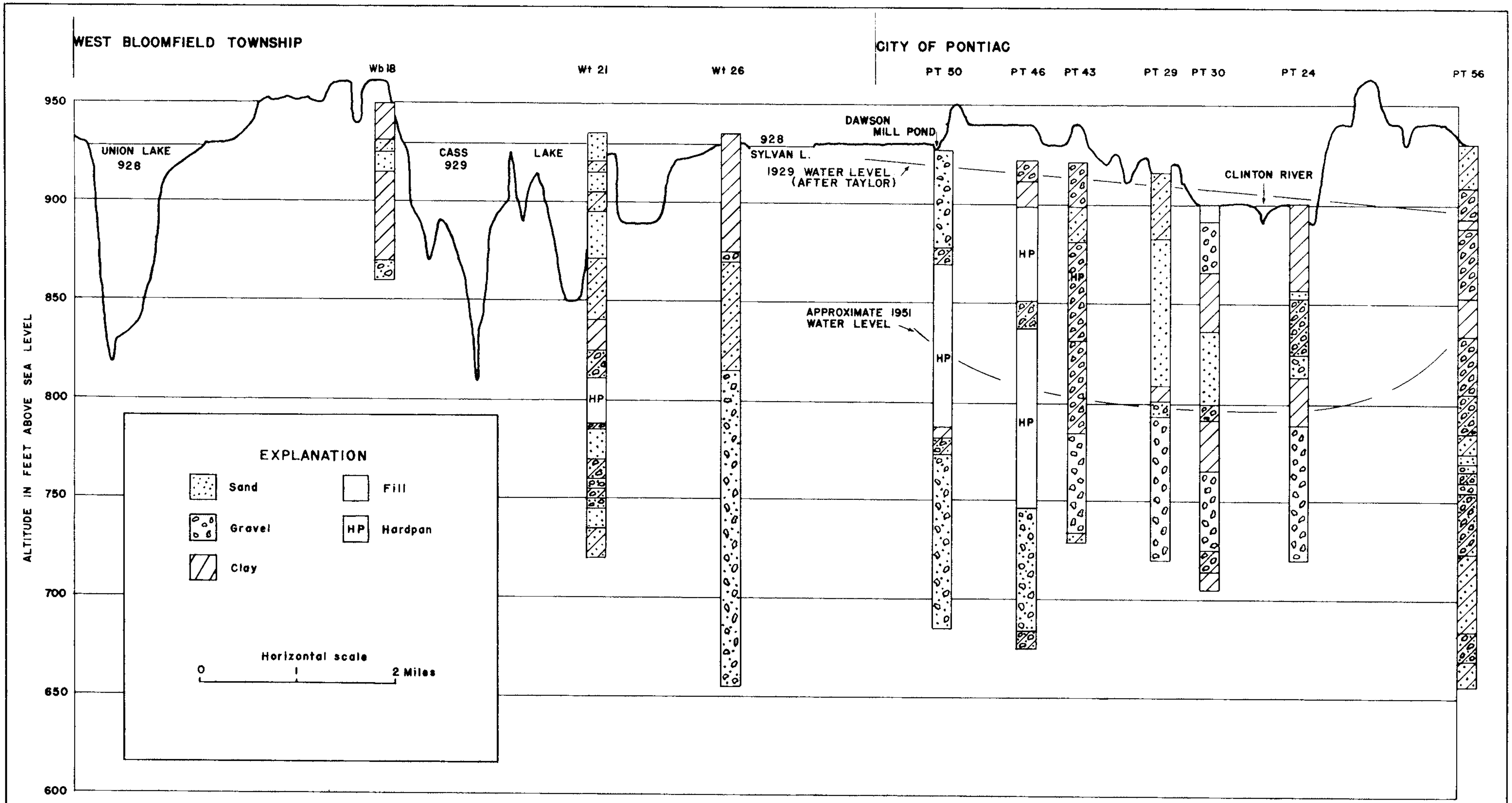

Figure 20. Generalized section and profile of piezometric surface along line X–X' shown on plate 4

drift deposits may be stored and to some degree transmitted to wells. For the most part, water obtained from such wells would be potable and essentially equivalent to the waters from the drift. Although data available are meager and inconclusive, it is probable that some of the deeper wells in the north and northwest part of Pontiac penetrate the Coldwater and obtain a little water from it. Although of little value as an aquifer, the Coldwater shale plays an important role in influencing the quality of ground water obtained from the overlying drift aquifers as shown by subsequent discussion.

Source and movement of ground water

The source of ground water in the glacial deposits of this area since glaciation is local precipitation. During periods of rainfall of sufficient intensity and duration to satisfy previously accumulated deficiencies of soil moisture, the subsurface percolation in excess of these needs goes into transient storage in the underground reservoirs. With increased storage, ground-water gradients are increased and subsurface discharge to nearby lakes and streams is increased proportionately.

When precipitation ceases, interceptions or diversions by wells and by natural influences of evapotranspiration have first priority in the capture of ground-water flow and the residual of subsurface discharge becomes stream flow. The large expanse of open water surface formed by the numerous lakes west of Pontiac; the still larger area of swamp or marsh land; and the equally large or perhaps larger area of lands where the water table is within a few feet of the surface represent in the aggregate a vast evaporating system which discharges to the atmosphere far more ground water than is now used by all of man's development in this county.

In addition to its role as a principal area of discharge, this lake-dotted outwash plain is also a principal area of ground-water recharge. The permeable outwash deposits permit ready infiltration of precipitation and provide a vast reservoir for underground storage at altitudes that are considerably greater than most of Pontiac and its environs. As shown by section X-X' (see fig. 20 and plate 4), many of the lakes are of sufficient depth to tap the buried outwash deposits and thereby facilitate recharge to these deeper aquifers.

To date, the collection of data on ground-water levels in this area has been limited to a few wells within the heavily pumped area of Pontiac. These observation wells are so greatly influenced by interference from the operation of nearby municipal and industrial wells that the effects of natural influences of recharge or discharge are masked completely. However, records of ground-water level are available for an observation well which taps the surficial deposits and an area where nearby pumping is moderate to small and intermittent. This well, number BH 2, is in Bloomfield Township. A hydrograph showing the fluctuation of water level in 1951 is shown by figure 21. Well OaBH 2 is finished at a depth of 65 feet. During 1951 the water level ranged from 12 to about 16 feet below land surface. The hydrograph of well GeBu 303 near Flint, Michigan, is shown for comparison. This well also is finished in surficial outwash but at a depth of only 8.4 feet below land surface. During 1951, the water level ranged from a few inches to about four feet below land surface. Insofar as general trend is

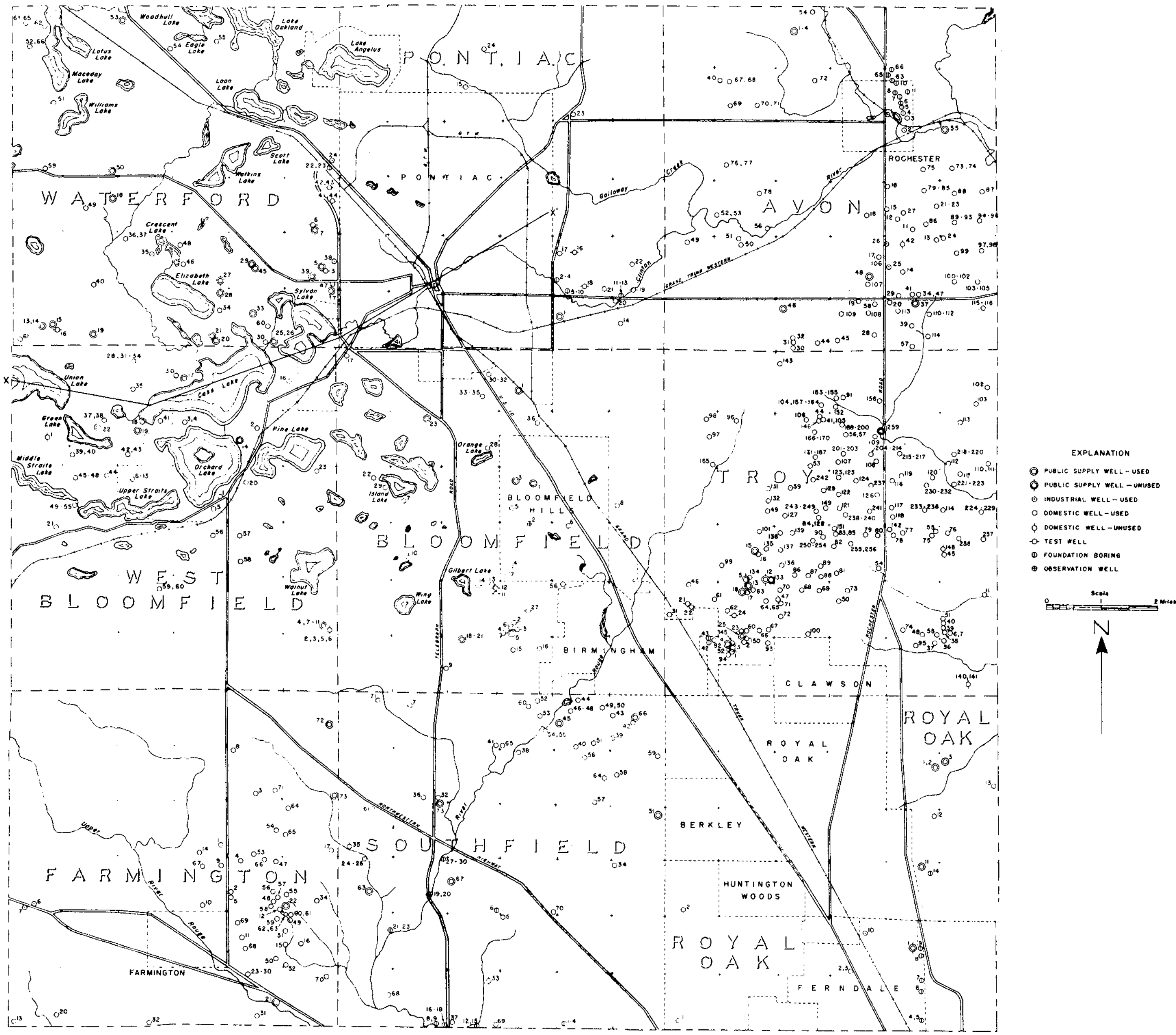

PLATE 4. WELL-LOCATION MAP OF SOUTHEASTERN OAKLAND COUNTY, MICHIGAN

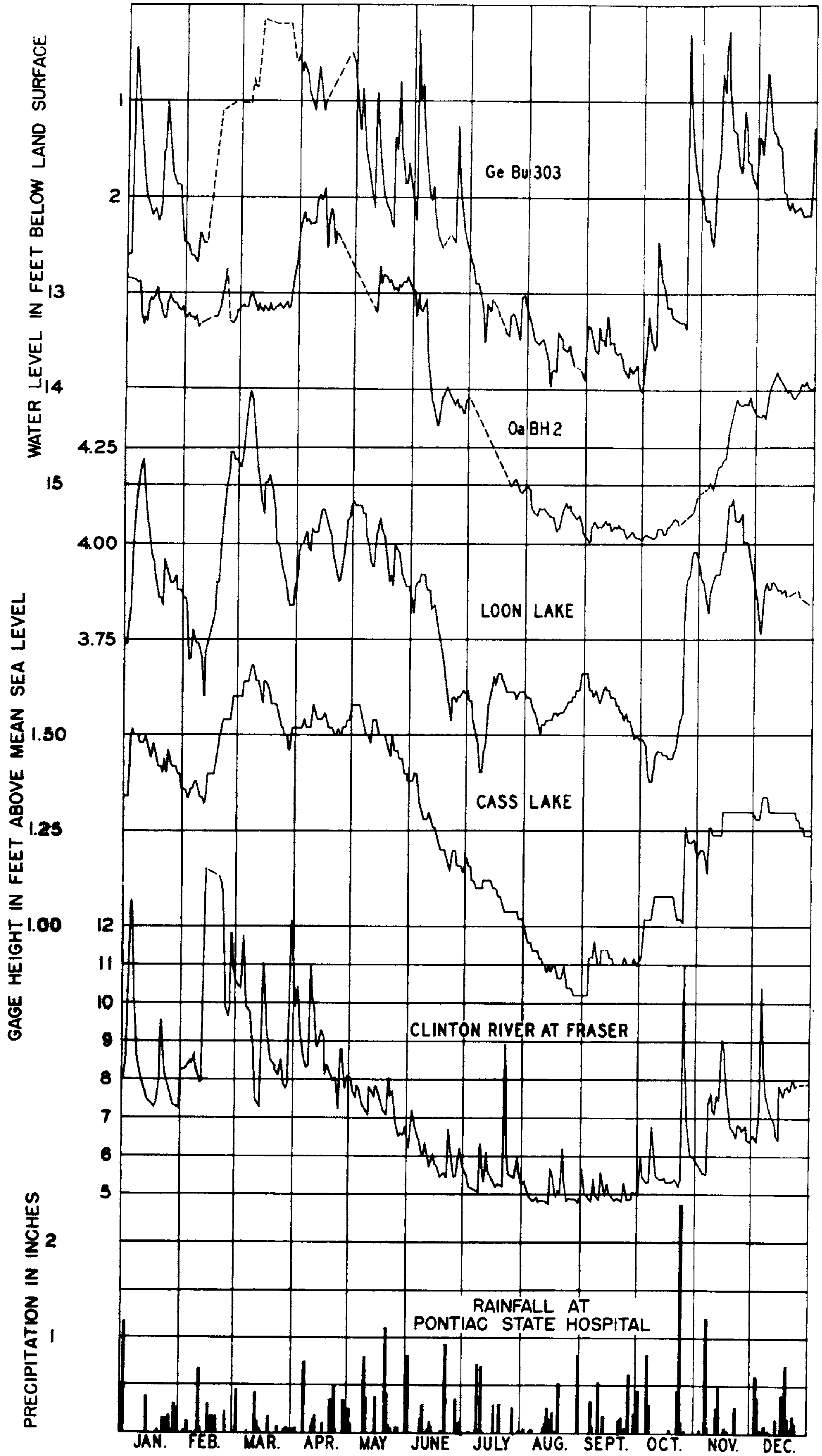

FIGURE 21. RELATION BETWEEN RAINFALL, RIVER STAGE, LAKE STAGE AND GROUND WATER LEVELS DURING 1951

concerned, the hydrographs of the shallow and the deep well conform, but in detail the shallow well shows earlier and more pronounced response than the deeper well. As a result of the greater depth to water at the deeper well, more time is required for recharge from the surface to reach the water table. In comparing the hydrograph of observation well OaBH 2 with the hydrographs of the other hydrologic stations shown on figure 21, it should be remembered that several wells are within a few hundred feet of well OaBH 2 and the intermittent pumping of these wells influences the water level in the observation well.

For the purpose of correlation, hydrographs of the stage of Loon Lake in Waterford Township, of Cass Lake in West Bloomfield Township, and of the Clinton River at Fraser, Michigan are also shown on figure 21. Records of stage at Loon Lake and Cass Lake are somewhat affected by regulation. Insofar as general trend is concerned, the hydrographs of the shallow and deep observation wells, the lakes, and the stage of the Clinton River are similar. As might be expected, the hydrograph of the shallow observation well GeBu 303 shows greater correlation in detail with the precipitation graph.

The fluctuations of water level in well GeBu 303 during the months of non-growing season are of interest. The response of water level during the non-growing season to any given period of precipitation is more pronounced than for equivalent precipitation during the growing season. These differences reflect in part the different requirements of soil moisture deficiency which must be met in the two seasons. Also, in the non-growing season the water table is steadier and at higher stages following each recharge interval. Likewise, the stages of the lakes and of the Clinton River are steadier during the non-growing season and are generally higher than during the growing season. Soon after the last killing frost in spring, the hydrographs of the wells, lakes, and streams start a general steady decline which continues throughout the growing season. They reach their lows about the end of September or in mid-October, at which time the first killing frost reduces or cuts off further growth of vegetation and accordingly reduces evapotranspiration. With reduction of evapotranspiration, ground-water levels, lake stages, and stream flow generally recover from mid-October through the balance of the year. By November and December the response of ground-water level to each period of precipitation resembles the magnitude of the response to comparable periods of precipitation during the previous spring and winter.

It is of interest to observe the decrease in the rate of decline of water levels and stream flow during July and August. The energy received from solar radiation provides the motivating force for evapotranspiration and as shown by Crabb (1950, p. 35), the peak of solar radiation in southern Michigan is reached about the latter part of June and the forepart of July. By the latter part of July or the forepart of August, solar radiation has decreased appreciably and evapotranspiration accordingly is reduced. With the decreased evapotranspiration discharge from the ground-water reservoir, a larger part of the ground-water outflow now reaches the stream.

In contrast to the hydrographs of water-level fluctuation shown by figure 21, note the graphs (fig. 22) of water level for observation wells PT 1 and 3 which tap the buried outwash deposits in Pontiac. These observation wells reflect principally the changes in rate and distribution of pumping in the artesian aquifer. Correlation with the trends of total municipal withdrawal is shown by figure 22. However, a number of responses in water level do not appear to conform with the pumpage trend at the corresponding time. Most of these seeming anomalies are caused by local interference from the starting or stopping of pumped wells located near each observation well. Whenever a nearby pumped well is started or stopped it effects the water level in the observation well to a greater degree than a corresponding change in pumping by a more distant well. For example, in the early part of 1944, a marked drawdown of water level in observation well PT 3 was noted in contrast to the recovery of water level during this time by observation well PT 1. The regional pumpage for this period was at a lower rate and a recovery of water level should have occurred, as illustrated by observation well PT 1. The seemingly anomalous response of observation well PT 3 indicates that a nearby pump was placed in operation during the period and its local effect was greater than the regional recovery trend.

Ground water in the buried outwash deposits is under artesian conditions. In an artesian aquifer, ground water is confined under pressure and changes in nearby pumping cause appreciable changes of water level that are transmitted over large distances in relatively short times. Thus the sawtooth pattern of the hydrographs of observation wells PT 1 and 3 reflects changing conditions of pumping distribution near these wells and also show the general regional trends of water level that result from over-all pumping in the area.

The relatively thick confining bed of clay and clay hardpan, which overlies the buried outwash deposits in central Pontiac, locally limits recharge from the surface to the gravelly outwash. To the west, however, in the lake-dotted outwash plain, many of the lakes are of sufficient depth to intersect the buried outwash or associated deposits. Furthermore, the logs of wells Wt 21, 27, and others indicate that the capping clays are absent west of Pontiac and recharge may be directly from the land surface.

Waters infiltrating into the buried outwash deposits to the west of Pontiac percolate down gradient and follow in modified form the general slope of the regional topography. The over-all lowering of water levels throughout Pontiac accentuates this gradient and induces the movement of ground water from the outlying areas toward the intensive well developments in Pontiac. Thus, the buried outwash deposits serve as a transmission main, extending from the upland outwash plain eastward to Pontiac. However, unlike any conventional pipeline, this natural conduit is choked with sand and gravel deposits and the movement of ground water is by slow percolation.

Before 1900, ground-water developments in the area were relatively small. At that time, seeps and springs were found on the low-lying lands, along the stream valleys, and on the lake plains east of Pontiac. In 1888, the municipal wells which tapped the buried outwash at the Walnut Street station of Pontiac flowed at or slightly above land surface. Thus, at this time the piezometric surface in the buried outwash stood at 920 feet above sea level.

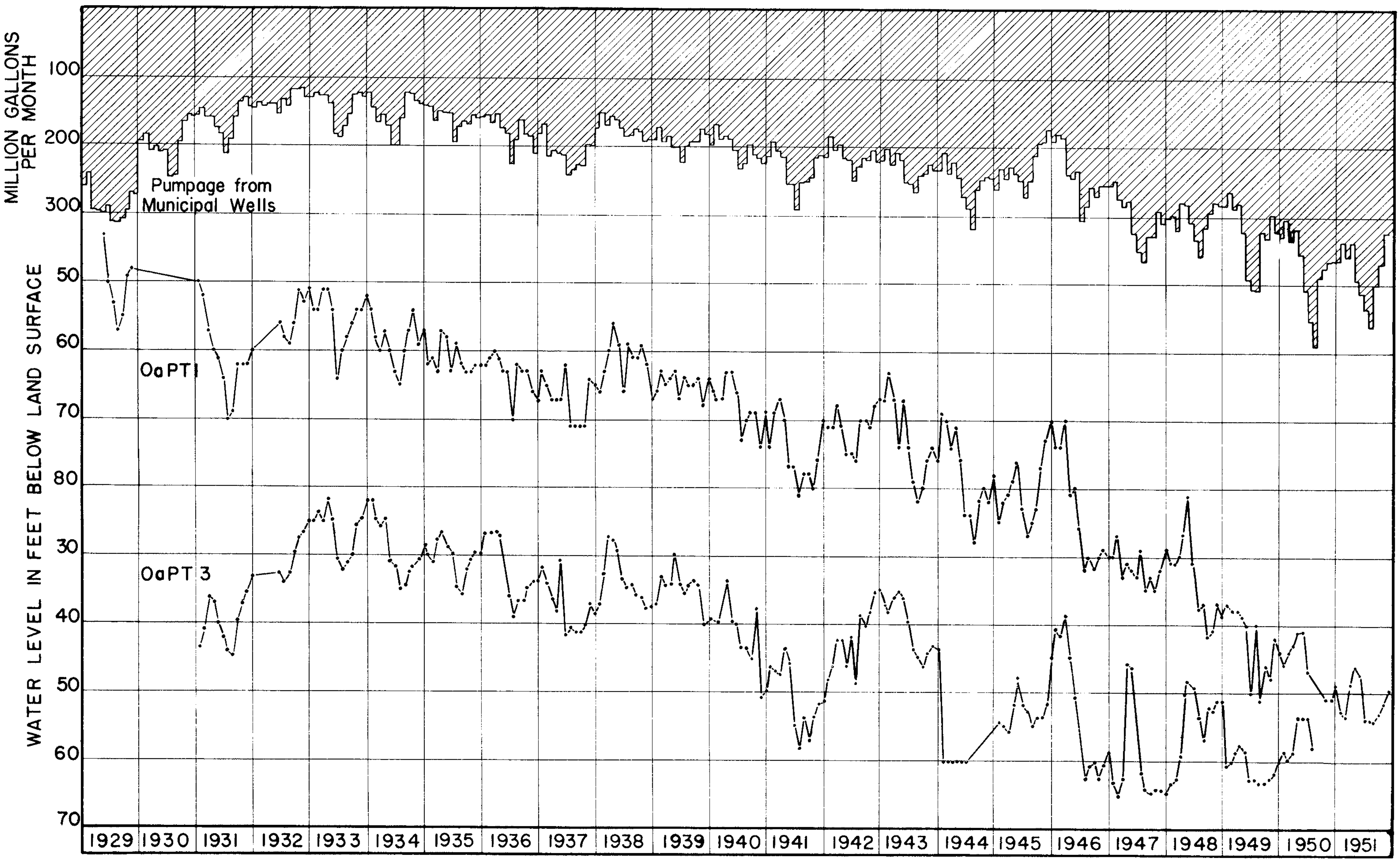

Figure 22. Hydrographs showing the relation between pumpage and decline of water levels in wells at Pontiac, Mich.

Hydraulic characteristics of principal aquifers

Surficial outwash

The development of ground water from the surficial outwash has been limited largely to small domestic supplies. In the construction of domestic wells, testing of water-bearing formations is limited to a short pumping period to determine if they will yield the few gallons per minute needed for domestic supply. Consequently, no specific information is available in this area concerning the permeability of the surficial outwash deposits. However, from aquifer-performance tests in other areas of similar deposits, it has been found that their permeability may range from several hundred for the fine sands to as much as a few thousand gallons per day per square foot for the coarse sands and gravels. Surficial deposits in the vicinity of the lakes and streams in the outwash plain are reported to be several tens of feet to more than a hundred feet in thickness and should furnish sufficient transmitting capacity to develop moderate to large capacity wells, particularly if infiltration from nearby surface sources might be developed.

Many of the small to moderate capacity wells drilled in this area are constructed without screens. This practice makes the search for water primarily a search for coarse gravels that are sand or silt free. Undoubtedly, many sands, fine gravels, and silty gravels rejected because of their silt or fine sand content might be developed to provide adequate water supplies by using proper screen construction and appropriate development techniques.

Buried outwash

The moderate to large capacity wells in Pontiac and the surrounding townships are now developed in the buried outwash deposits. Generally, records are maintained of the construction of the larger wells. Some records comprise only a log of the materials penetrated in the drilling of the test well; perhaps the length of casing used, and the size and position of the screen placed are included in the log. Other records include pumping tests in which the discharge of the pumped well was observed and the drawdown of water level was measured during the test period. In a few instances the drawdown of water level in one or more observation wells was measured and recorded.

Specific capacity reports

Reports of drawdown versus yield for wells that tap the buried outwash deposits in Pontiac and its environs indicate that the specific capacity ranges from 2 to as much as 425 gallons per minute (g.p.m.) per foot of drawdown. However, the majority of reports range between 40 and 120 g.p.m. per foot of drawdown. Although the specific capacity of the pumped well bears some relation to the transmissibility of the water-bearing formation, the relationship is not linear and may be so masked by inherent properties of the well construction as to be quite misleading if not worthless. Inasmuch as the specific capacity is based on the drawdown of water level in the pumped well, it includes any head losses occasioned by inadequate development of the water-bearing formation in the vicinity of the well screen; losses arising from turbulence where wells are pumped at high rates; and losses which may result from partial penetration of the pumped well into the water-bearing formation.

Pumping tests

Specific-capacity tests: The first test for which records are available was conducted by C. W. Hubbell, consulting engineer, who investigated the water problems of Pontiac and appraised the potential of the buried outwash for development of additional water supply. The test, run February 12, 1918, consisted of about a 4-hour period of steady pumping from 3 air-lift wells near the Walnut Street station with a combined output of 2830 g.p.m. The rate of pumping was maintained constant through the test period and water levels were observed in 4 nearby observation wells.

Methods of aquifer-test analysis now used were not known at the time of this test. Consequently, no interpretation was made concerning the transmission or storage properties of the outwash deposits. During the test, water levels were lowered about 6.1 feet in an observation well 1,400 feet distant and 7.1 feet in a well 600 feet from the center of the air-lift well group. Some concern was expressed because the drawdown of water level was almost as large at the distant observation wells as in the vicinity of the pumped wells. It was concluded that the potential of this well site was somewhat limited.

The drawdown in the pumping wells was not reported, but it is estimated as 9 feet. If we assume that the yield per well pumped was uniform, then the average discharge from each of the three air-lift wells was about 940 g.p.m. Thus, the indicated specific capacity of each well is estimated as 104 g.p.m. per foot of drawdown.

A second test was conducted in the period November 9, 1921 through January 28, 1922 under the supervision of a citizen's committee appointed by the city commission. A group of 6 air-lift wells at the Walnut Street station was pumped daily for periods ranging from 12 to 24 hours. The discharge averaged about 3.3 million gallons per day (m.g.d.) through November and December; ranged from 2.6 to 5.7 m.g.d. in the interval January 1 to 20 inclusive; and was steady at 6.1 m.g.d. for the balance of the test. It is reported (Taylor, 1930, p. 123) that water levels were measured hourly during the test at two observation wells in the vicinity and less frequently at several other wells nearby. Original records on file at the Pontiac Department of Water Supply, show that excepting the start and close of the test period, measurements of water level were made only once daily through most of the test.

The procedure was one of pumping at nearly steady rates for a prolonged period and observing the net drawdown of water level in the vicinity of the air-lift wells. This particular test followed a period when the aquifer had not been used for several months while Pontiac was supplied from the Clinton River. If, as in the 1918 test, we assume a uniform yield per well, then the individual specific capacity indicated is 24 g.p.m. per foot of drawdown after about 2 months of steady pumping at an average rate of 3.3 m.g.d. from the 6-well group. Note the marked decline from the 4-hour specific capacity of 105 g.p.m. per foot drawdown to the 60-day specific capacity of 24 g.p.m. per foot drawdown. It is evident that prolonged pumping brings into action certain variables which are not apparent from short term specific-capacity data. If the drawdown at the end of the first day of pumping is used, the specific capacity indicated is 45 g.p.m. per foot of drawdown or nearly twice the value for the 60-day period.

On August 21, 1929, a test of 75 minutes duration was run and is referred to by Taylor (1930, p. 126) as the Featherstone test. In this test, the Pontiac municipal wells, Featherstone 1 (PT 31) and 2 (PT 32), and the East Boulevard well (PT 24) were operated. The drawdown of water level was observed in each well pumped and the individual discharge of each pumping well was measured. This test was conducted to appraise the extent of mutual interference between the several wells. Although the reported drawdowns are inconsistent, it is indicated that the 1-hour specific capacity of the Featherstone wells ranged from 150 to more than 200 g.p.m. per foot of drawdown. The 15-minute specific capacity for the East Boulevard well is reported at 425 g.p.m. per foot of drawdown.

On April 10 and 16, 1930, a regional test of the municipal wells was conducted with the objective---"to determine the time of transmission of the effect of localized pumping to other portions of the stratum" (Taylor, 1930, p. 121). In the first test, the Mechanic (PT 26), Paddock (PT 30), East Boulevard (PT 24), North End (PT 28), and Walnut 24-inch (PT 39) wells were operated at a combined rate of 6.1 m.g.d. for 5 hours and then the air-lift wells were added to increase this rate to 8.1 m.g.d. for the last 6 hours of the test. Water levels were observed hourly in the Perry (PT 38), City Hall (PT 36), Market (PT 29), Orchard Lake (PT 48), Walnut 8-inch (PT 1), and Lake Street (PT 2) wells. The drawdown of Walnut 24-inch well (PT 39) was the only record reported for the pumped wells and it was evidently adjusted by Taylor (1930, pp. 127-129) to correct for so-called screen friction.

In the April 16 test, the Perry, City Hall, Market, Mechanic, and Paddock wells were operated at a combined rate of 5.9 m.g.d. for 7 hours and then the air-lift wells were added, which increased the combined rate to 7.9 m.g.d. for the last 4 hours of the test. Drawdowns were reported for the pumped wells, but again were adjusted for "screen friction".

In determining the drawdowns of the wells pumped in the 1930 test, Taylor (1930, pp. 127-129) used a rather unique approach which resulted in much larger specific capacities than previously obtained. Evidently, Taylor had observed from his own experience that water levels in the pumped wells drew down instantaneously with the start of pumping. He concluded that most if not all of the initial drawdown was the result of screen friction. He established a so-called "screen-friction correction" by measuring the initial drawdown and recovery of the pumped well immediately following the starting or stopping of the well. This initial value of drawdown was labeled screen friction and was subtracted from the total drawdown observed in the pumped well at the end of the pumping test. The net drawdown remaining was used as the drawdown for the pumped well and supposedly was indicative of the aquifer drawdown. As a consequence of the deduction of this initial drawdown, the computed net drawdowns were appreciably smaller than those observed. Thus, the indicated specific capacities were considerably larger than those reported for previous tests.

Although Taylor's approach to the problem of well-entrance losses has merit, considering how little information was available at that time concerning the hydraulics of well or aquifer performance, it resulted in appreciable error. Taylor's observation that the initial drawdown of the pumped well was almost instantaneous, indicates that the storage coefficient of the aquifer lies in the artesian range and the capping bed over the buried outwash deposits must be extensive. Whenever a well tapping an artesian formation is pumped, it is invariably observed that a marked initial drawdown occurs within a very short time after the start of pumping. True enough, a part of the initial drawdown in the pumped well may be attributed to entrance losses, but a large part may also be attributed to the small storage coefficient of the artesian formation. That part of the initial drawdown which reflects well-entrance losses would be observed within a matter of seconds. Thus, it would be most difficult, even under the best of circumstances to approach the problem of entrance losses by Taylor's procedure. Furthermore, the method gives no clue as to when entrance losses reach their full value or if formation losses at this time can be ignored. Entrance losses can now be determined by methods described by Jacob (1946, pp. 629-646) and by Rorabaugh (1949).

By restoring Taylor's "screen friction" correction to his adjusted drawdown for the corresponding wells pumped in the April 10 and 16 tests, it is found that the specific capacity of individual wells ranged from 40 to 75 and averaged 56 g.p.m. per foot of drawdown. These values include the influence of the pattern of pumpage distribution, which in this test was a linear array of 6 wells.

On May 7 and 8, 1930, another regional tests of the buried outwash deposits was conducted in two steps. In the first test, the East Boulevard (PT 24), Paddock (PT 30), Orchard Lake (PT 48), Mechanic (PT 26), Market (PT 29), City Hall (PT 36), Perry (PT 38), and Walnut Street 24-inch (PT 39) wells were pumped continuously for a period of 24 hours at a combined rate of 10.2 m.g.d. At the end of this period all wells were shut off for a period of 6 hours. Then the second test period began and wells East Boulevard, Paddock, Orchard Lake, Market, City Hall, and the 24-inch well at Walnut Street were pumped continuously for a period of some 14 hours at a combined rate of 8.3 m.g.d. Throughout both test periods and the recovery interval between, water levels were measured in each of the pumping wells and at several observation wells. From the results of these tests, Taylor estimated (1930, p. 128) that the over-all specific capacity of this assemblage of wells was 870 g.p.m. per foot of drawdown. This specific capacity determination applies to the over-all performance of the linear array of 8 wells and is not directly comparable with previous determinations.

Revising Taylor's data by restoring the "screen friction" correction that he subtracted provides the total drawdown observed and permits computation of the specific capacity for the wells used in this test. On this basis, it is found that the 24-hour specific capacity for wells used in test No. 1 on May 7, 1930, ranged from 35 to 56 and averaged 48 g.p.m. per foot of drawdown. These values are comparable with the April test of the 5-well linear array.

A summary of the specific-capacity determinations obtained from the several tests is shown by table 6 with the pattern of well distribution noted for each test. As more than one well was in operation in each test, the drawdown reported for any individual well includes the effect of mutual interference between the several pumping wells. Consequently, the specific-capacity values for the tests of extended duration are smaller than if the wells had been pumped individually for comparable periods. Appreciable error may be involved also because of the simplifying assumption that the total withdrawal in the 1918 and 1921-22 tests was uniformly distributed among the several wells pumped. It is evident, however, from table 6 that the specific-capacity determination declines appreciably as the time of pumping is increased.

Aquifer tests: The original field data are available from the files of the Pontiac Department of Water Supply for the 1921-22 and the 1930 tests. Detailed study of these data shows that inherent difficulties either in the control of pumping rates, the measurement of water levels in the initial phases of each test, or changes in withdrawal rate limit the interpretation of the data by present methods of aquifer-test analysis.

Of the several tests described, the only one with proper control of the pumping rate and distribution and an adequate program of water-level observation was the short test run in 1918. In addition to maintaining adequate records of the rate of pumping and proper control of pumping rate, antecedent water-level trends in the area were observed for a brief period prior to the start of the test and the recovery of water levels was observed during the shutoff period of the test. A map showing the location of the air-lift wells pumped and the several observation wells measured is shown by figure 23. A hydrograph of the water level measured in observation well PT 12 is shown by figure 24.

Analysis of the observation well data was made by the Theis non-equilibrium method which has been described in detail by Brown (1953, pp. 844-866). The Theis equation is identified as follows:

$$T = \frac{114.6\ Q\ W(u)}{s} \qquad (1)$$

where:

T = coefficient of transmissibility, in g.p.d. per foot

Q = rate of pumping in g.p.m.

s = drawdown or recovery of water level, in feet

W(u) = well function of u

Table 6.-Summary of specific-capacity results from pumping tests conducted by Pontiac Department of Water Supply.

Date of test	Specific capacity (gpm/ft.)	Duration of test (days)	Distribution of pumping		
			Number of wells	Pattern	Length of major axis of pattern (feet)
1929	425	0.01	3	linear	500
1929	150-200	0.04	2	linear	500
1918	105	0.17	3	triangular	230
April, 1930	40-75	0.21	5	linear	5,400
1921-22	45	1.0	6	rectangular	435
May, 1930	33-56	1.0	8	linear	8,400
1921-22	24	60.0	6	rectangular	435

$$\text{or } W(u) = \int_{\frac{1.87\, r^2 S}{T\, t}}^{\infty} \frac{e^{-u}}{u}\, du \qquad (2)$$

$$\text{and } u = \frac{1.87\, r^2 S}{T\, t} \qquad (3)$$

r = distance from pumping well, in feet

t = time since pumping started or stopped, in days

S = coefficient of storage

Equations (1) and (3) are solved by the type-curve technique wherein the well function W(u) is plotted versus the argument u on log-log graph paper and the field observations of drawdown or recovery of water level are plotted versus the ratio of distance squared divided by time since pumping started. The log-log graph of the field data is superposed on the log-log graph of the well function and moved with the axes of the two graphs always held parallel, until a position of congruity is found. With the graphs in this position a point convenient for computation is selected and the four coordinates of this match point, obtained from the scales of each graph, permit solution of equations (1) and (3) for the values of T and S, the transmissibility and storage coefficients.

If the aquifer is of infinite areal extent and if all other conditions assumed in the development of the Theis equation are met, the field data for this test should follow the trace of the type curve W(u). From figure 25, it is noted that although the first observations match the type-curve trace, subsequent observations rise at a steeper rate and lie above the type curve. An increase in the rate of drawdown might imply that the rate of withdrawal from the aquifer increased. However, it is known that pumping from the air-lift wells was maintained at a steady rate throughout the pumping period and that no other large ground-water developments existed in the area at this time. Thus, in the absence of other pumping only one other possibility remains as an explanation for the increased rate of drawdown. It has been shown by Jacob (1950, pp. 354-355), Ferris (1949, pp. 247-259) and others that where an aquifer is made semi-infinite by a bounding plane of impervious sediments the hydrologic effect of that boundary is comparable to the influence of a competing well, which discharges at a rate equivalent to the real pumped well and lies at an imaginary position symmetrical about the boundary plane. Thus, the effect of the image well is to double the rate of drawdown caused by the discharge of the real well. From the log-log graph of figure 25, note that the increased rate of drawdown in the observation well is twice the initial rate as shown by the evidence that the second part of the log-log graph matches the type curve at twice the drawdown intercept of the initial match for the corresponding value of W(u). A procedure that might be followed with greater clarity, is to plot the departures of the field observations from the extrapolated trace of the original type-curve match on the log-log graph. Then match the departure data to the type curve and note that it will match at the same drawdown intercept as the solution for the initial data.

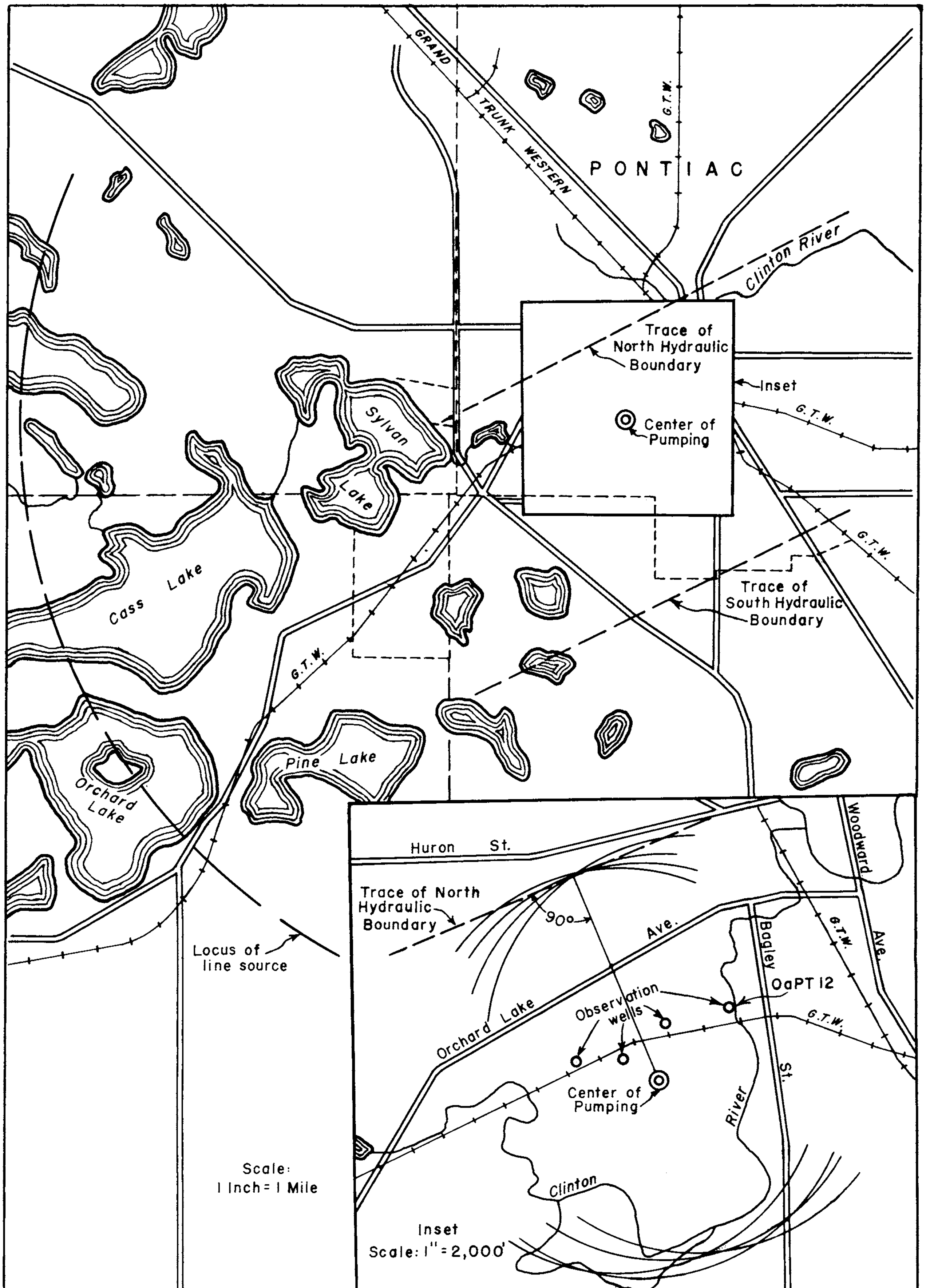

Figure 23. Location of wells and trace of hydraulic boundaries as determined from Pontiac pumping tests.

The position of the hydraulic boundary which caused the deviation in drawdown may be located by the method of images as described by Ferris (1948, pp. 11-12). Arcs of the boundary-locus circles as determined from the 1918 test are shown by the inset of figure 23. The most concentrated clustering of arc intersections is the group which lies north of the air-lift wells. The south group represents complementary intersections and is much more dispersed. The strike of the hydrogeologic boundary is obtained by drawing a perpendicular to the line connecting the center of pumping of the air-lift wells and the point on the boundary marked by the north group of arc intercepts and passing this perpendicular through the boundary point as shown by figure 23.

The hydraulic boundary located by the image method delineates a hydraulic system that shows the same performance as the real aquifer, but it may not coincide with the geologic boundary in detail. In the image method of analysis, it is necessarily assumed that the aquifer is cut completely by an abrupt boundary. In the physical picture found in the field this generally would not be so except where the boundary is a fault. The hydraulic boundary indicated by the Pontiac pumping test reflects a decrease in thickness of the permeable deposits and is confirmed by the geologic evidence. This change does not occur abruptly, but is graditional over a large area. Wells PT 28, 110, 167, and 168 prove that the buried outwash deposits continue for some distance beyond the trace of the hydraulic boundary indicated by figure 23. It is of interest to note, however, that considerable difficulty was experienced in obtaining satisfactory yields and the performance of these wells is markedly poorer than the performance of neighboring wells on the more permeable side of the boundary.

The close clustering of the boundary arc intersections gives assurance of the consistency of the test data and the adequacy of the boundary interpretation. Good agreement was obtained between results from analysis of the drawdown data versus results from analysis of the recovery data for the 1918 test. Using the initial match-point coordinates, the coefficients of transmissibility and storage of the aquifer are calculated from equations (1) and (3) as follows:

Coordinates of initial match point:

$$u = 0.1 \qquad r^2t = 1.42 \times 10^8$$

$$W(u) = 1.82 \qquad s = 2.1$$

from equation (1)

$$T = \frac{114.6 \times 2830 \times 1.82}{2.1}$$

$$T = 280{,}000 \text{ g.p.d. per ft.}$$

from equation (3)

$$S = \frac{0.1 \times 280{,}000}{1.87 \times 1.42 \times 10^8}$$

$$S = 1.0 \times 10^{-4}$$

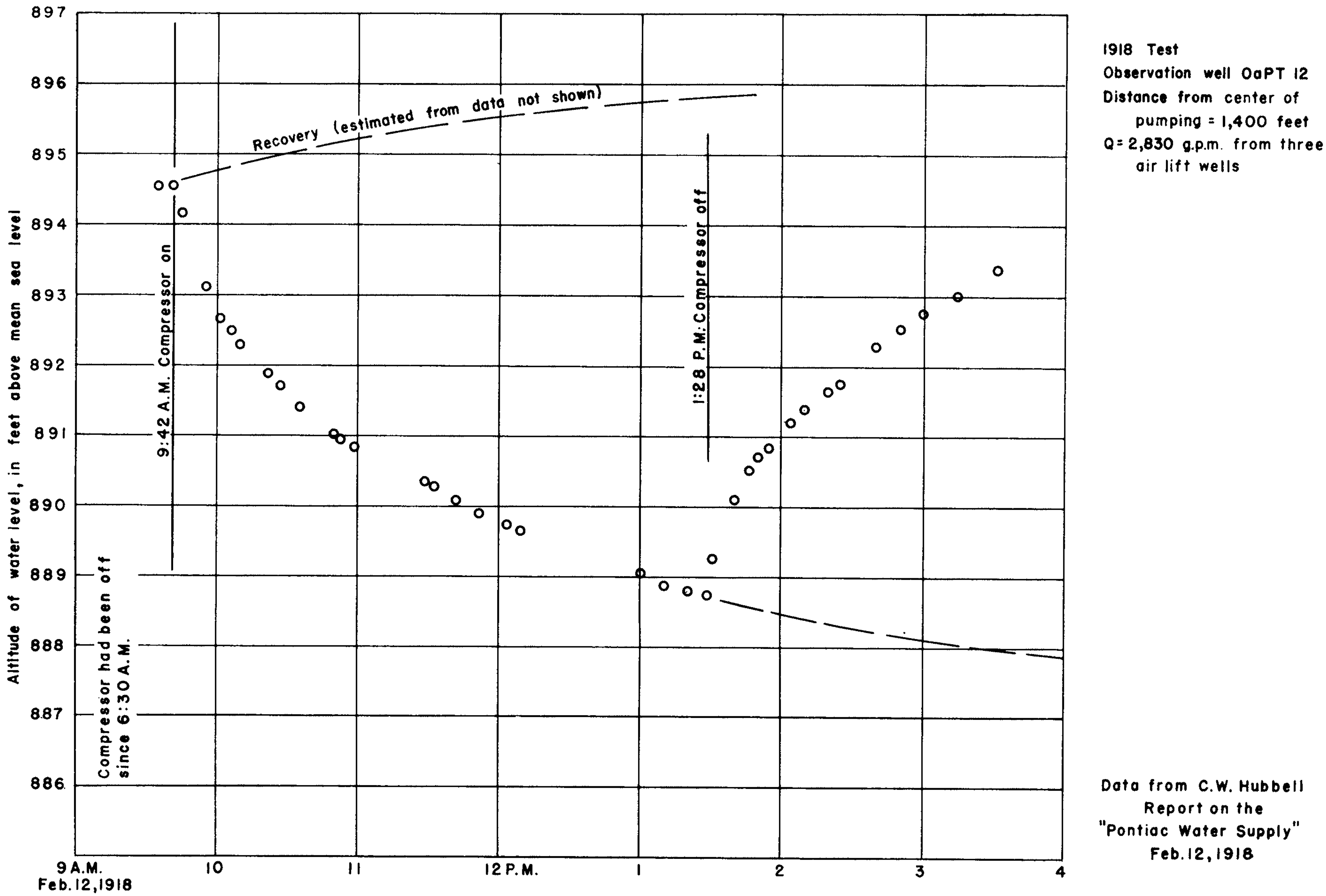

Figure 24. Fluctuation of water level in well OaPT 12 produced by pumping wells at the Walnut Street Station at Pontiac, Mich.

The coefficient of storage lies well within the artesian range and thereby conforms with the geologic controls which indicate a widespread capping or confining stratum in this area.

From figure 17, it is estimated that the thickness of the buried outwash in the Walnut Street area averages about 120 feet. The effective average permeability of these deposits is computed by the following equation:

$$T = P\,m \qquad (4)$$

T = coefficient of transmissibility g.p.d. per foot

P = coefficient of permeability g.p.d. per square foot

m = saturated thickness of aquifer, in feet

then

$$P = \frac{T}{m} = \frac{280{,}000}{120}$$

$$P = 2300 \text{ g.p.d. per square foot}$$

With the hydraulic characteristics of the aquifer obtained from the brief test of 1918, it is now possible to analyze significant portions of the longer tests that followed. The very limited program of water-level observation and the widely dispersed pattern of pumping distribution in the 1930 tests make it impractical to utilize these data. In the prolonged test of November 1921 through January 1922, the pattern of pumping was concentrated among the air-lift wells near the Walnut Street station. The combined withdrawal from the six wells may be considered acting at the midpoint of this well group. Unfortunately, no record of antecedent water-level trend in the area was obtained prior to the test and measurement frequency through most of the test was limited. A hydrograph of available water-level measurements is shown by figure 26. In addition, through all except the last week of the test the schedule of day by day pumping was intermittent. During the last week of the test, however, pumping was continuous at an average rate of 6.1 m.g.d. For more than two months previously, withdrawal from the air-lift wells averaged 3.3 m.g.d. Thus, the net increase in pumping during the last week was 2.8 m.g.d.

Daily measurements of water level were made in several observation wells through the two months preceding the week of peak withdrawal. Numerous but somewhat sporadic, measurements of water level in the observation wells were made through the last week of the test. Some difficulty arises in the interpretation of the antecedent water-level trends because of a 6-hour shutdown of all pumping just prior to the start of the final week of pumping at the higher rate. Within this shutdown period, water levels in the area recovered appreciably and the water levels prior to the 6.1 m.g.d. test were several feet above the stages that had obtained for most of the antecedent period. In analyzing the drawdown data for the final week, this brief period of recovery was ignored and the drawdown

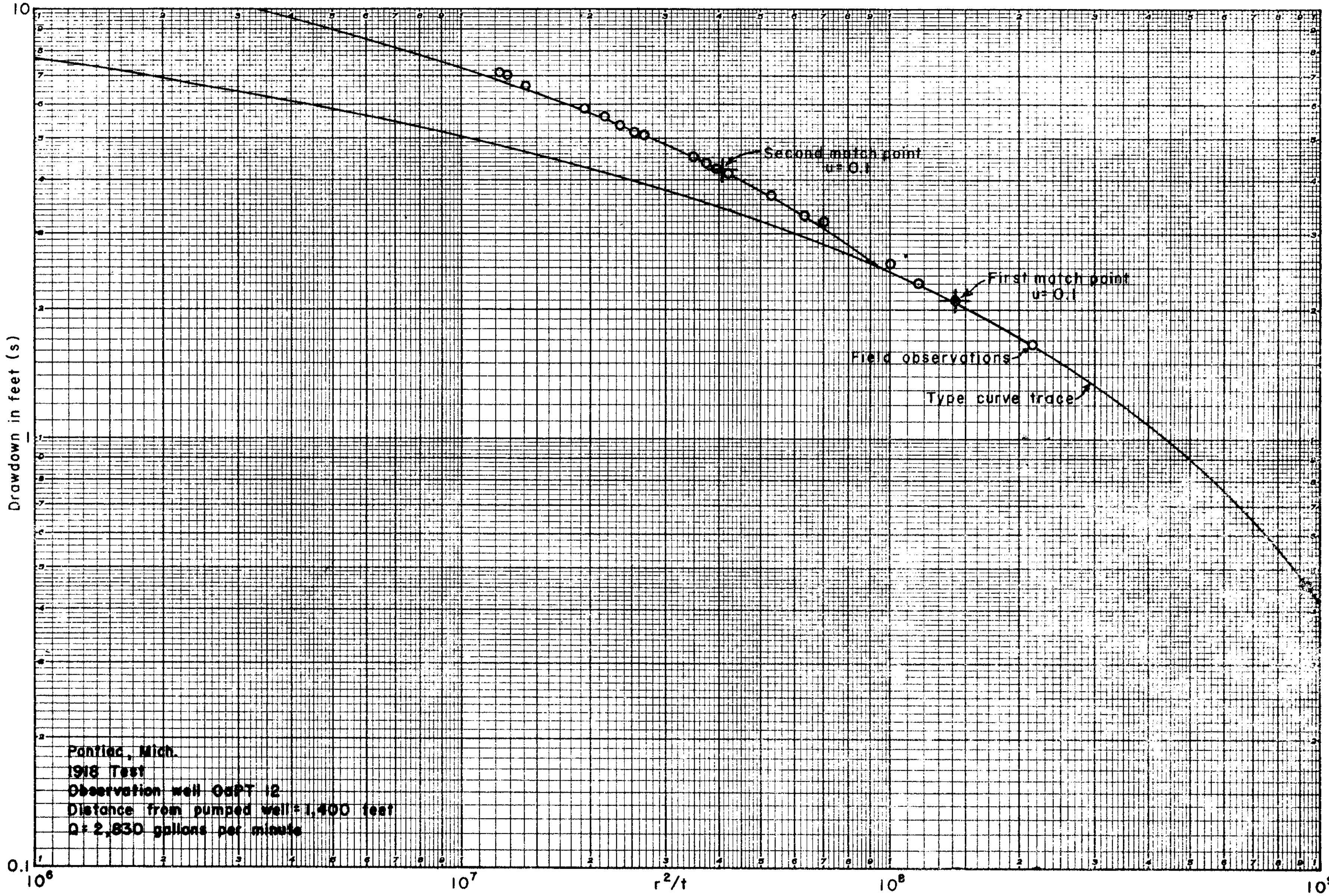

Figure 25. Logarithmic graph of the drawdown in well OaPT 12 produced by pumping wells at the Walnut Street Station at Pontiac, Mich.

corresponding to the 2.8 m.g.d. increase in pumping rate was computed from extrapolation of the stage which had prevailed in each observation well during the 10 days preceding the step increase in pumping rate. This method of analysis involves some error in the drawdown values for the first few hours, but after pumping has continued for a period comparable to the 6 hours of recovery the influence of the recovery interval is minimized and subsequent drawdown data show little or no residual effect.

The drawdown data for observation well PT 7 is shown by the log-log graph of figure 27. Using the coefficients of transmissibility and storage and the single boundary location determined from the 1918 test a trial computation was made of the drawdown that would occur for the conditions of the 1922 test and these data are shown as trial 1 on figure 27. Note that the observed drawdown is considerably larger than the computed values and the slope of the observed data is considerably steeper than indicated by the computed data for a semi-infinite aquifer.

The geologic evidence implies that a second impervious boundary occurs in the southeast part of Pontiac. The 1918 test was too short to reveal the influence of this second boundary. With the geologic data as a guide, several trial positions were assumed for the south boundary and each trial was computed to determine the magnitude and slope of the resultant drawdown graph. The position for the south boundary that gives closest conformance to the observed drawdown data is shown on the map of figure 23.

Time is plotted in reciprocal form and the earliest value of drawdown observed is farthest to the right on figure 27, and subsequent drawdowns plot to the left of this point. As expected, the drawdown values observed for the first 6 hours of the test do not fit the computed values or conform with the balance of the observed data, because the 6-hour shutoff prior to this test resulted in a higher non-pumping level than the value extrapolated from the previous weeks of steady pumping.

During the first few hours of the 6.1 m.g.d. test, water levels in the vicinity of the pumped wells were higher than the stages which were extrapolated from the previous pumping period and used as the base of drawdown computation. This higher water-level stage would be a valid datum for drawdown computation for the first hour or two of the test, but these drawdowns would refer to the full magnitude of the pumping change or 6.1 m.g.d. If the drawdown at 0.75 hour and 1.5 hours after the start of pumping is computed on the basis of the higher datum and is adjusted downward in accord with the 2.8 m.g.d. rate, the result represents the drawdown that would have occurred at the lower rate. As shown by figure 27, these adjusted drawdowns agree closely with the computed values. This method of adjustment is not applicable to drawdown values beyond the first 2 hours because the influence of the brief recovery interval is greatly modified with time and other complexities are involved. Therefore, the drawdowns from the second to the sixth hour were not adjusted.

Thus, it is demonstrated that the first 15 hours of drawdown in well PT 7 can be reproduced in both magnitude and slope on the log-log plot of figure 27 by using the hydraulic boundary positions of figure 23 with their related images and the T and S values from the 1918 test. Beyond this time,

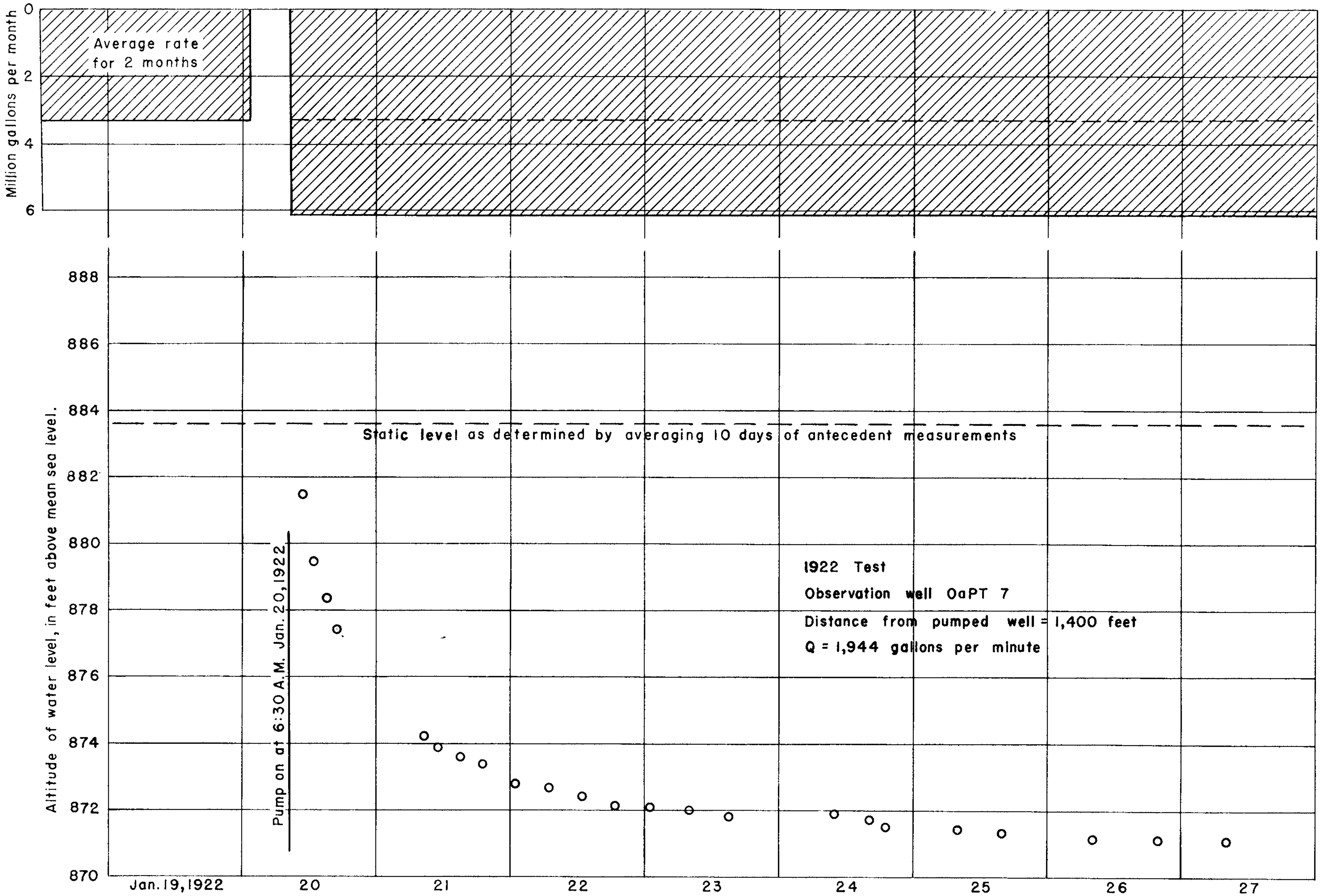

Figure 26. Fluctuation of water level in well OaPT 7 produced by pumping the air-lift wells at the Walnut Street Station at Pontiac, Mich.

however, the observed data show a marked decrease in drawdown trend. As in the 1918 test, interference from other wells or a change in pumping of the air-lift wells can be ruled out on the basis of records available. The possibility remains that an image recharge well may account for the reduction in drawdown. As shown by Muskat (1937, pp. 175-181) and by Theis (1941, pp. 734-738) a recharging image well represents the hydraulic influence of a line source, such as a stream or lake recharging the aquifer.

From departures of the observed data below the trend computed for trial 2, the distance to this line source is estimated at about 23,000 feet. Although several observation wells were measured in the 1921-22 test, all were less than 2,000 feet from the center of pumping and thereby were of little added value in fixing the position of the recharge source. An arc describing the locus of the recharge boundary is scribed on the map of figure 23. Theoretically, the recharge area may be anywhere on the circumference of the boundary circle, but the data available are not adequate to pinpoint its location. However, to a large extent the geologic evidence rules out the eastern half of the boundary circle and points westward to the vicinity of the deeper lakes. It was previously stated that the deeper lakes in this area are of sufficient depth to intersect the buried outwash deposits and that the origin of these lake basins may be correlative with the buried channel of outwash.

It is desirable to inquire about means of checking the hydraulic characteristics evaluated from the several tests. If a line source recharges an aquifer at moderate distance from the area of withdrawal, equilibrium is established in relatively short times, particularly if artesian conditions prevail as in Pontiac. When the aquifer is bounded by relatively impervious material, the mutual interference from the numerous image well counterparts of the pumping development produces a trough-like depression of water level across the buried channel. Thus, in the steady state, the Pontiac municipal well developments serve like a buried intake across the channel and intercept the ground-water flow which moves eastward from the lake-dotted upland, in response to the lowering of head produced by the pumping of these wells. Near the pumped wells the shape of the piezometric surface reflects the local geometry of the well-location pattern, but at some distance from the wells the piezometric surface will be essentially an inclined plane from the area of intake at the line source to the vicinity of the transverse trench produced by the wells. It has been shown by Theis (1941, p. 737) that in an artesian formation intersected by a line source only a short time is required before most of the water withdrawn by wells comes from the line source.

Knowing the coefficients of transmissibility and storage and the effective hydraulic width of the channel aquifer, the underflow through the buried channel can be calculated by Darcy's law (Wenzel, 1942, pp. 3-4) if the gradient along the channel is determined. In the 1918 and 1921-22 tests, the observation wells used were relatively close to the pumped wells and influenced by their spacing geometry. Data presented by Taylor (1930, p. XIII) provides a basis for determining the regional gradient from the line source to the pumping locale. In the period November 1929 to March 1930, water levels in the Orchard Lake well (PT 48) were observed while this well was out of service and its average stage was 881 feet above sea level. The total withdrawal from wells in the buried outwash average

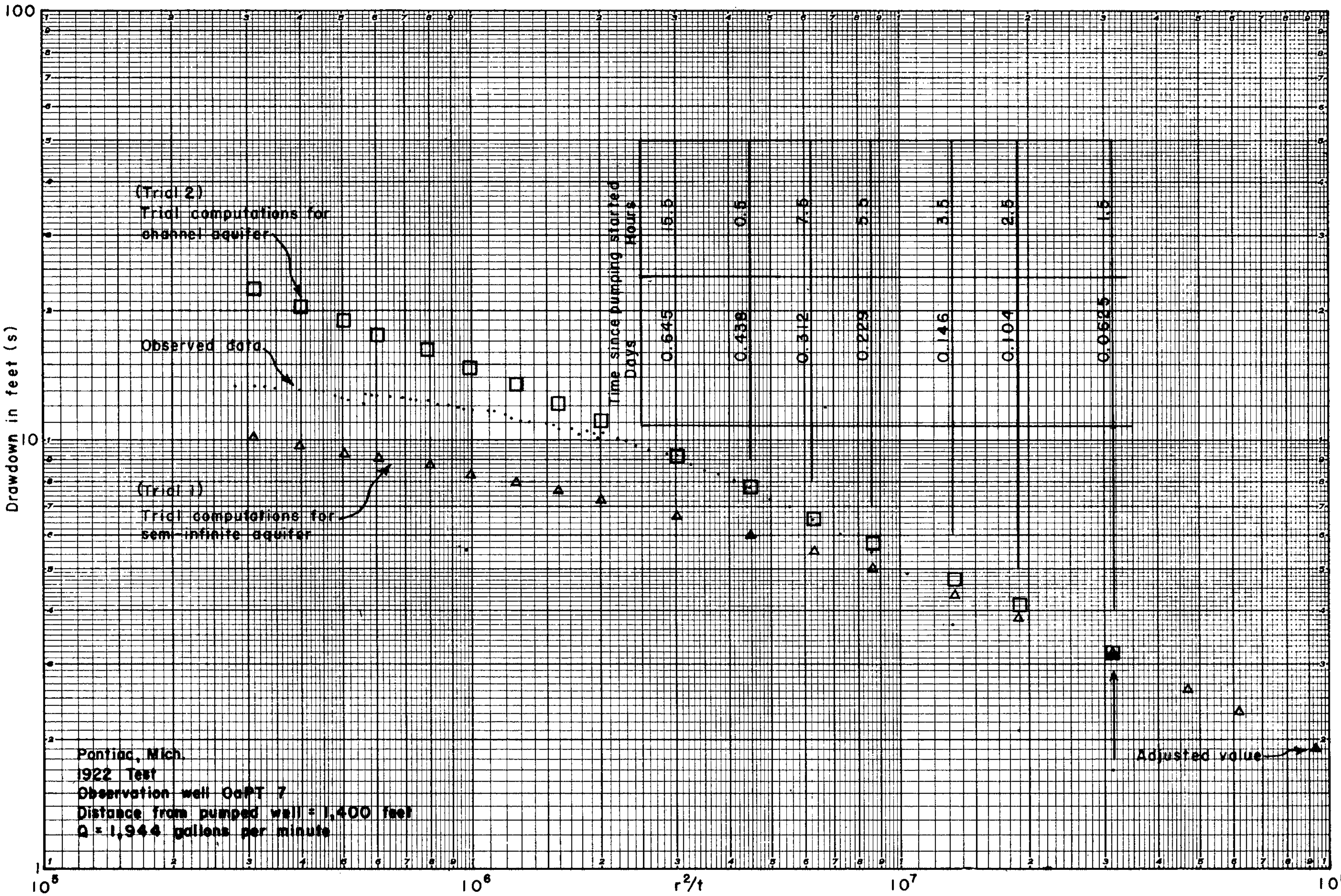

Figure 27. Logarithmic graph of the observed and computed drawdown in well OaPT 7 produced by pumping the air-lift wells at the Walnut Street Station at Pontiac, Mich.

6.5 m.g.d. The distance from the Orchard Lake well to the line source is about 20,000 feet. The altitude of lake level in the recharge area is 929 feet above sea level or 48 feet above the ground-water stage at the Orchard Lake well. From Darcy's law the following relation is developed:

$$Q = T\ I\ W \tag{5}$$

where

Q = underflow in g.p.d.

T = coefficient of transmissibility, in g.p.d. per foot

I = gradient of piezometric surface

W = width of underflow channel, in feet

Inserting the field data, the underflow is computed from equation (5) as:

$$Q = 280{,}000 \times \frac{48}{20{,}000} \times 10{,}000$$

$$Q = 6.7 \text{ m.g.d.}$$

Thus, the computed value of underflow checks within 3 percent of the municipal pumpage reported and confirms the hydraulic analysis of the Pontiac tests. These hydraulic characteristics may be used to examine the specific capacity reports of table 6. The trend of specific-capacity for a hypothetical well in the central part of Pontiac was computed and the results are shown by figure 28. The progressive decline of specific capacity during the first 10 days reflects the influence of the limited width of the aquifer and the subsequent leveling off shows the supporting influence of the line source. The computed data of figure 28 refer to a single well and are not directly comparable with the reported data of table 6 which apply to patterns of several wells. However, it is of interest to note the good agreement between the computed data of figure 28 and the report that most well users in Pontiac indicate specific capacities range between 40 and 50 g.p.m. per foot of drawdown.

The Pontiac municipal pumping-test data provide a striking example of the advantages of the aquifer-test method of analysis as contrasted to the specific-capacity method so widely used. The summary of table 6 represents the end result of the specific-capacity method of test analysis. Although these data include the influence of the aquifer's hydraulic characteristics and it's hydrogeologic boundaries, this method of analysis cannot identify them. The extrapolation of these data is permissible over short periods, but only under conditions comparable to the pattern and location of wells used in the original test. In contrast the aquifer-test method of analysis identifies the hydraulic properties of the aquifer and its hydrogeologic controls. With these data the performance of any pattern of wells at any location can be evaluated for various time intervals and the influence of adjacent developments can be appraised.

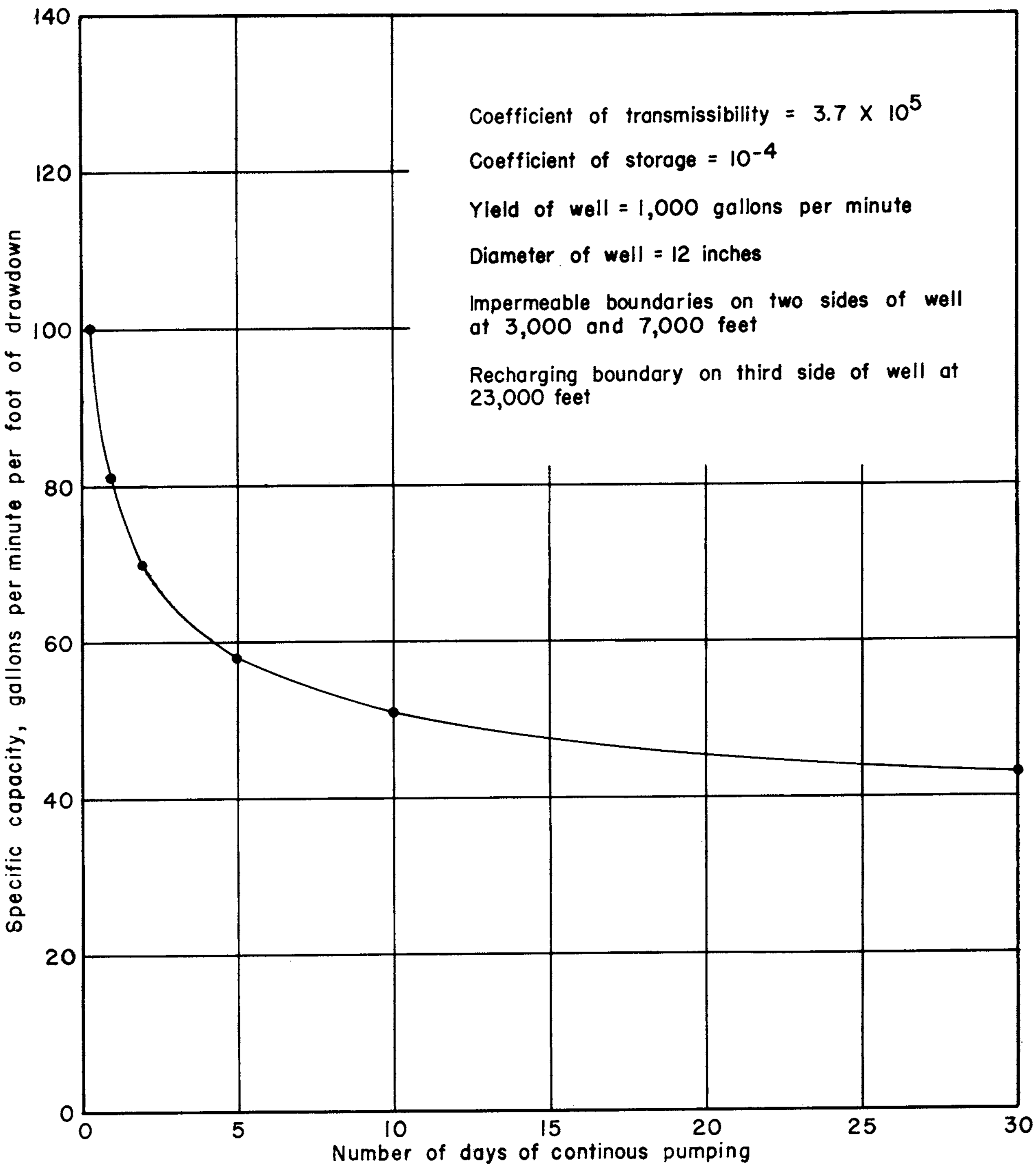

Figure 28. Variation of computed specific capacity in a hypothetical well at Pontiac, Mich.

In referring to the tests of April 10 and 16, 1930, Taylor indicated that the objective was to determine the time of transmission of the effect of pumping to various parts of the buried outwash deposits. He concludes that "The results of the test indicate conclusively the very open character of the water-bearing materials". The basis of his conclusion was presumably the rapid rate of transmission of interference effects from the centers of pumping. It is true that the rate of transmission of the interference effect is related in part to the open character of the water-bearing materials as he puts it, but more is involved in this relationship. The rate of transmission of artesian pressure is determined by the hydraulic diffusivity of the aquifer which is represented by the ratio of the transmissibility and storage coefficients of the aquifer. The T/S ratio is an index of the rate of transmission of artesian pressure and indicates that this rate is directly proportional to the transmissibility of the aquifer and inversely proportional to the coefficient of storage. In the buried outwash deposits in the Pontiac area the coefficient of transmissibility is large and the coefficient of storage is very small. The hydraulic diffusivity of the buried outwash deposits falls within the upper range observed for artesian aquifers. It follows then, that the transmission of pumping influences through the aquifer will be most rapid, which is just what Taylor observed as indicative of the open character of the water-bearing deposits.

Quality of water

In the course of their slow migration through the earth's crust, ground waters are continually in contact with the component rocks and dissolve mineral matter. In this area, the more soluble materials are the limy constituents of the bedrock and the limestone pebbles in the glacial drift. Accordingly, we find the ground waters of this area are principally of the calcium bicarbonate type and range from moderately hard to very hard, but are amenable to chemical treatment. According to Palmer's classification (1911), the ground waters of this area possess secondary alkalinity wherein the chemical properties of the waters are dominated by alkali earths and weak acids. For most supplies, the total dissolved solids and the individual content of various chemical constituents are within the standards for drinking water recommended by the U. S. Public Health Service.

Observations of ground-water temperature in five wells in Oakland County during March and April 1953 show a range from 47.8 to 51.2° F. The annual range of ground-water temperatures in Michigan may vary from a few degrees to as much as 30° F. depending on the depth of the well and local hydrogeologic conditions. Generally, where the water table is 20 feet or more below land surface, the annual temperature range is only a few degrees Fahrenheit and the average ground-water temperature approximates the mean annual air temperature for the region. The stable low temperature of ground water makes it particularly desirable for industrial cooling or air conditioning and for drinking water supply, where the low temperature enhances palatability during the summer.

Prior to the present cooperative investigation of the ground-water resources of Michigan, no continuing systematic program of sampling the ground waters of this state was in effect. Consequently, the number of comprehensive chemical analyses of ground water in this area is small. With few exceptions earlier records of chemical quality are of industrial or municipal water supplies in the areas of intensive development. It was necessary to discard some of these earlier analyses because of lack of agreement between the balance of anions and cations reported, which cast some doubt upon the accuracy of the analyses. The complete analyses of ground water for which the balance of anions and cations checked within a few percent are shown in table 7.

In addition to the comprehensive analyses, numerous partial analyses were obtained by the inventory of wells in the area. Unfortunately, the partial analyses provide no check as to the accuracy of each individual analysis. As a guide, however, the records of comprehensive analyses were used as an index to screen the partial analyses and where magnitudes reported seemed to be out of line the partial analyses were discarded. The analyses remaining after this screening process are recorded in table 8.

As an aid to illustrate the areal distribution of ground-water quality the hardness, sulfate, and chloride content for each recent analysis are shown on plate 5, adjacent to the well sampled. With reference to Pontiac and vicinity, observe the range in hardness from 155 p.p.m. for well OL 14 to as much as 632 p.p.m. for well Av 58. Well OL 14, which represents the softest water reported in table 7, is finished in the surficial sand and gravel at a depth of 80 feet and is adjacent to Orchard Lake. The soft water indicates that recharge to the formation tapped by this well is from the immediate vicinity, perhaps from the nearby lake. Well Av 58 is reportedly finished in surficial sands at a depth of 35 feet, but the extreme mineral content reported raises some question as to the source of the water. With the exception of these two extremes, the hardness for the balance of the wells in or near Pontiac shows the much narrower range from 205 p.p.m. in well Tr 259 to 450 p.p.m. in well PT 29. The chloride content ranges from 2 to 124 p.p.m. and the same wells again mark the extremes of range. Note also that wells Wt 13 and 4, for which chloride content is reported at 100 p.p.m., are among the wells of higher hardness. An equally wide range in sulfate content is indicated from the 2 to 3 p.p.m. evidenced by wells Tr 259, OL 14 and Wb 4, to the 142 p.p.m. reported for well BH 2. Again the extremes are marked by the wells with extremes of hardness or chloride.

Well BH 2, which marks the upper limit of sulfate content stands alone at this magnitude excepting wells within central Pontiac and, as will be demonstrated, the large sulfate for the Pontiac wells results from local pumpage concentration which is not true at the site of well BH 2. No evidence is reported about local sources of sulfate contamination near well BH 2, nor does any evidence point to the existence of localized sources of sulfate within the drift tapped by this well.

Well BH 2 with high sulfate and well Av 58 with high chloride and total hardness are both on a topographic ridge, most of which was mapped by Leverett as the Birmingham moraine. As shown by plate 1 and figure 6, this topographic high coincides in general with the contact of the Coldwater shale and the Berea-Bedford-Sunbury formations. The few drilling records along the ridge report relatively thick drift. However, if this topographic high reflects an underlying high on the bedrock surface, such as an

Table 7.-Chemical analyses of water from wells and the Clinton River in southeastern Oakland County. Analyses given in parts per million, except pH and specific conductance.

Well Number	Owner	Date	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Total Hardness (as $CaCO_3$)	Specific conductance in micromhos at 25° C	pH
			Part A - Pontiac												
PT 2	Pontiac Dept. of Water Supply	Mar. - 1929	4.8	1.1	70	31	40	316/1	28	45	-	376	300	-	-
24	do.	Jan. - 1929	16	.9	77	30	28	372	8.2	45	-	380	315	-	7.3
24	do.	Jan. 4, 1952	13	-	67	28	29	373	16	17	.5	354	284	450	7.7
26	do.	June 17, 1926	12	-	68	27	23	358	13	24	-	340	-	-	-
26	do.	Jan. - 1929	11	.79	72	27	23	351	15	28	-	350	292	-	7.2
26	do.	Oct. 10, 1950	8	1.8	94	34	18	354	87	23	.5	460	372	-	-
26	do.	Jan. 4, 1952	12	.6	98	36	20	360	105	20	.5	492	394	605	7.5
28	do.	Jan. - 1929	7.2	.95	64	27	43	350	9.6	47	-	369	270	-	7.4
29	do.	do.	13	.86	73	28	28	368	11	31	-	362	295	-	7.3
29	do.	Jan. 4, 1952	14	2	116	39	15	385	140	15	.3	558	450	660	7.5
30	do.	Jan. - 1929	17	1.4	78	29	17	332	55	16	-	364	314	-	7.3
30	do.	May 19, 1952	11	1.6	98	27	20	340	90	14	.3	446	355	540	7.4
31	do.	Feb. 7, 1929	10	1.5	57	27	42	338	9.9	44	-	350	253	-	7.3
31	do.	May 19, 1952	13	1.3	80	34	34	428	37	23	.5	432	340	485	7.5
32	do.	July 3, 1941	9.2	.72	67	27	33	371	11	24	-	370	278	-	-

/1 CO_3 = 23 p.p.m.

Table 7.-Chemical analyses of water from wells and the Clinton River in southeastern Oakland County. Analyses given in parts per million, except pH and specific conductance. (Continued)

Well Number	Owner	Date	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Total Hardness (as $CaCO_3$)	Specific conductance in micromhos at 25° C	pH
							Part A - Pontiac								
PT 32	Pontiac Dept. of Water Supply	Sept. 25, 1950	12	1.2	80	32	27	400	28	22	.6	400	330	-	-
34	do.	May 19, 1952	7.1	.95	48	29	25	317	23	9	.6	300	240	425	7.7
35	do.	do.	13	1	82	35	30	366	60	34	.5	456	350	600	7.6
38	do.	July 3, 1941	15	.92	75	32	25	371	22	32	-	387	320	-	-
38	do.	May 19, 1952	12	.6	80	33	34	381	45	34	.5	430	335	525	7.6
44	do.	Oct. 19, 1950	7.2	1	68	28	34	361	17	31	.5	372	280	-	-
48	do.	Feb. - 1928	tr.	.72	74	28	19	361	11	24	-	337	300	-	7.3
48	do.	Jan. - 1929	10	1.3	72	27	23	361	12	24	-	336	288	-	-
48	do.	July 15, 1941	12	1	64	30	25	334	29	20	-	342	280	-	-
49	do.	Sept. 26, 1950	8	1.3	79	29	27	367	40	22	.6	386	325	-	-
49	do.	May 19, 1952	13	1.4	82	33	26	386	50	19	.5	416	345	580	7.4
50	do.	Jan. 4, 1952	14	1	62	25	31	337	7.4	34	.6	336	258	460	7.7
160	Pontiac State Hospital	June 23, 1931	12	7.3	111	36	20	429	99	10	-	510	425	-	-
167	do.	Feb. 23, 1945	11	1.3	75	24	17	348	23	10	.5	356	285	-	-
167	do.	Mar. 17, 1953	13	1.2	80	24	19	339	40	15	.5	370	300	680	7.7
	Clinton River at Dawson Mill Pond	Feb. 18, 1928	-	-	46	17	4.6	190	24	5	-	176	185	-	-

Part B - Berkley, Birmingham, Clawson, and Royal Oak

BK	2	City of Berkley	Aug. 1, 1924	12	.48	31	19	123	323	tr.	110	-	461	-	-	-
	2	do.	May 9, 1927	10	.63	42	21	101	315	4.8	105	-	447	190	-	-
	4	do.	Aug. 24, 1929	11	tr.	39	21	92	316	4.6	86	-	408	180	-	-
	7	do.	Mar. 16, 1944	13	.5	45	27	64	342	5.2	55	.8	378	224	-	-
	8	do.	Feb. 10, 1948	7.2	.8	52	29	66	364	2.3	65	.8	396	248	-	-
BR	1	City of Birmingham	Apr. 9, 1926	24	3.2	65	25	77	333	6.2	107	-	473	264	-	-
	2	do.	Nov. 16, 1938	14	1.0	66	24	19	326	2.3	25	-	306	263	-	-
	2	do.	Jan. 9, 1947	10	1.2	64	24	23	332	2.6	23	.5	330	258	-	-
	3	do.	Jan. 14, 1947	11	1.1	72	26	54	394	4.6	56	.5	430	288	-	-
	4	do.	Nov. 16, 1938	7.2	2.1	74	24	12	352	4.6	11	-	300	283	-	-
	4	do.	Jan. 14, 1947	8.8	1.2	65	24	20	332	2.8	20	.5	319	258	-	-
	5	do.	do.	9.6	.9	65	23	35	334	1.3	42	.5	342	255	-	-
	6	do.	do.	20	1.3	77	27	37	392	7.6	38	.4	418	305	-	-
	6	do.	Oct. - 1947	15	1.7	78	27	37	395	10	37	-	406	308	-	-
	68	do.	Nov. 16, 1938	9.6	.3	31	18	670	392	3.3	900	-	1,824	151	-	-
Composite		City of Birmingham	Oct. 9, 1923	20	5.2	75	27	33	349	25	41	-	387	-	-	-
do.		do.	Apr. 5, 1927	15	tr.	78	26	45	351	38	51	-	404	298	-	-
CW	4	City of Clawson	Apr. 10, 1924	18	.9	44	23	108	332	2.0	116	-	463	-	-	-
	5	do.	May 1, 1936	8.8	.23	44	23	172	289	1.6	240	-	638	200	-	-
RO	7	City of Royal Oak	Dec. 20, 1923	14	tr.	28	16	245	251	6.8	332	-	740	-	-	-
	8	do.	May 10, 1926	13	-	29	14	283	274	5.0	365	-	846	128	-	-
	8	do.	July 17, 1930	9.6	tr.	16	5.6	172	286	2.6	140	-	474	60	-	-
	8	do.	Sept. 23, 1936	12	.3	23	11	250	280	4.6	290	-	736	100	-	-
	11	do.	Sept. 23, 1936	13.6	.7	64	26	96	366	2.6	120	-	500	262	-	-
	11	do.	July 6, 1942	6.8	.8	60	24	76	355	7.2	80	-	437	250	-	-
	20	do.	July 6, 1942	7.6	tr.	8	3.4	150	288	3.7	80	-	402	34	-	-

Table 7.-Chemical analyses of water from wells and the Clinton River in southeastern Oakland County. Analyses given in parts per million, except pH and specific conductance. (Continued)

Well Number	Owner	Date	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Total Hardness (as $CaCO_3$)	Specific conductance in micromhos at 25° C	pH
Part C - Remainder of southeast Oakland County area															
BH 2	Cranbrook School	Apr. 28, 1953	8	2.0	112	30	13	317	142	20	-	532	405	750	7.4
OL 14	St. Mary's College and Seminary	do.	12	1.0	40	13	10	217	3	2	.2	186	155	400	7.8
Composite	Village of Rochester	Jan. 26, 1923	18	2.0	84	27	10	378	20	8	-	340	-	-	-
	do.	Apr. 16, 1928	12	.68	83	27	13	370	22	14	-	310	318	-	-
BF 5	Bloomfield Village	Oct. 3, 1945	8.8	1.1	68	23	23	342	7.6	18	.5	323	264	-	-
Fa 72	Franklin Hills Country Club	Apr. 28, 1953	14	1.15	70	26	33	361	6.6	40	.2	380	280	700	7.7
73	Sarah Fisher Children Home	do.	13	1.8	80	30	57	388	15	86	.2	490	325	850	7.6
So 73	Lancaster Hills Country Club	do.	14	1.6	68	29	20	345	21	24	.3	396	290	670	7.5
Tr 3	City of Clawson	Sept.12, 1945	11	1	78	27	107	390	6.6	150	.55	570	305	-	-
12	Troy Township	Jan. - 1947	8.8	1.4	68	28	70	342	8.2	105	.7	460	285	-	-
13	do.	do.	7.2	-	65	25	21	345	6	15	.45	326	262	-	-
259	Sylvan Glen Golf Club	Apr. 28, 1953	12	.9	36	28	90	323	2	100	.8	434	205	810	7.8
Wt 7	Waterford Township	Mar. 17, 1953	14	1	64	29	37	358	8	45	.5	386	280	730	7.7
17	do.	Jan. - 1948	7.2	1.6	75	35	13	405	15	7	.8	360	330	-	-

41	Oakland County Infirmary	Mar. 17, 1953	14	1.1	70	26	18	348	17	10	1	352	280	640	7.6
44	do.	do.	14	1.6	80	30	17	349	63	7	1.1	426	325	680	7.5
45	Waterford Township	do.	13	2.	70	22	10	323	15	7	.4	296	265	550	7.7
Composite	Oakland County TB Sanitarium	do.	13	2.2	108	33	24	345	35	100	.1	574	405	900	7.4
Wb 4	Knollwood Country Club	Apr. 28, 1953	13	.5	52	27	45	356	3	32	.4	350	235	660	7.7

Table 8.-Partial chemical analyses from wells, Clinton River, and Sodon Lake, southeastern Oakland County. Analyses in parts per million

Well Number		Owner	Date	Chloride (Cl)	Sulfate (SO_4)	Hardness as $CaCO_3$	Remarks
CW	3	City of Clawson	- - -	109	-	255	
PT	2	City of Pontiac	Feb. - 1918	37	-	236	
	36	do.	July 1, 1941	-	18	297	Calcium 72. Magnesium 29.
	39	do.	July 3, 1941	-	-	308	Calcium 74. Magnesium 30. Sodium and Potassium 19. Bicarbonate 362.
	41	do.	June 27, 1941	-	10	248	Calcium 56. Magnesium 26.
	42	do.	June 26, 1941	-	29	273	Calcium 64. Magnesium 28.
Clinton River			Feb. - 1918	7	-	172	
RO	8	City of Royal Oak	July 6, 1933	-	-	100	Calcium 26, Magnesium 8.6.
	8	do.	Oct. 16, 1944	465	-	146	
	8	do.	July 16, 1948	350	-	116	
	8	do.	Apr. 13, 1949	-	-	150	
	8	do.	Apr. 5, 1950	360	-	160	
	8	do.	Apr. 7, 1950	420	-	165	
	11	do.	Feb. 28, 1949	-	-	210	
	11	do.	Aug. 17, 1949	-	-	225	
	11	do.	Jan. 10, 1951	70	-	220	
	20	do.	Feb. 5, 1945	-	-	100	
	20	do.	Feb. 19, 1945	-	-	100	
	20	do.	Mar. 3, 1945	-	-	115	
	20	do.	Aug. 17, 1945	103	-	-	
	20	do.	Jan. 29, 1948	110	-	120	
	20	do.	July 7, 1948	120	-	165	

	20	do.	Jan.	24, 1949	-	-	145	
	22	do.	Jan.	23, 1951	170	-	155	
	25	do.	Jan.	10, 1951	95	-	170	
	27	do.	Dec.	30, 1949	925	-	270	
	36	do.	May	22, 1950	110	-	190	
	55	do.	May	22, 1950	320	-	135	
Av	58	Gulf Service Station	Jan.	19, 1952	124	40	632	Calcium 162. Magnesium 55.
Bf	29	J. R. Davis	Jan.	21, 1952	14	28	316	Calcium 75. Magnesium 31.
Sodon Lake			Feb.	3, 1949	-	40	-	
do.				do.	-	20	-	
do.				do.	-	44	-	
do.				do.	-	40	-	
do.			Apr.	- 1949	-	16	-	
do.				do.	-	38	-	
Fa	71	Gulf Oil Company	Jan.	21, 1952	58	6	316	Calcium 78. Magnesium 29.
So	70	do.		do.	6	40	160	Calcium 40. Magnesium 15.
	71	H. Huetter	Jan.	22, 1952	158	40	368	Calcium 99. Magnesium 29.
Tr	4	City of Clawson	Feb.	14, 1950	90	-	300	
	151	Mrs. Pretzhow	Jan.	21, 1952	252	2	272	Calcium 59. Magnesium 30.
Wt	59	Richardson Farm Dairy	Jan.	19, 1952	6	38	244	Calcium 59. Magnesium 23.

escarpment of Coldwater shale, Sunbury shale, or Berea sandstone, the quality of water from these wells may indicate induced infiltration of mineralized water from the underlying bedrock. High sulfate suggests infiltration from the shales of the Coldwater or the Sunbury, whereas high chloride suggests infiltration from the sandstones of the Berea.

Leverett (1906, p. 191) pointed out that in 1905 most wells in eastern Troy Township flowed salty water, whether finished in the sandstones or in the basal drift deposits. He attributed the high saline content of the waters from flowing wells in this area to the escape of mineralized waters from the underlying bedrock. A salt spring was reported in the area but not visited by Leverett. The chloride content of ground water reportedly (1906, p. 192) was as great as 2829 p.p.m. in one sample. The widespread reports of water salty to the taste indicates that the chloride must have been several hundred p.p.m. in many wells.

As shown by tables 7 and 8, the chemical quality of the waters of the Clinton River and of Sodon Lake resemble the quality of the ground waters. These data add confirmation to the close interrelation of the surface and ground-water resources of the area. Of course, during periods of flood flow, the quality of the surface waters is influenced by contribution from overland runoff.

Nature and extent of ground-water developments and their effect

Past and present development

The earliest large-scale development of ground water in Pontiac, was the municipal water supply constructed in 1888. The original group of 8-inch wells at the Walnut Street station was developed in the buried outwash at depths ranging from 146 to 198 feet below land surface. Ground-water levels then stood at or slightly above land surface and the wells were pumped by direct suction. However, as the demand for water increased, additional wells were installed and by 1917 the lowering of water level in the area had reached a stage where it was necessary to pump by air lift.

The air-lift wells were in service for little more than a year when it was decided to abandon ground water as a source and utilize the surface waters of the nearby Clinton River. A filtration plant was constructed adjacent to the Walnut Street station and placed in operation in 1921. Within a very short time, however, the operation of the filter plant was discontinued because of objectionable tastes, odors, and high summertime temperatures of the surface water obtained. Since then, Pontiac has been supplied entirely from ground-water sources.

By the early 1920's, Pontiac had grown so large that its water demands required the installation of additional wells. A line of turbine wells was installed along an axis parallel to the Clinton River. Later, several air-lift or suction wells were equipped with turbine-type pumping equipment.

The growth of population and the cumulative withdrawal of ground water for municipal water supply are shown by figure 29. For most of the period, metered records of municipal withdrawal are available. Where records are missing, the withdrawal was estimated from population data and estimated per capita water use. For recent years metered records are available for many of the other ground-water installations in the area, but for earlier years records are few and the data for other water users are largely estimates.

In 1952, the average daily withdrawal of ground water in Pontiac and its environs averaged more than 21 m.g.d. with 72 percent pumped from public supply installations and the balance from industrial wells. The average per capita consumption of ground water was more than 280 g.p.d. in 1952 and more than 80 percent of this consumption was for industrial use. Nearly 95 percent of the ground water pumped for public supply was withdrawn by the municipal wells of Pontiac.

The areal distribution of ground-water withdrawals in Pontiac during 1952 is shown by figure 30. This pumpage pattern has prevailed for the past 25 years and most of the increases in withdrawal during this period were additions at the existing sites. In 1952 the effective center of pumping was located near the Bagley Street crossing of the Clinton River, or less than a quarter mile north of the original center at the Walnut Street well station.

Effect on water levels

Prior to 1900, water levels in the buried outwash deposits at the Walnut Street station were several feet above land surface or more than 920 feet above sea level. However, with the steady uptrend in ground-water use, water levels declined steadily through the years as shown by figure 29. By 1952, ground-water levels in the Walnut Street area had declined to about 120 feet below land surface or 800 feet above sea level. In the summer of 1953 water levels in a number of the municipal wells were at or slightly below the top of the perforated pipe that was used in lieu of a screen. Thus, in the vicinity of some wells the aquifer has been dewatered. However, through most of the area ground-water levels still remain above the aquifer and artesian conditions prevail.

Available information on ground-water levels in the Pontiac area are not adequate to construct regional maps showing contours on the piezometric surface but data are sufficient to construct selected profiles of water level. Data on water levels reported in test holes must be used with caution because the levels may be influenced by antecedent bailing of the well and by entrance losses into the undeveloped test hole. Apparently in some municipal wells water levels were observed while the well was pumping or shortly after the pump was shut down.

From detailed study of the water-level reports, generalized profiles of the piezometric surface were constructed along the lines of the geologic section A-A' and B-B' (figs. 17 and 18) through Pontiac. The profile along line A-A' nearly parallels the course of the channel of buried outwash deposits. A rather extensive depression of water level is shown by the several profiles of water level for each year noted. In general, the lowest water levels are

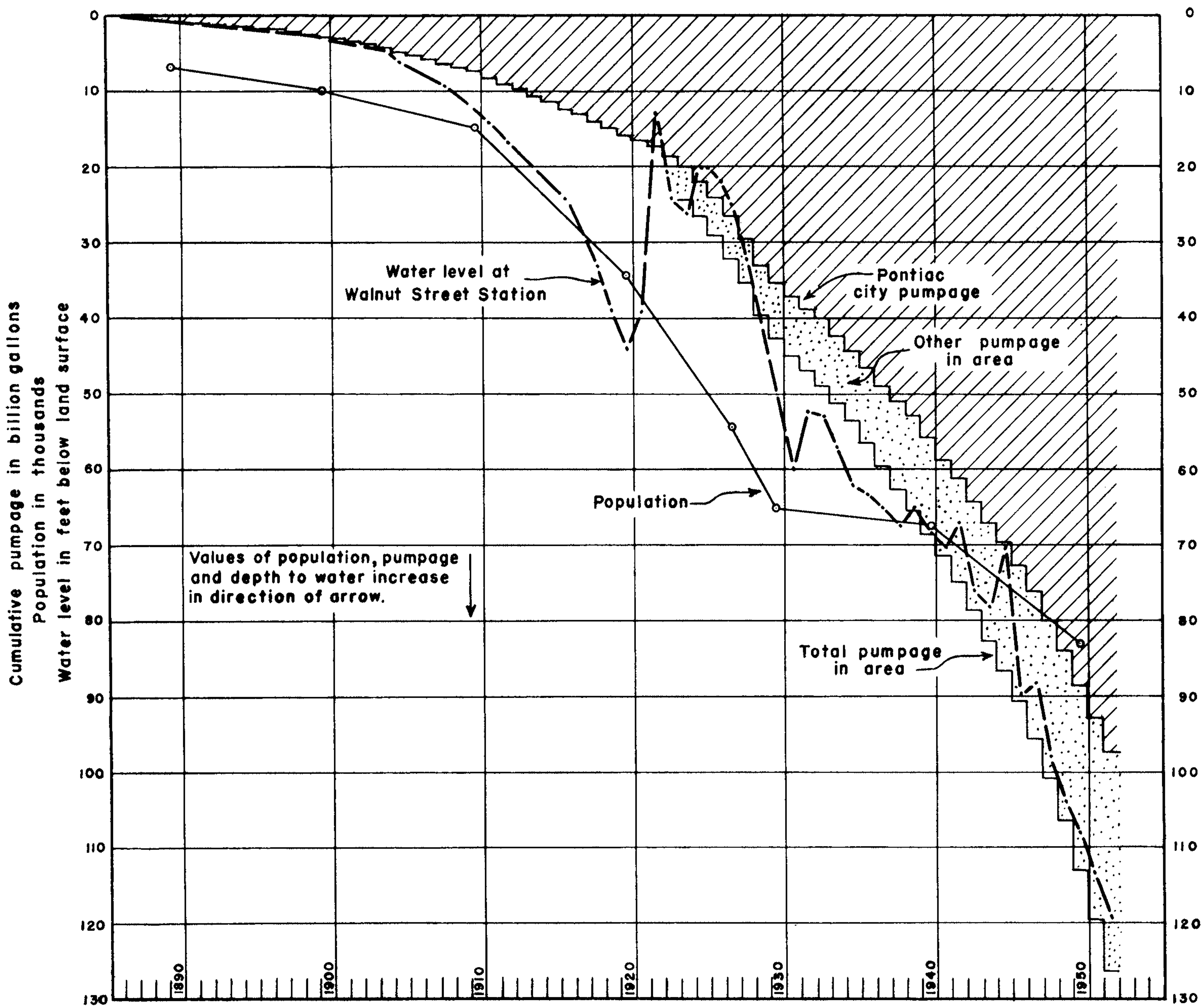

Figure 29. Relation between population, cumulative withdrawal, and water level in Pontiac, Mich.

between the Walnut Street station and the secondary pumpage concentration of the Perry-Paddock Street group of municipal wells. The effective center of over-all ground-water withdrawal in Pontiac lies between these centers of municipal pumping concentration.

The water-level profile shown by figure 18 follows the axis of geologic section B-B' and reflects the influence of the hydraulic boundaries which are identified on this section. Note that water levels reported for wells north of the north hydraulic boundary are at considerably higher stages than water levels in the outwash channel. Most of these wells were drilled to sufficient depth to completely penetrate the buried outwash deposits of the channel aquifer if they extended into the north part of Pontiac. If these wells are finished in glacial drift as reported by the drillers, the permeable deposits apparently are a few scattered thin beds, or beds poorly connected hydraulically with the buried outwash in the principal channel. Whatever the nature of the water-bearing deposits north of the north boundary, the water-level gradient indicates that some water moves from this direction toward the buried channel in response to the greatly lowered water level in the channel aquifer.

In the southern industrial area of Pontiac, the few reports of water levels available show that ground-water levels in this area have declined 50 feet or more in the past 25 years. Within the past few years the use of ground water by industry has greatly increased and it is probable that water-level declines in the southern area of intensive development will increase.

The concentration of ground-water developments into a small segment of the buried-channel aquifer and the considerable distance from the center of this pumping to the area of recharge has caused the development of a large drawdown of water level throughout central Pontiac. The correlation between the drawdown of water level and the total withdrawal of ground water in Pontiac is illustrated by figure 31, wherein the total withdrawal by wells in the buried outwash is plotted versus the water-level stage observed at the Walnut Street station.

Future trends of water level in the area cannot be extrapolated from the trend of the graph shown by figure 31, because of the imminence of extensive dewatering of the aquifer. When dewatering occurs, the coefficient of storage for the channel aquifer will increase from the present artesian value of 0.0001 to a water-table value of 0.20 to 0.30 and the amount of water available to wells from storage will increase several thousand times. As a result of the greatly increased storage release near each pumping well, ground-water levels in the area will appear for some time to stabilize at or near existent levels. However, as pumping rates increase and new well installations are added, further declines of water level will dewater the aquifer and reduce its saturated thickness. The coefficient of transmissibility of the aquifer is proportional to its saturated thickness and as the saturated thickness is reduced the coefficient of transmissibility is correspondingly reduced. As the coefficient of transmissibility decreases, the capacity of the buried channel to transmit water at the rate and gradient which formerly prevailed is reduced. Decreased transmissibility requires increased drawdown to maintain a constant withdrawal rate, but greater drawdown further decreases the transmissibility. As this vicious cycle continues, pumps must be set at successively deeper stages in order to

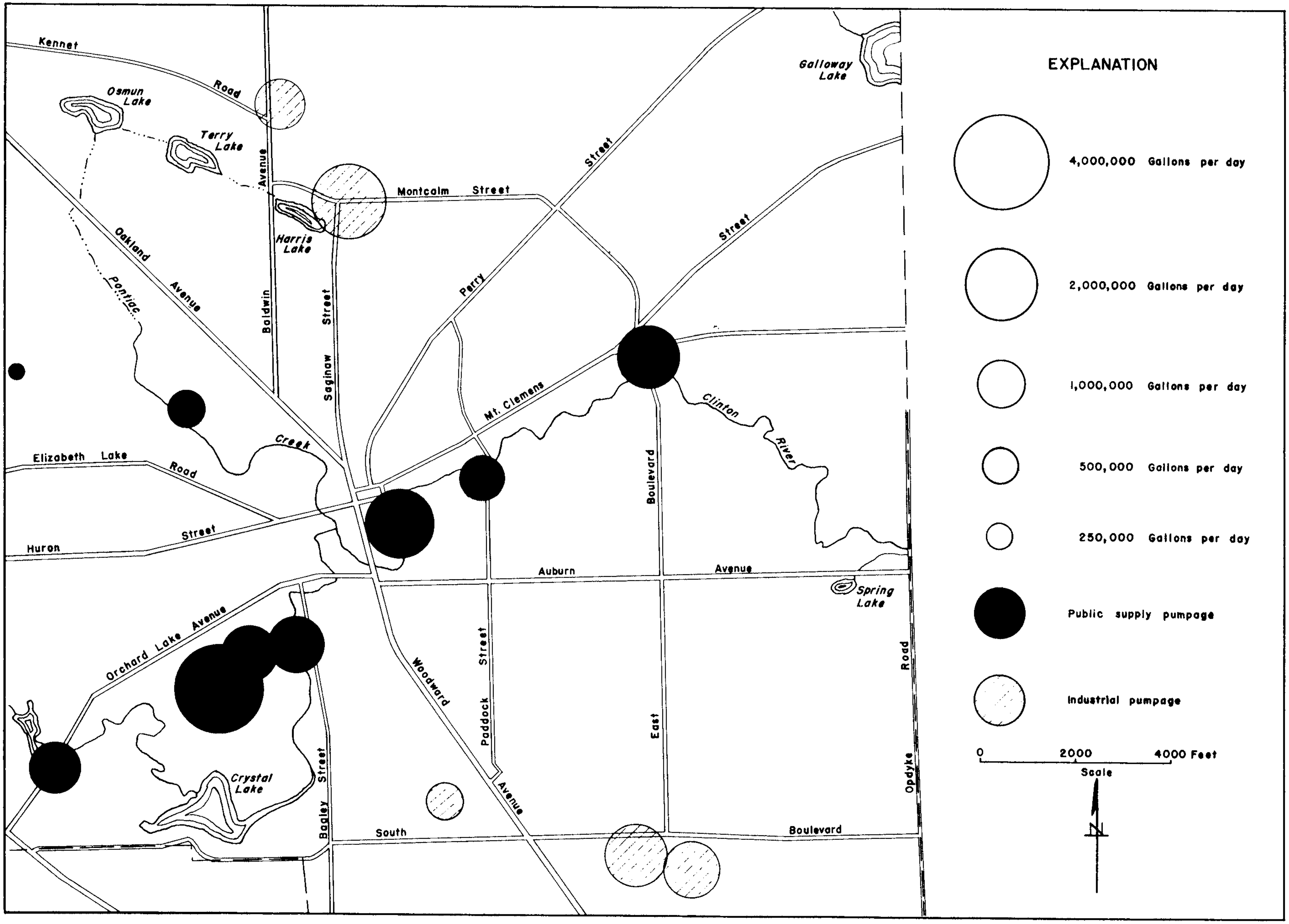

Figure 30. Areal distribution of ground water withdrawals in Pontiac during 1952

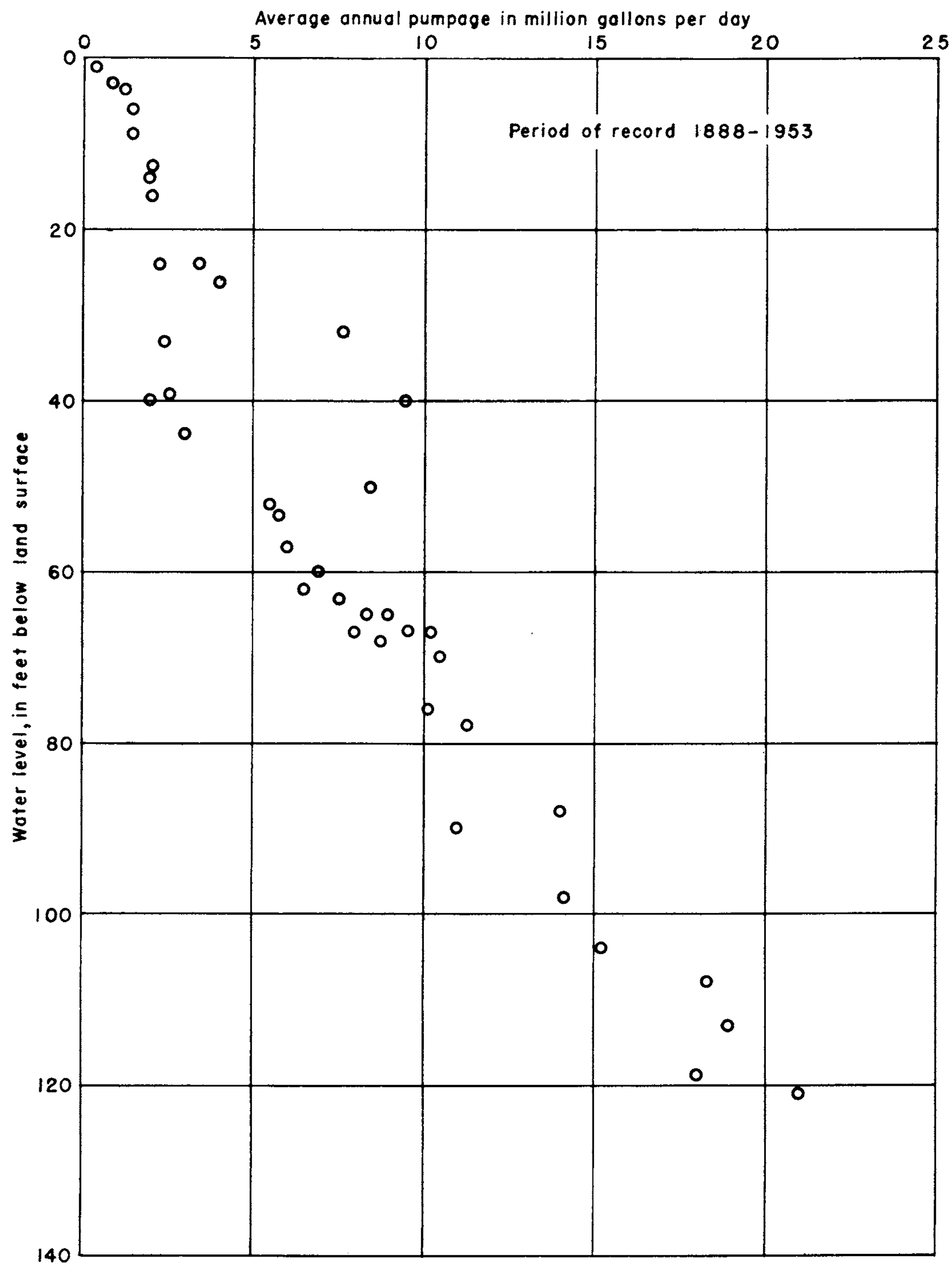

Figure 31. Pumpage and decline of water levels at the Walnut Street Station at Pontiac, Mich.

keep pace with the declining water level. Before long, pumps must be throttled to maintain well output commensurate with the saturated thickness required for that rate of well yield. Thus, unless remedial measures are adopted, extension of the seemingly straight-line correlation of figure 31 may continue for some time at its present slope; then seemingly level off for some time; and later renew its decline at a much more rapid rate than previously.

Continuing records of water level are not available for wells tapping the buried outwash deposits outside the city of Pontiac. It is probable, that water levels in the outwash channel beyond Pontiac have declined substantially as a consequence of the intensive withdrawal of ground water in this area during the past 50 years. Several reports of water levels in test holes to the west of Pontiac, where a few test wells have penetrated the buried outwash deposits, indicate that in some areas water levels in the buried outwash are below the levels of surrounding lakes. Taylor (1930, p. 38) reports that deeper wells near Crescent Lake in Waterford Township had strong artesian flows in 1929. In contrast, the water levels reported by drillers for many deep wells near Cass, Orchard, and Sylvan lakes, in 1929 and recently, are several feet to a few tens of feet below lake levels. These reports are not necessarily indicative of influence by developments in Pontiac, but may represent the effect of nearby withdrawals by the many wells installed by local residents who have intensively developed these lakeside lands in the past few decades. Appropriate water-level observation programs in this area would identify each influence.

Effect on water quality

A review of plate 5 shows an orderly pattern in the areal distribution of sulfate and total hardness of ground waters sampled in central Pontiac. Also, data given in figure 32, shows that the sulfate content of ground water from wells in central Pontiac is progressively increasing. Local pollution or contamination by sulfate wastes is not evident. Only one source of sulfate contamination remains - induced infiltration of mineralized waters from the underlying Coldwater shale in the manner illustrated by figure 15. The amount of sulfate provides a good index of such infiltration inasmuch as sulfate is high in water from the Coldwater shale, but as shown by table 11 it is low in waters that have not been in contact with the Coldwater.

The pattern of sulfate distribution along the axis of geologic section A-A', which nearly coincides with the course of the buried channel and the line of municipal well stations, is shown by figure 33. Patterns are shown for both January and May 1952. To compensate somewhat for differences in pumping rates during each month, the data for each well are plotted in terms of sulfate content per unit of pumping rate. This procedure tends to adjust the differences in pumping rate at each well sampled and the resultant sulfate index reflects principally the over-all or regional pumping influence.

Greater sulfate content in the several municipal wells in May 1952 compared to January of that year confirms the interrelation between sulfate content and the lowering of water level in the buried outwash aquifer. The over-all rate of ground-water withdrawal was much larger in May and

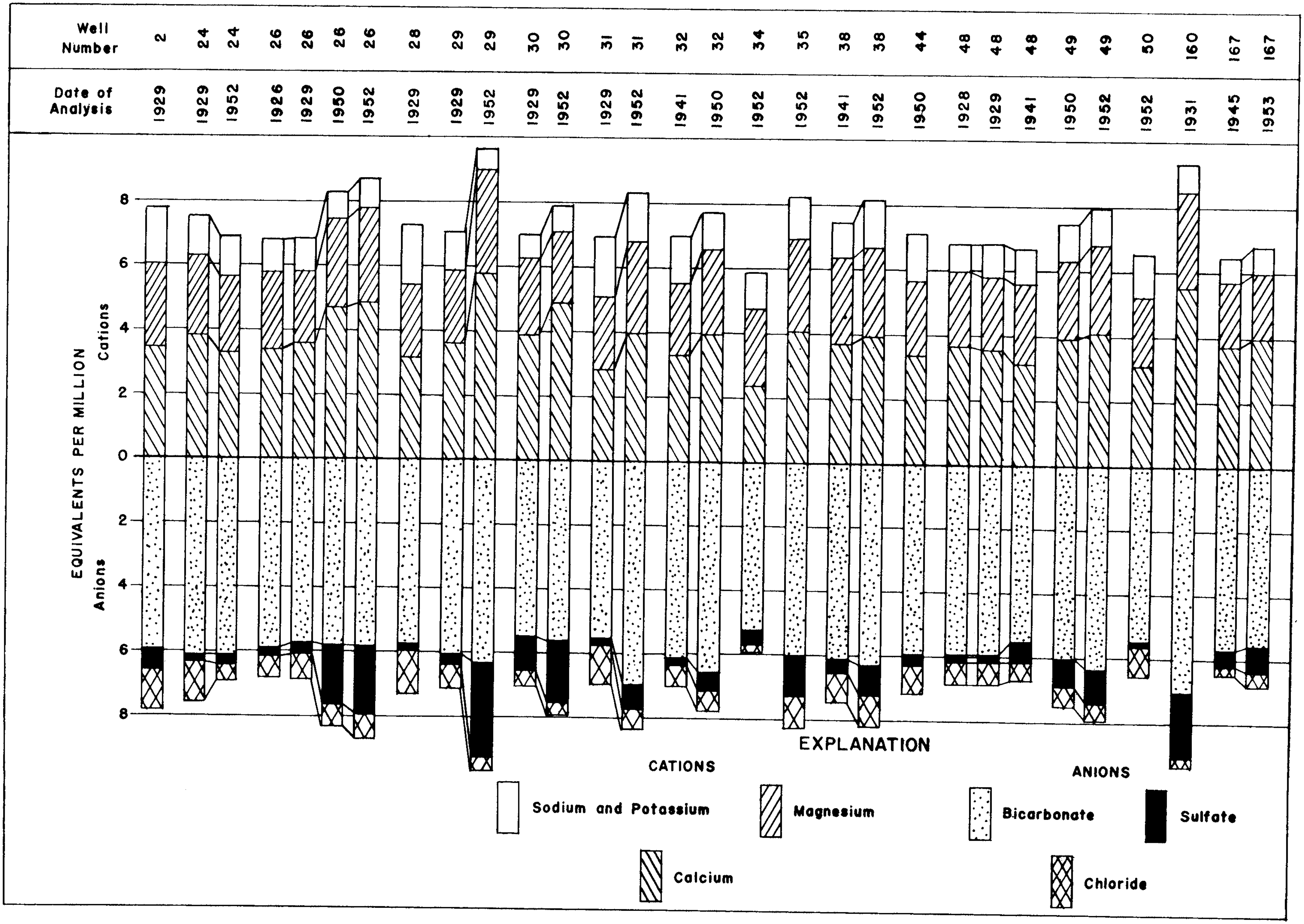

Figure 32. Composition of ground water in Pontiac, Mich.

consequently water levels throughout the area were lower at this time. Thus, a larger head differential existed between the buried outwash and the underlying Coldwater shales or other deposits of small permeability that bound the buried outwash channel. Under this condition the rate of leakage from adjacent strata was increased.

The pattern of sulfate distribution along the axis of the buried channel is of particular interest and affords further evidence of the interformational leakage. In general form, the sulfate distribution shown by figure 33 resembles the cone of water-level depression with the apex of greatest sulfate content near the Perry Street (PT 38) - City Hall (PT 36) - Market (PT 29) - Mechanic Street (PT 26) - Paddock Street (PT 30) concentration of municipal wells. Although the wells at the Walnut Street station are as closely spaced as the Perry - Paddock Street group and their combined pumping is greater, the sulfate content was much smaller in both sampling periods. Thus, the rate of withdrawal is not the only factor which influences the interformational leakage. Other contributing factors are the setting and length of the well screen, the proximity of the well to other developments, the distance from the hydraulic boundaries of the channel and from the line source, and the relative permeability of the underlying shales and the drift deposits that intervene between the shale and the bottom of the well screen. The greater length of screen used in most of the Walnut Street wells and the smaller pumping rate per well permits these wells to operate with smaller drawdowns or higher pumping levels and less interformational head differential than wells in the Perry - Paddock Street group. In addition, the upgradient location of the Walnut Street wells gives this group higher priority in the interception of water from the distant line source.

It would be expected that the Orchard Lake wells (PT 49, 50) produce water of lowest sulfate content because these wells are nearest the line source of recharge from the lakes to the west and most distant from the effective center of pumping in Pontiac. The samples of January 4 show the expected alignment, but the May 19 samples do not.

The Orchard Lake wells serve to illustrate the importance of local conditions in modifying the general correlation of sulfate content with pumpage and resultant water level stage. The consistently high sulfate content of the Perry - Paddock Street well group reflects the influence of its proximity to the effective center of pumping, the mutual interference of concentrated well developments, and the effect of the hydraulic boundaries and attendant image wells. The lower water levels near this center of pumping permit greater interformational leakage, which results in higher sulfate and hardness. The benefits in improved water quality by reducing the average withdrawal from each well are best illustrated by examination of table 7 with reference to the water quality of the Pontiac wells during the earlier years when the average monthly withdrawal from each well was smaller. The relatively large sulfate content shown by the Orchard Lake wells (PT 49, 50) in May 1952 reflects the influence of intensive withdrawal by closely spaced wells with short screens and a deeper than average screen setting of one well at this station.

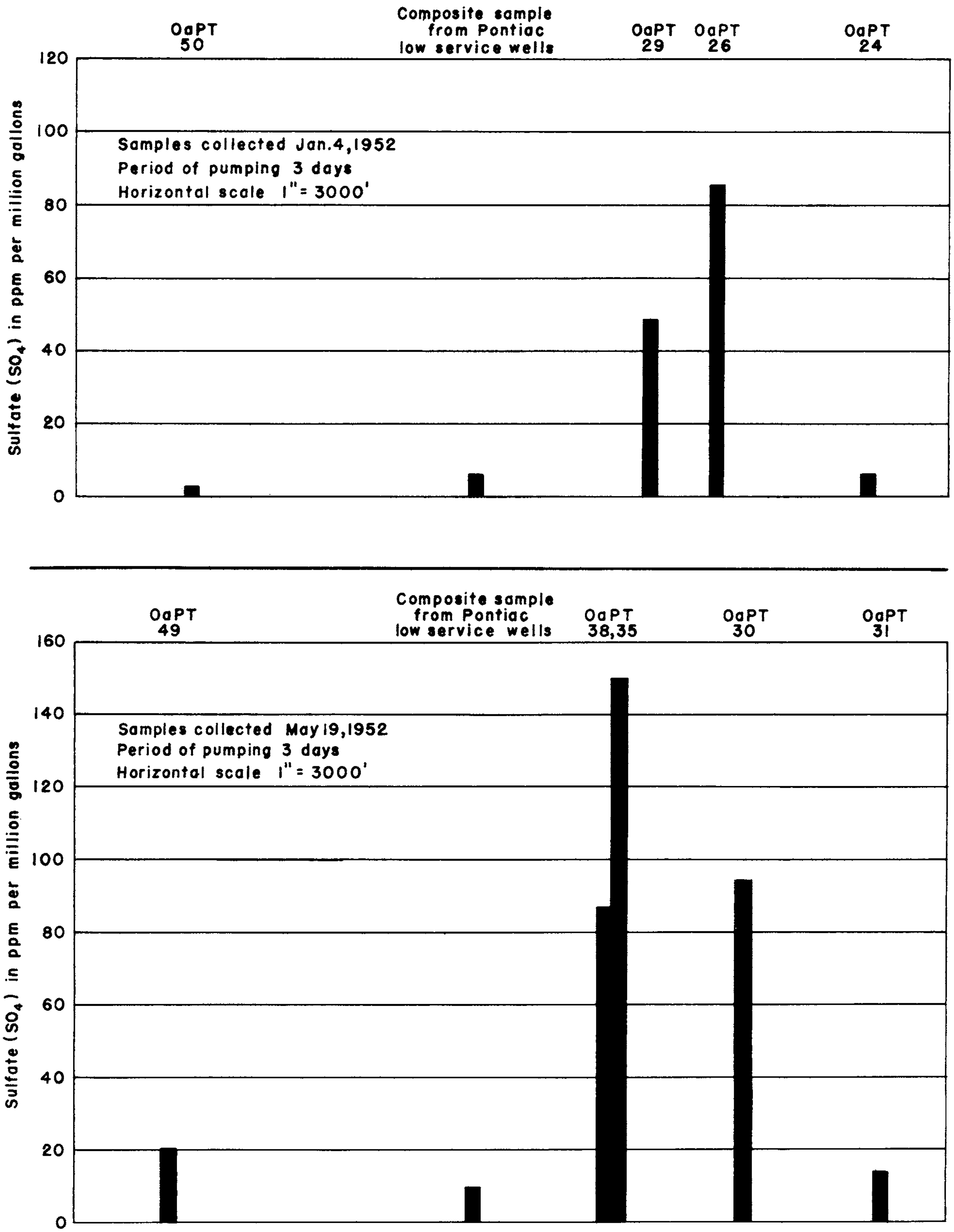

Figure 33. Relation of sulfate and pumpage in the Pontiac municipal wells.

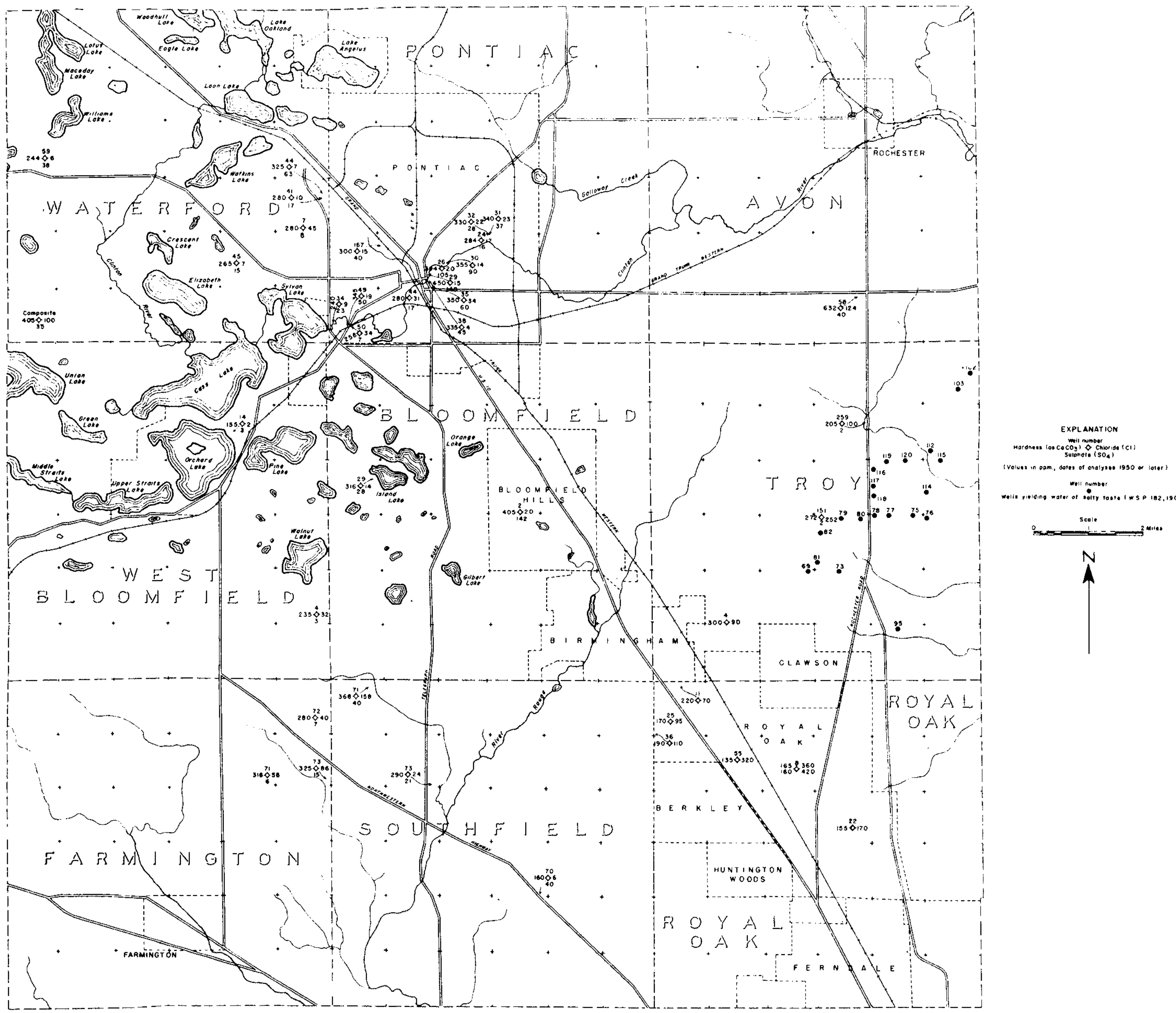

PLATE 5 COMPOSITION OF SELECTED SAMPLES OF GROUND WATER IN SOUTHEASTERN OAKLAND COUNTY, MICHIGAN

Birmingham-Royal Oak area

Nature and extent of water-bearing formations

Surficial deposits

The Birmingham-Royal Oak area (see plate 6) is another principal concentration of ground-water developments. As shown by plate 1, most of the Birmingham-Royal Oak area is mantled by lacustrine deposits of former glacial lakes. Elsewhere, the area is covered by glacial tills of the Birmingham moraine and the Detroit Interlobate moraine. The beaches of the former glacial lakes are the most permeable of the lacustrine deposits, but their elevation above the lake plain permits the ground water to escape locally and thereby limits their storage capacity. In addition to the beaches, other sandy phases of the lacustrine deposits provide limited capacity locally for the storage of ground water.

Many residents of the area formerly obtained domestic water supplies from shallow wells which tapped the sandy lenses of the lacustrine deposits or the "roots" of the beach ridges. By the 1920's residents of Hazel Park, Ferndale, Oak Park, Pleasant Ridge, and Huntington Woods were troubled each summer with water shortages because of failure of their shallow domestic wells. Water haulage was general in the area at that time. During the 1920's and 1930's these communities contracted with Detroit to supply water to the area.

The area is now so intensively developed that the surficial deposits may be subject to contamination. The small thickness and areal extent of the permeable zones rule out any extensive development of either moderate or large ground-water supplies in the lacustrine deposits. Locally, small to perhaps moderate supplies might be obtained by intake systems adapated for development of thin aquifers. In the aggregate, the thin lacustrine deposits provide storage capacity for a considerable volume of ground water, but a vast network of sewers and drains (nearly 500 lineal miles in the aggregate) intercepts much of the annual replenishment to these surficial deposits. The deposits that now yield water to the sewers or drains would receive water from them when gradients were reversed by heavy pumping. In addition, because of the intensive land development, these deposits may receive contamination directly from the surface.

Buried outwash deposits

The water-bearing formations of principal importance to the development of relatively large ground-water supplies in the area are the buried outwash deposits. The locations of wells, foundation borings, and test holes for which records are available are shown by plate 6. Geologic sections along axes indicated by plate 6 are shown as figures 34 to 38 inclusive. The mantle of glacial drift in the area ranges in thickness from less than 100 feet in the southeastern part of Royal Oak to nearly 300 feet in northwestern Birmingham. A relatively thick formation of clay, gravelly clay, or clay hardpan caps the buried outwash deposits throughout the area.

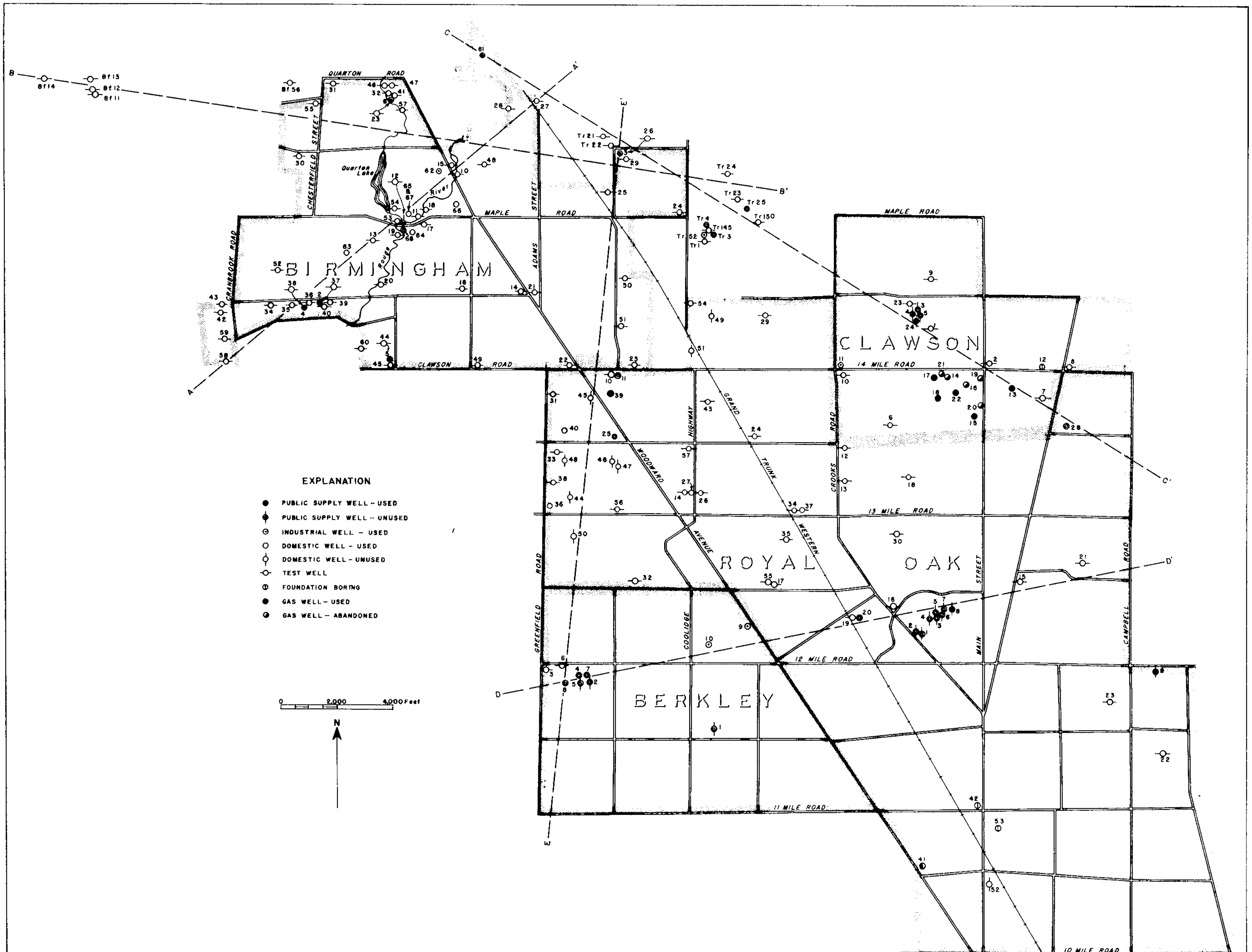

PLATE 6. WELL-LOCATION MAP OF THE BIRMINGHAM-ROYAL OAK AREA, MICHIGAN

The graphic logs of figures 34 to 38 inclusive show numerous differences in the reported materials penetrated by test wells within a stone's throw of each other. Notable examples include wells BR 11, 12, 31 and 55, CW 5 and 23, and BK 3, 7, and 8. A cursory examination of the geologic sections of figures 34 to 38 inclusive, causes one to wonder what constitutes the vast reservoir that has supplied the large aggregate total of water pumped by the many wells in the area during the past several decades, since most logs record small permeability or essentially impervious materials. Note that in several wells screens were placed and wells were finished in what was reported or logged as clay and gravel.

Identification of the bedrock surface from the records available is subject to considerable question. More reliable identification would require intensive study of each subarea. Many well logs record a thick basal section logged as hardpan, clay, clay and sand, clay and gravel, or clay, sand, and gravel. Where some test holes penetrated shale, adjoining test-well logs record clay and gravel or clay hardpan. Drill cuttings of sandy shales or shaly sandstones may be logged by the driller as clay, sand, and gravel. Sandstone cuttings may be reported as sand and gravel or sandy hardpan. The driller's classification of bedrock is generally based on resistance to drilling or to driving casing and is seldom supported by lithologic studies of drill cuttings. In this area it is not unusual to encounter zones within the drift mantle that are more resistant than some of the bedrock strata. In some places the cementing material may have been leached from the bedrock and its resistance to drilling thereby reduced to a minimum. Identification of the bedrock, particularly shales, is most difficult if not impossible when drilling resistance is used as the principal index. Much of the drift mantle consists of reworked bedrock and identification by any means of the drift-to-bedrock contact may be difficult.

In reviewing the well records, one is struck forcibly by the driller's frequent use of the modifying terms "hard" or "tight" in referring to some of the clayey gravels or gravelly clays encountered. In many logs, strata to which the modifier "hard" or "tight" was applied mark stratigraphic positions that correlate with the screen settings in nearby producing wells.

A sample study was made of well logs in the Birmingham area to determine what correlation, if any, existed between the reports of "hard" or "tight" drilling and the positions of well screens. It was found that in the test holes at sites which were considered nonproductive, the majority of reports of hard or tight clayey gravel or gravelly clay corresponded to the stratigraphic positions of the gravels in which well screens were placed in producing wells that were later developed nearby. The question arises as to why materials classified as impervious in some test wells were found to be highly pervious in wells nearby. A plausible explanation is that in drilling through the overlying clays or clay hardpans, which cap the buried outwash deposits, muddy fluids from the drill cuttings may have been carried along and served as a mudding compound to seal off the permeable deposits. Whereever highly permeable deposits were penetrated, the loss of drilling fluid would be so noticeable that the drillers would realize the presence of water-bearing deposits. But, where the outwash deposits contain appreciable quantities of fine materials, little mud would be needed to effectively seal the formations during the relatively short period required to drill through the stratum.

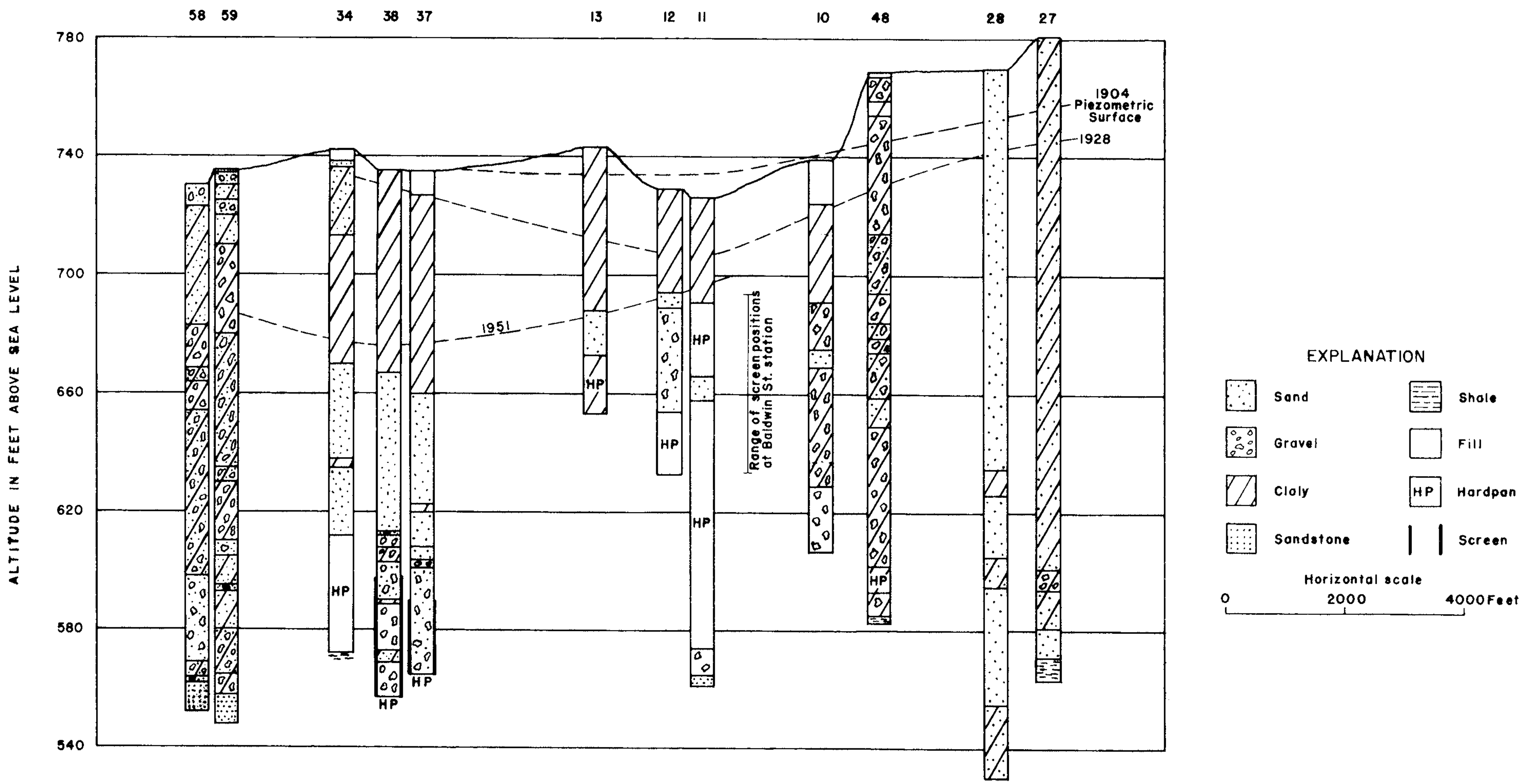

Figure 34. Geologic section and profile of piezometric surface along line A-A' shown on plate 6

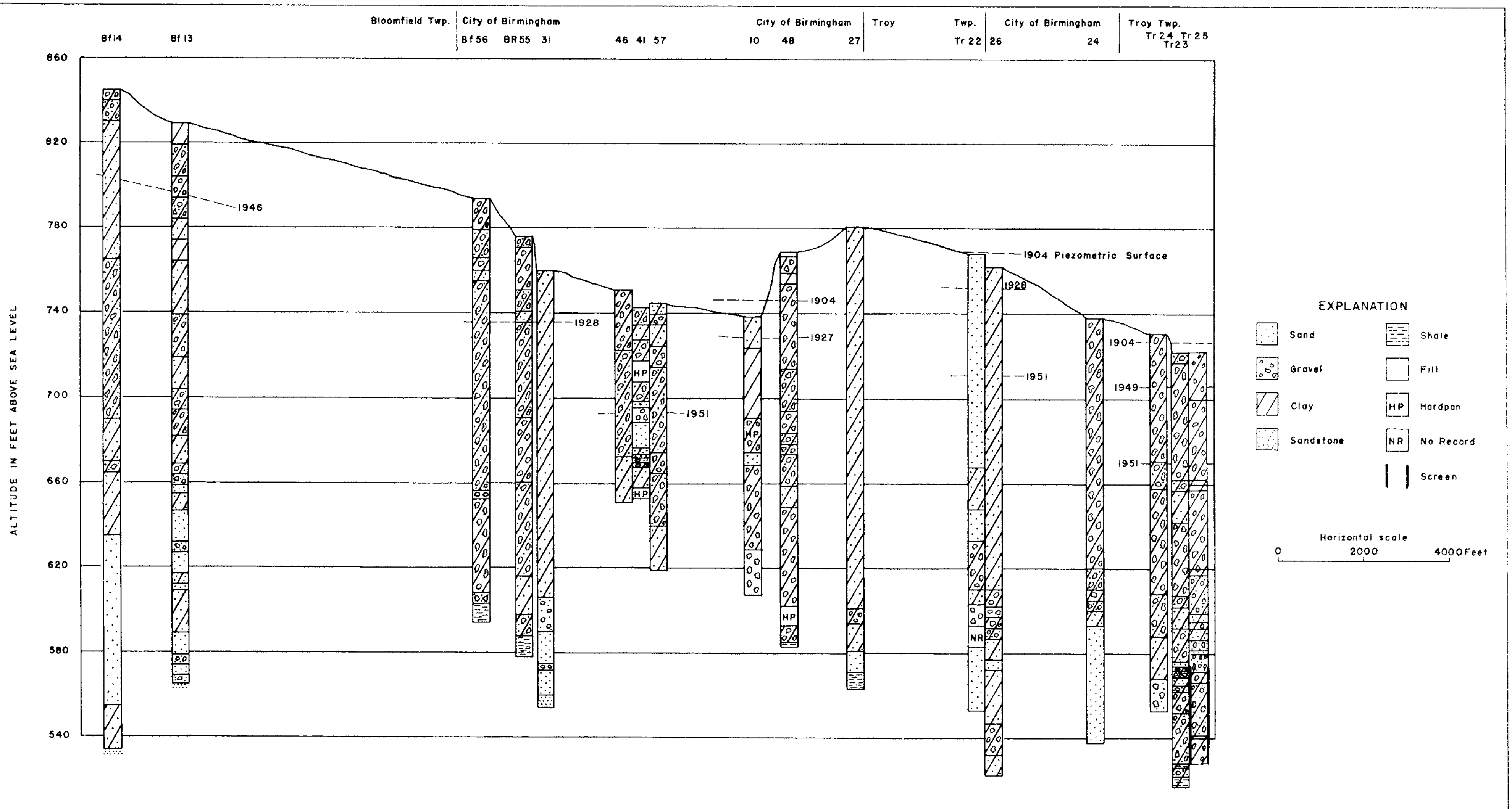

Figure 35. Geologic section and profile of piezometric surface along line B-B′ shown on plate 6

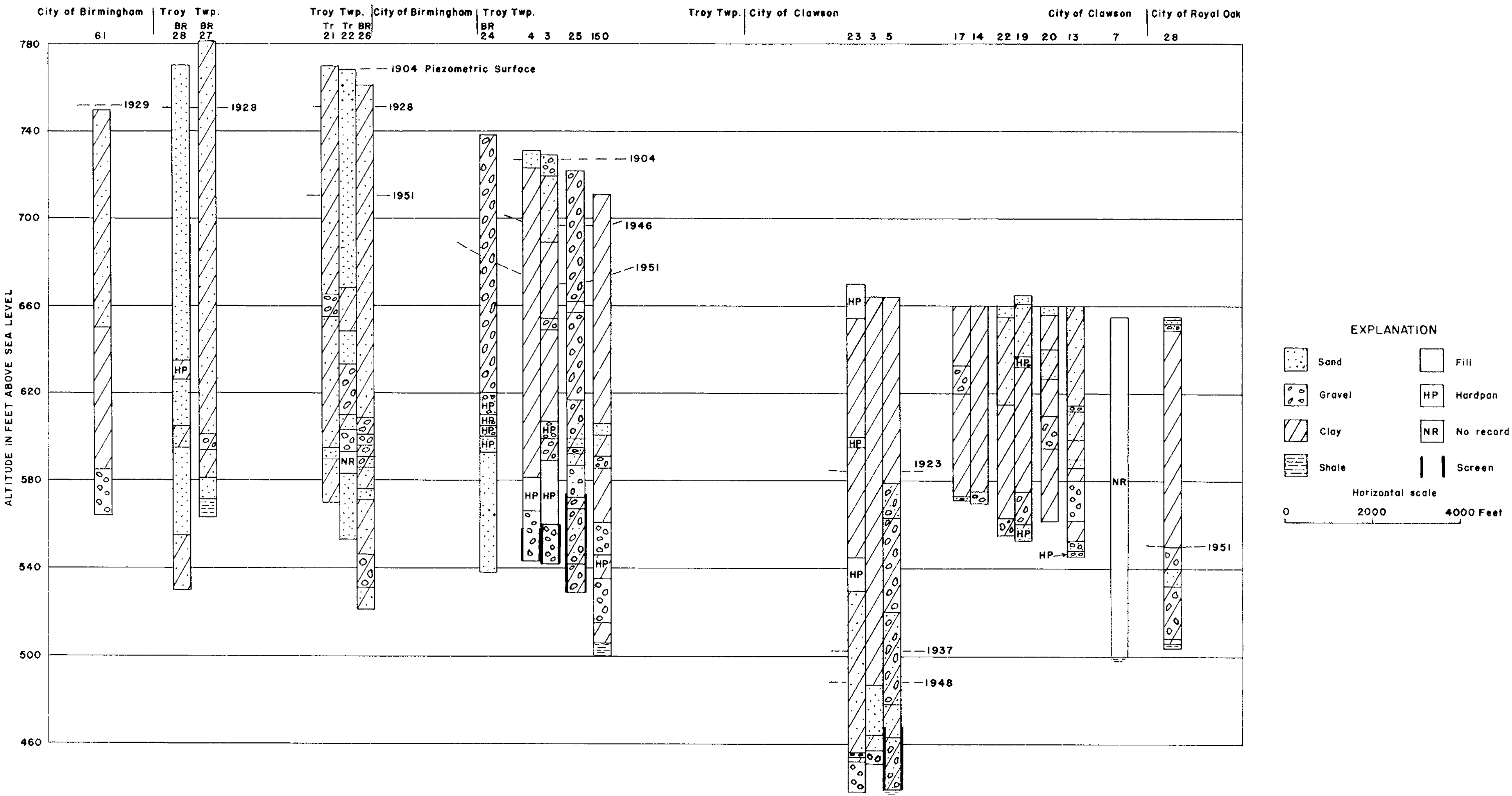

Figure 36. Geologic section and profile of piezometric surface along line C–C' shown on plate 6

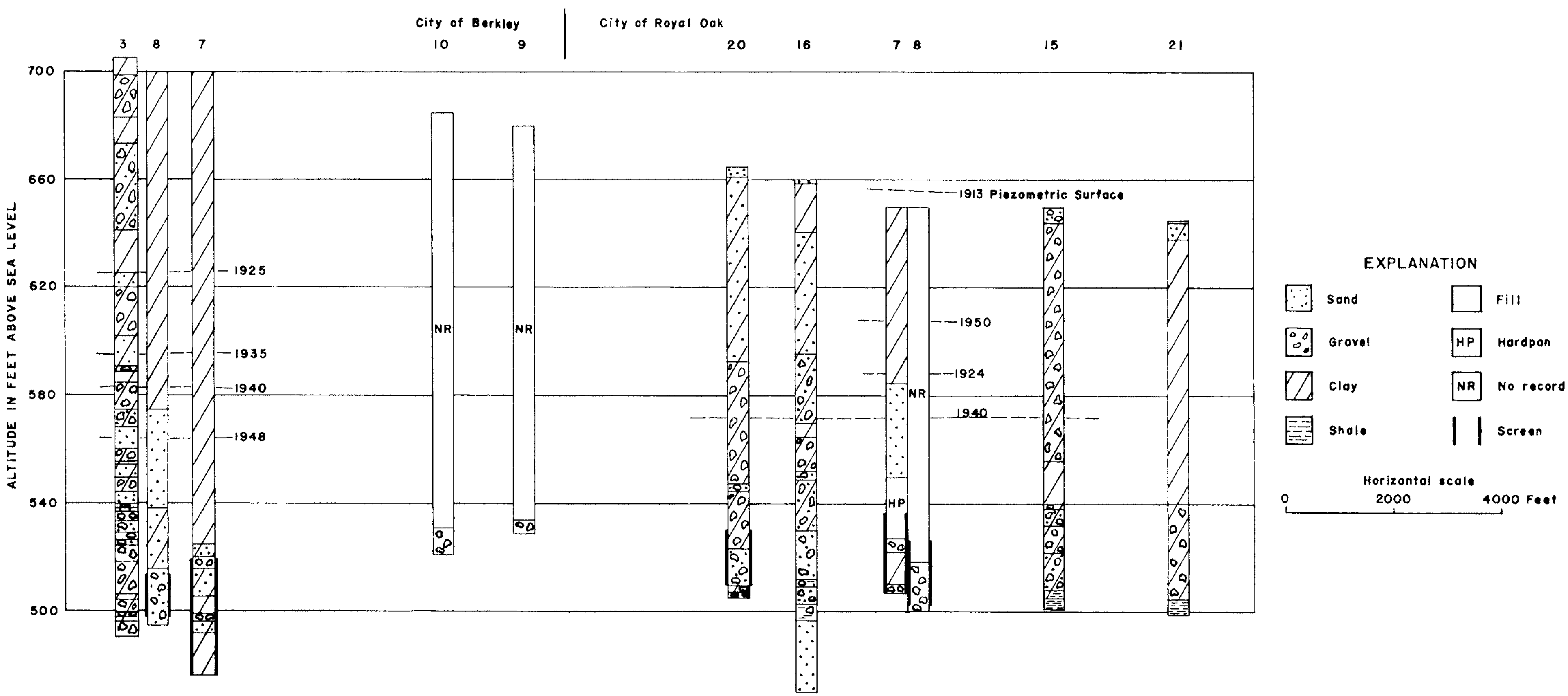

Figure 37. Geologic section and profile of piezometric surface along line D-D' shown on **plate 6**

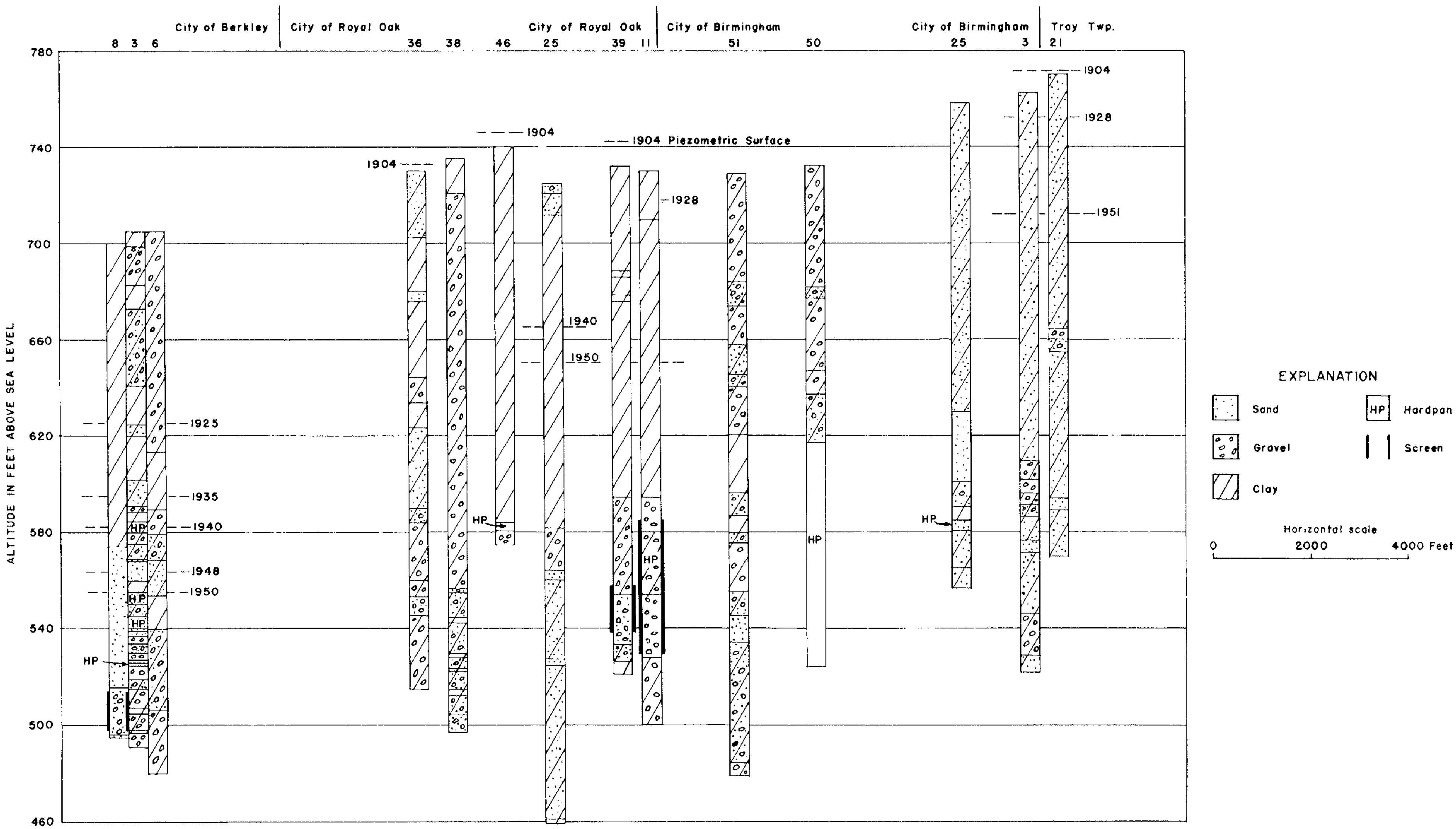

Figure 38. Geologic section and profile of piezometric surface along line E-E' shown on plate 6

The geologic sections of figures 34 - 38 show that in general the thicker and more continuous deposits of buried outwash are in the northern and western parts of the area, underlying Birmingham and adjoining Troy and Bloomfield townships. In Royal Oak, Clawson, and Berkley, the buried outwash deposits are thin and of small areal extent. The geologic section B-B' (fig. 35) through the Birmingham area indicates that the buried outwash deposits thicken and are composed of finer particles to the west. Consideration should be given of the possibility that the sands or fine sands reported near the base of well logs Bf 13 and 14 may be sandstones rather than unconsolidated drift deposits as reported.

The buried outwash deposits have been extensively explored in that part of Troy Township which borders Birmingham, Royal Oak, and Clawson. Although the deposits of permeable outwash in this area are not as thick as those reported to the west in Birmingham, it appears that they may be somewhat cleaner or freer of fine materials because a larger percentage of logs report gravels and a greater proportion of successful wells have been finished in the area.

Bedrock formations

The bedrock underlying the drift mantle (see fig. 6) in the area to the south or east of Birmingham consists of the carbonaceous shales of the Antrim formation. Although not wholly impervious, these shales are not sufficiently water bearing to permit the development of large or even moderate water supplies. Furthermore, the ground waters within the Antrim shales are highly mineralized and quantities of methane gas are found in many places at or near the top of the formation. A number of wells within the Royal Oak area (plate 6) have developed small supplies of gas sufficient for home heating use. The movement of gas from the shales into the basal drift deposits and into wells that tap the shales has been a problem in the Royal Oak area. Several serious explosions have occurred in water-supply installations in the area.

From Birmingham westward, the bedrock formations underlying the drift deposits are the Bedford, Berea, and Sunbury formations which are undifferentiated in this report. Locally, domestic wells obtain ground water from the fine-grained sandstones and shaly sandstones of this group. Where these rocks are found at shallow depth, potable water is obtained, but where encountered at greater depth, the ground waters are moderately to highly mineralized and have a relatively large sodium chloride content.

The maximum thickness of the Bedford - Berea - Sunbury group (table 5) is estimated to be 250 feet, but the aggregate thickness of strata sufficiently permeable to furnish small supplies to domestic wells is only a small part of this section. Although the effective average permeability of these formations is very small, their total surface area is very large and induced leakage from these rocks into the overlying drift deposits is a significant factor influencing the quality of water in the areas of intensive ground-water development.

Source and movement of ground water

As in the Pontiac area, the source of ground water in the Birmingham - Royal Oak area is precipitation. As shown by figure 12, recharge from precipitation infiltrates into the permeable outwash deposits on the uplands to the north and west of the area, migrates downward to recharge the buried outwash deposits, and moves regionally along the hydraulic gradient to follow in modified form the general slope of the topography in this area. In addition, local recharge to surficial deposits may aid in replenishing the deeper reservoirs.

Ground water in the buried outwash is confined under artesian conditions and as late as the 1920's wells on the lowland areas along the River Rouge through central Birmingham and in Royal Oak and Troy townships flowed at altitudes several feet above land surface. Flows were reported also in wells on the lake plain in Royal Oak.

With the rapid growth of urban development in this area following the first World War, the withdrawal of ground water by the municipal supplies of Birmingham and Royal Oak increased considerably and in the 1920's public supplies were constructed by both Berkley and Clawson. In the adjoining townships, a similar uptrend in the number of domestic and industrial wells has been in progress since the 1920's. In addition, the widespread construction of drains and sewer systems throughout the area has added to the regional withdrawal from ground-water reservoirs. The flowing wells and natural seeps or springs which were once so widespread in this area are now found in only a few localities.

Conditions of recharge to and discharge from ground-water reservoirs in the area are integrated in and exemplified by the hydrograph of observation well BH 2 which, as shown by figure 21, correlates with local lake stages and stream flow. This observation well taps the glacial drift deposits in the village of Bloomfield Hills which adjoins the area on the north. The interrelation and mutual interdependence of the ground-water reservoirs and the surface lakes and streams of the area were explained in discussion of the water resources of the Pontiac area.

Hydraulic characteristics of buried outwash

Specific-capacity reports

In the course of the well inventory and review of municipal records on well drilling and installation, many references were found concerning short-term tests made by drilling contractors at the time of completion of well installations. Most of these tests were of only a few hours duration. Occasional measurements of pumping rate and a few air-line measurements of water level in the pumped well were obtained. From these data, specific capacities were computed and their areal distribution compared. Specific capacities ranged from 1.4 in well CW 3 to 150 in well BK 7 and averaged 60 g.p.m. per foot of drawdown for the wells reported.

The very small specific capacity reported for well CW 3 reflects the thinness and small areal extent of the aquifer in the central part of Clawson. The specific capacity of the Derby well BR 3 and wells RO 11 and 39 were also below average and likewise show limited thickness and areal extent of the aquifer. The values reported for the Berkley municipal wells may have been influenced by the mutual interference of adjacent wells which were also pumped during the tests. Two of the larger municipal wells are side by side in the same pump house and the influence of one upon the other is most marked. The geologic section of figure 37 indicates that the aquifer tapped by the Berkley municipal wells is limited in thickness and areal extent.

Pumping tests

Specific-capacity methods

The only available records of extended specific-capacity tests pertain to the Derby (BR 3), South (BR 5), and West (BR 4) wells of the Birmingham municipal supply. In the Derby well test the specific capacity declined from 16.7 g.p.m. per foot of drawdown at 2 hours after the start of pumping to 10.4 after 8.5 days of pumping. In the test of the South well, the specific capacity declined from 70 g.p.m. per foot of drawdown at the end of the first hour to 50 by the tenth hour of the test, and this despite an appreciable decrease in the rate of pumping through this interval. During the test of the West well, the specific capacity declined from 22.8 g.p.m. per foot of drawdown at the first hour to 20.3 by the eighth hour, but this was a considerably smaller rate of decline than either the Derby or the South well and, furthermore, the nearby Lincoln well (BR 2) was in operation during the test.

Appreciable decline of specific capacity with extended pumping may indicate limited areal extent of the buried outwash as in the Pontiac area. If that is the case, then on the basis of the proportionate declines in specific capacity the Derby and South wells are nearer to the boundaries or limits of the aquifer than the West well. The smaller specific capacities for the West and Derby wells may reflect mutual interference from pumping of other wells, and it may indicate that redevelopment of these wells would reduce local entrance losses. This possibility is affirmed by the evidence that test wells within a few hundred feet of the Lincoln and West wells show water-level declines that are only a small fraction of the drawdown in the pumped wells when either of these wells is operated.

Aquifer-test methods

A brief test of the aquifer in the Birmingham area was conducted by the U. S. Geological Survey on February 20, 1947. The Lincoln well was pumped for nearly 4 hours at 440 g.p.m. and water-level observations were made in a test well 200 feet distant and in the West well about 360 feet distant. Prior to this test the Lincoln and West wells had been idle for several hours. From analysis of the drawdown data by the Theis graphical method, the coefficient of transmissibility of the buried outwash was calculated as 200,000 g.p.d. per foot and the coefficient of storage obtained was 0.0004.

The buried outwash (fig. 34) in the vicinity of the Lincoln and West wells averages 90 feet in thickness. The apparent average permeability of these deposits is calculated as about 2,200 g.p.d. per square foot which is comparable with the average permeability of the buried outwash in the Pontiac area. The storage coefficient is of the proper magnitude for an artesian aquifer and thereby conforms with the geologic evidence and the reports of artesian pressure in the aquifer.

Within the brief span of this test the drawdown observations conform point by point with the trace of the Theis type curve for the infinite aquifer. However, the transmissibility and storage coefficients indicate that specific capacities for the Lincoln and West wells should be much larger than the values reported for these wells, which again points to the possibility that well-entrance losses are significant. Some part of the difference observed between estimated and reported specific capacity for these wells may also be attributed to the influence of hydrogeologic boundaries which limit the extent of the aquifer. The geologic evidence of lateral gradations in permeable deposition, the decline of specific capacity with time of pumping, and the reports of well output declines with time point consistently to limitations in areal extent of the buried-outwash aquifer. The brief aquifer test of 1947 indicated that in the vicinity of the Lincoln and West wells the aquifer is at least a few thousand feet wide. Aquifer tests of several days duration and with adequate observation facilities would be required to determine the position and nature of the hydrogeologic boundaries.

An aquifer test was conducted by the drilling contractor at the site of the Cooper well (RO 11) in Royal Oak on July 17, 1950. The well was permitted to recover for 5 hours after pumping continuously at 850 g.p.m. Water-level observations were made both in the Cooper well and in the Buckingham test well (RO 39), 840 feet distant. Data obtained indicate an apparent coefficient of transmissibility of 11,000 g.p.d. per foot and a storage coefficient of 0.000034. The very small storage coefficient indicates that the aquifer is thin if it consists of unconsolidated outwash as reported.

Assuming a porosity of 30 percent and a reasonable value for the compressibility of the aquifer "skeleton", the thickness of this aquifer is estimated (Jacob, 1950, p. 334) to be about 30 feet. Logs of the Cooper and Buckingham test wells indicate 26 to 28 feet of coarse gravel with some sand and clay. The apparent average permeability is computed to be about 400 g.p.d. per square foot. This value of permeability is too small for coarse gravel as reported by the well logs, unless these gravels contain a large percentage of sand and clay. The contractor's analysis of the test indicates no boundary influence and that the aquifer extends over a considerable area. A gravel and sand stratum of comparable thickness and stratigraphic position is reported in logs of several test wells in the northwest and central parts of Royal Oak.

Quality of water

Available records of comprehensive chemical analyses of ground waters from buried outwash in the Birmingham - Royal Oak area are shown by table 7 and records of partial analyses are summarized in table 8. The areal distribution of total hardness, sulfate, and chloride content are shown by plate 5. Ground waters in this area are similar in quality to the ground waters of the Pontiac area and are principally of the calcium-bicarbonate type.

Water from the glacial drift is moderately hard to very hard, but amenable to treatment. In most wells the total dissolved solids and the individual content of various mineral constituents are within the standards for drinking water recommended by the U. S. Public Health Service, excepting local occurrences of high chloride. In some places mineralized waters from the underlying Bedford, Berea, and Sunbury formations have infiltrated.

It is of interest to compare the chloride and sulfate content of ground waters in this and the Pontiac areas. The contact between the Coldwater shale to the northwest and the Bedford-Berea-Sunbury sequence to the southeast is, in effect, a boundary between high sulfate and high chloride waters. Wells tapping drift deposits underlain by the Bedford-Berea-Sunbury sequence show higher chloride content whereas wells in areas underlain by the Coldwater show higher sulfate content.

The larger chloride contents are found east and south of Birmingham and in these directions the glacial drift mantle generally decreases in thickness and grades into less permeable deposits. In addition, the development of ground water from the buried outwash is more concentrated here than in Birmingham. The lower altitude of land surface to the southeast, where the Bedford-Berea-Sunbury formations outcrop beneath the glacial drift, marks this area as a region of escape for the mineralized artesian waters of the rock strata.

Ground-water temperatures in the area and their seasonal range are comparable to temperatures reported in the Pontiac area. From data observed in Oakland County, average water temperatures are about 50° F. and the seasonal range may vary from a few degrees in wells 30 feet or more in depth to several tens of degrees for wells less than 10 feet deep.

Nature and extent of ground-water development and their effect

Extent of past and present development

In 1890 Birmingham constructed a municipal water supply near the present Baldwin well (BR 1). This was the first intensive ground-water development in the area. The second development of importance was the construction in 1913 of wells at Water Works Park (RO 1 and 2) for the municipal water supply of Royal Oak. Because of the rapid expansion of this area after the first World War, these cities added several other well stations and the adjoining cities of Berkley and Clawson installed well systems. Later Southfield Township also developed a ground-water supply. The trends of ground-water withdrawal by these systems from 1933 to 1951 inclusive is shown by figure 39. In 1951, the withdrawal of ground water for public supply in this area ranged from 3.8 to 6.6 m.g.d. and averaged 5.2 m.g.d. for the year. These data are based on metered records furnished by the several public-supply systems. It is estimated that in this period other ground-water withdrawals by industrial wells averaged 5.0 m.g.d. or the total draft within the area exceeded 10 m.g.d. The distribution of ground-water development in 1940 and in 1950 is shown by figure 40. During this decade most of the new well developments were installed near the joint boundaries of Birmingham, Royal Oak, and Troy Township.

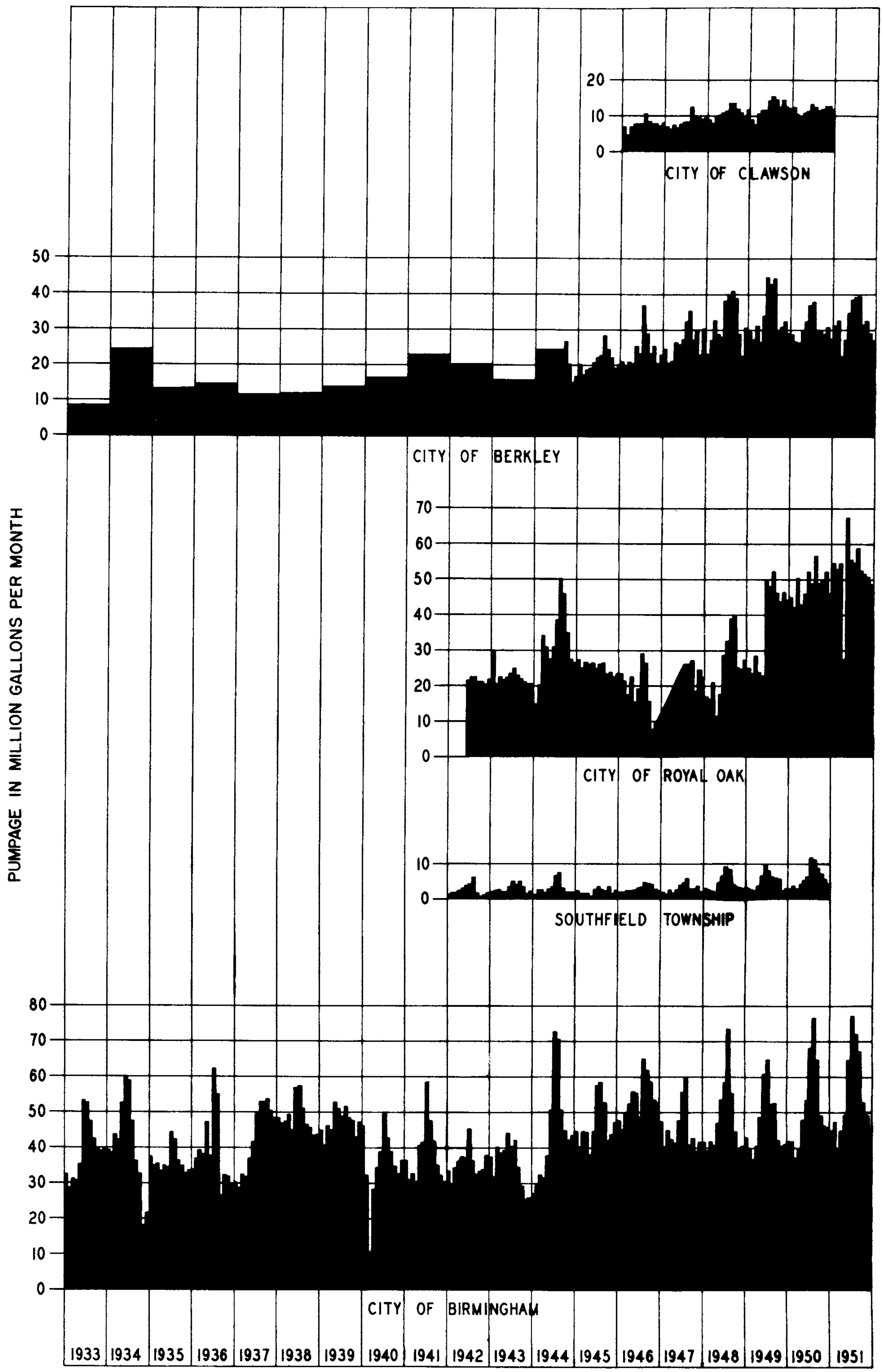

FIGURE 39. GROUND WATER PUMPAGE FOR PUBLIC SUPPLY BY THE CITIES OF BERKLEY, BIRMINGHAM, CLAWSON, ROYAL OAK, AND SOUTHFIELD TOWNSHIP.

Effect on water levels

The only extended records of ground-water level available in the area are the measurements made by Birmingham in each of its operating wells. Selected monthly reports of water level in these wells for the interval 1933 to 1952 are shown by figure 41. The water-level data are reported as static levels and represent the stage observed when the well is at rest. The period of rest preceding the reported static measurement may range from less than an hour to as much as several days.

Until about 1948, water-level stages in the Lincoln, West, East, and South wells of Birmingham were relatively steady from year to year, although considerable seasonal fluctuation occurred. As shown by figure 39, the total annual withdrawal of ground-water by the Birmingham municipal wells was slightly larger in the years 1944 through 1951 than in the years 1940 through 1943, but not much greater than in the years 1937 through 1939. Thus, the relatively steady annual stage of ground-water level preceding 1948 is in agreement with the equally steady annual rates of total withdrawal. Since 1948, however, the water levels in the 6 wells observed show a marked downtrend in contrast to the relatively steady pumping rate by the Birmingham wells. In the 4-year period ending 1951, ground-water levels in the Lincoln, West, East, and South wells declined from 20 to 30 feet. The water level in the Baldwin well declined little more than 15 feet but did not reach stages as low as in the 1936-40 interval because it had been out of service for about 7 years and a considerable recovery of stage had occurred by 1948. By 1951 the new Walker well showed a decline in water level from the initial level of about 70 feet.

The distribution of pumping (fig. 40) in this area changed markedly between 1940 and 1950. Most of the change occurred between 1948 and 1950 as indicated by the table of well records (see appendix) which show the dates that public-supply wells were added by Birmingham, Clawson, and Royal Oak either in Troy Township or near their common boundary with that township. In addition, several industrial wells were added in the area during this period. Records of industrial-well withdrawals are not available, but metered records of municipal pumpage by Birmingham, Clawson, and Royal Oak were totaled and plotted on figure 41 as a continuous graph rather than the bar graph used on previous figures. A close correlation is now evident between water-level trends in the Birmingham wells and the trend of total ground-water withdrawal by Birmingham, Clawson, and Royal Oak.

The water-level records from the Birmingham wells indicate that drawdowns as much as a few tens of feet have occurred over distances of several miles as a result of intensive ground-water development in the corner of Troy Township that adjoins Birmingham and Royal Oak. Although drawdowns of this magnitude over so large an area are significant, they are not necessarily indicative of over-development. In the vicinity of any new ground-water development some progressive drawdown of ground-water level must always occur after the start of pumping or following each increase of pumping. This initial phase of drawdown represents the deepening and expansion of the cone of depression as the ground-water reservoir adjusts to the new pumping regimen. Regional drawdown of water level must occur to provide the gradient necessary to move water from the outer regions of the

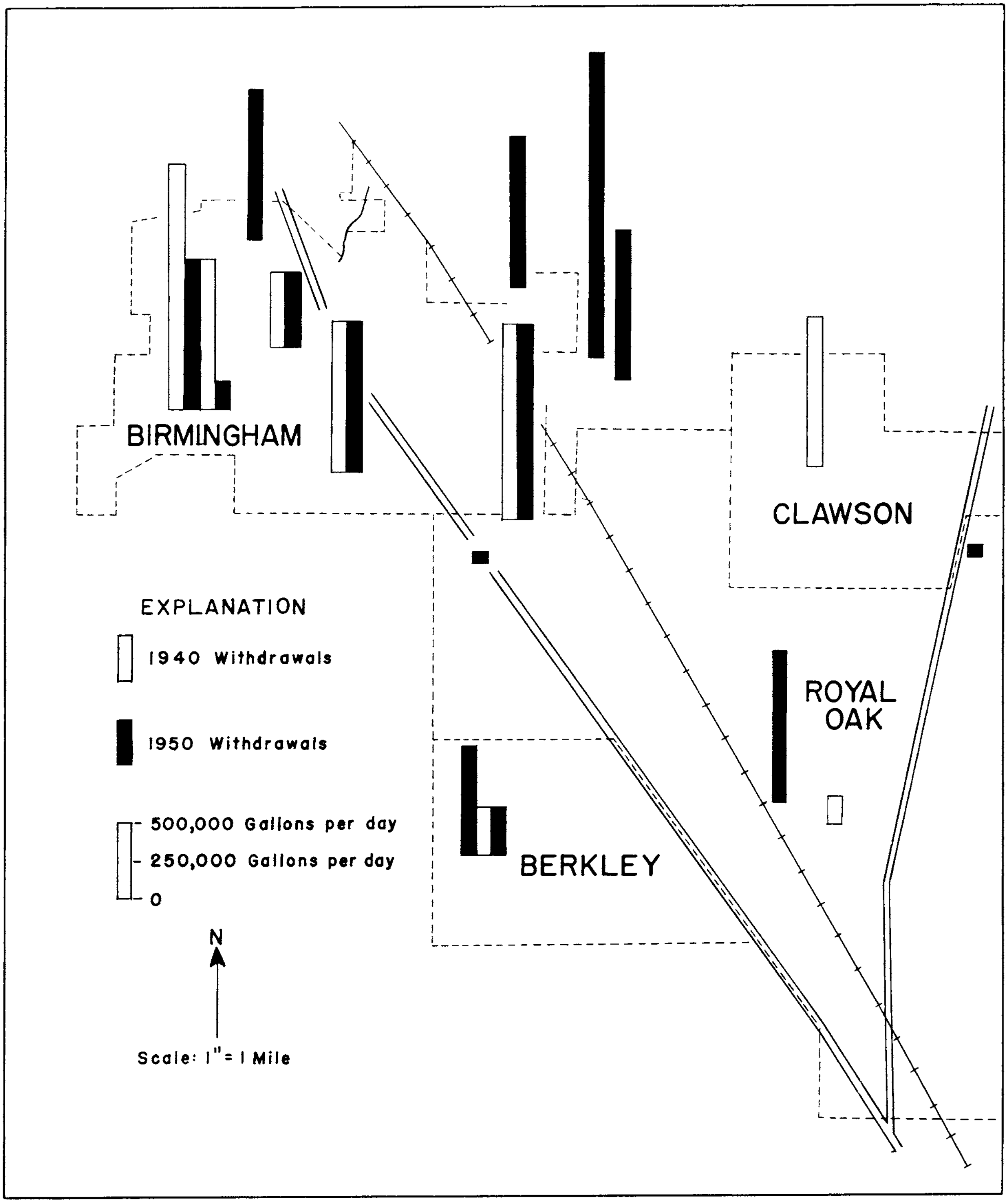

Figure 40. Map of the Birmingham – Royal Oak Area showing municipal pumpage in 1940 and 1950.

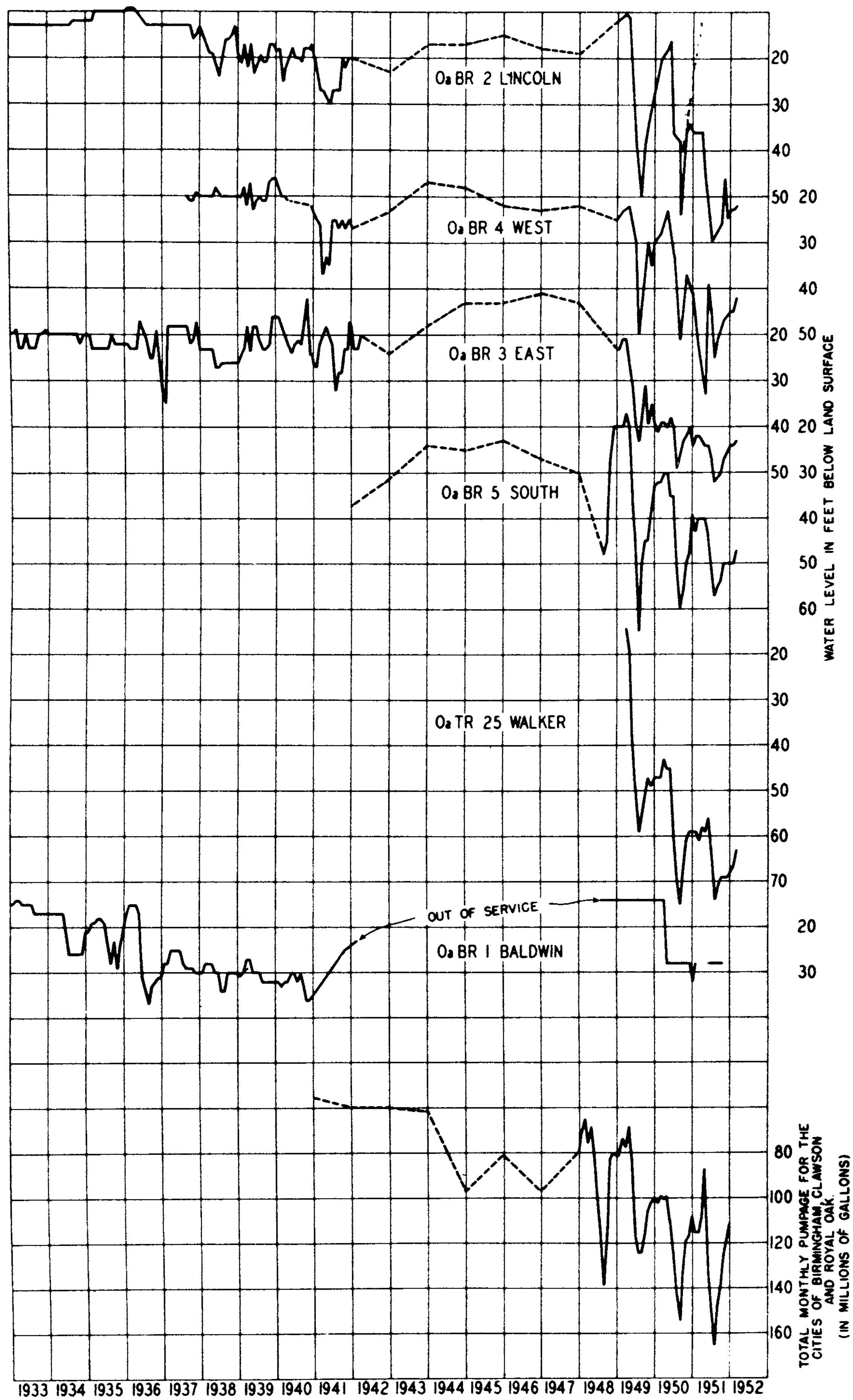

FIGURE 41. HYDROGRAPHS SHOWING MONTHLY FLUCTUATIONS OF WATER LEVELS IN THE CITY WELLS AT BIRMINGHAM, AND TOTAL MONTHLY PUMPAGE FOR THE CITIES OF BIRMINGHAM CLAWSON, AND ROYAL OAK, MICH

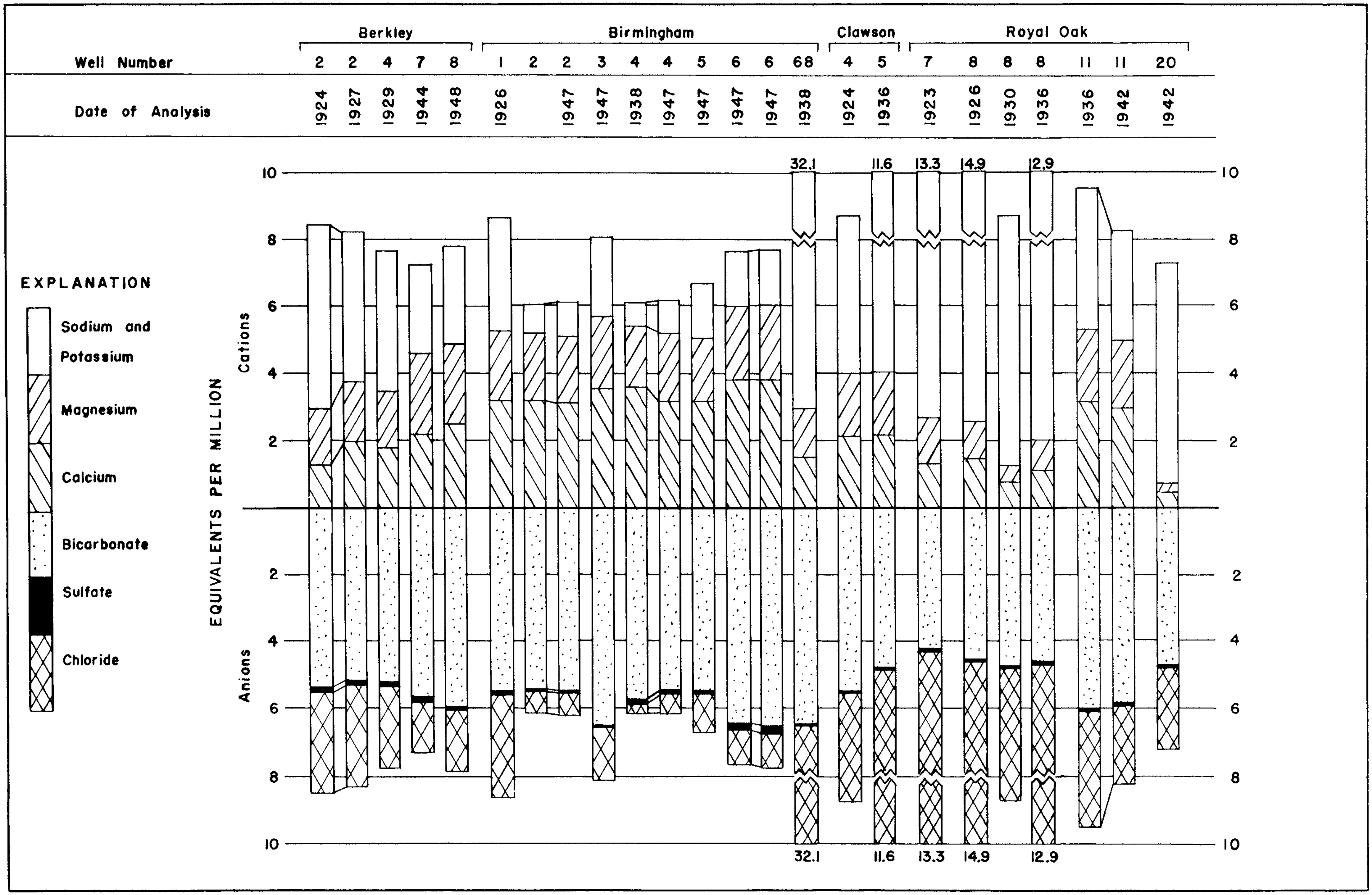

Figure 42. Composition of ground water in Berkley, Birmingham, Clawson, and Royal Oak, Mich.

underground reservoir to the focal centers of pumping. If pumping continues at a steady rate and if that rate of withdrawal can be furnished by the salvage of rejected recharge, by decreasing natural discharge, or by increasing the area of recharge, and without appreciable reduction of saturated thickness, then the downtrend of water level will decrease and ultimately stabilize at stages commensurate with that condition of pumping rate and distribution. The downtrend of water level in 1951 (fig. 41) was markedly smaller than in the preceding 3 years. Considering that from one-third to perhaps one-half of the total withdrawal in this area did not occur until 1950, it is evident that the adjustment of the cone of depression in the region was effected in a relatively short time as in any artesian aquifer of finite extent. Further increases in pumping from this area are to be expected and further drawdown of water level throughout the area must accompany increased withdrawal.

Numerous measurements of water level in Bloomfield, Troy, Royal Oak, and Southfield townships were made during the latter part of 1904 in the course of an investigation of flowing well "districts" by Leverett and others (1906, pp. 2, 188-194). Other isolated reports of water level were obtained from driller's records and municipal files. These data are included on the geologic sections of figure 34 to 38 inclusive. The water-level profiles indicate that in 1904, when the use of ground water in this area was relatively small and widely dispersed, the regional movement of water was from the upland areas which lie to the north and west. Most of the 1904 well developments were in the lowlands where flows could be obtained. The flowing wells along the River Rouge in Birmingham and the lowland in southwestern Troy Township had locally lowered the regional water level as early as 1904 as indicated by section B-B' of figure 35. The low stage of 1951 on the east end of this profile reflects the influence of the recent intensive development of ground water in southwestern Troy Township.

Section A-A' of figure 34 shows the result of the change in pumping rate and distribution in Birmingham since 1904. In 1904 the public supply was obtained from the group of flowing wells near the site of the present Baldwin well (BR 1). Daily use was relatively small and the cone of depression accordingly was rather shallow. By 1928 pumping had increased considerably and the flowing wells had been replaced by the large-diameter Baldwin well. Now the cone of depression was deeper and considerably expanded. In 1951, the Baldwin well was used only occasionally and the nearest withdrawals of consequence were the Lincoln and West wells (BR 2 and 4). With this shift and increase in pumping, the cone of depression deepened and expanded further and moved westward in response to the redistribution of pumping.

In comparing the water-level stages from well to well along each profile section or from section to section, it should be noted that these sections are not taken at right angles to the water-level contours and several wells used on the sections are offset some distance from the line of the section. Study of sections C-C' of figure 36, D-D' of figure 37, and E-E' of figure 38, raises the question if any direct relation exists between the formations tapped by the original wells of Clawson (CW 3, 4, 5), of Royal Oak (RO 1-8), and the present Berkley wells (BK 2, 4, 5, 7, 8) and the formations tapped by the Birmingham, Royal Oak, and Clawson wells now in use near the southwest corner of Troy Township. The 1904 water-level stages indicate that steep gradients from the north and west existed and that recharge from the permeable uplands in Bloomfield and Troy townships moved southeasterly to the lake-plain lowlands of Royal Oak and Troy townships. The belts of flowing wells along these lowlands contributed to the steepening of these gradients. In addition, the reduced thickness and smaller permeability of the water-bearing deposits to the southeast required steeper gradients to move water through these beds of small transmission capacity. Further evidence of the small capacity of the aquifers in the Royal Oak, Clawson, and Berkley areas is the pronounced drawdown of water level reported near each focal center of ground-water development.

The cumulative cycle of increasing drawdown with decreasing transmissibility, described as a potential threat in parts of central Pontiac, has been experienced by Royal Oak, Clawson, and Berkley as proved by the large drawdowns reported in the vicinity of earlier well developments and the discontinuance of some wells. Further ground-water development in these cities will be small unless remedial measures are adopted.

Effect on water quality

The comprehensive chemical analyses available for waters pumped by the municipal wells of Berkley, Birmingham, Clawson and Royal Oak are presented graphically by figure 42. In addition, this plot includes a comprehensive chemical analysis for water from well BR 68 which formerly flowed and supplied a public fountain at Water Works Park near the Baldwin wells. The bar scales of chemical equivalents per million (e.p.m.) for wells BR 68, CW 5, RO 7 and RO 8 are broken and the total e.p.m. values for anions and cations are recorded. The wells of Berkley, Clawson, and Royal Oak show markedly larger quantities of sodium chloride than any of the Birmingham municipal supply wells, but the largest total mineral content is shown by the "artesian well" (BR 68) at Birmingham. Although a log of this well is not available, the depth reported indicates that it penetrated the underlying bedrock and the chloride content conforms with the chlorides noted in test well RO 27 which penetrated the bedrock in the Royal Oak area.

When the drawdown of water level (fig. 15) in the buried outwash is appreciable the resultant gradient developed between the drift aquifer and the underlying bedrock induces the upward migration of bedrock water, which in this area is charged with sodium chloride. The large drawdowns of water level reported for the Berkley, Clawson (CW 4 and 5), and Royal Oak wells correlate with the large chloride contents found in these wells. The interrelation between pumping rate or water level versus chloride is perhaps best illustrated by comparison of the chemical quality for wells RO 8 and 11. In 1930, Royal Oak increased the quantity of water purchased from Detroit and reduced pumping from well RO 8 because the chlorides in water from this well had risen enough to be objectionable. In addition, a greater part of the pumping load was shifted to their Cooper well (RO 11). This marked reduction in pumping from the Magnolia well (RO 8) promptly reduced the chloride content. In 1936, increased draft raised the chlorides.

Although pumped at about the same rates and separated by a relatively small distance, wells RO 8 and RO 20 deliver water of markedly different chloride content. Several explanations are possible for the higher chloride water from well RO 8. First, the induced migration of mineralized water might be accentuated by leakage from old wells adjacent to RO 8 when this well is pumped. Little information is available concerning the depth and construction of the older wells. A number of these wells were drilled to the base of the drift and some may have penetrated bedrock. In Royal Oak, gas evolves from the Antrim shale and it is known that well RO 7 produced appreciable quantities of gas until an explosion wrecked the pump house. Well RO 8 nearby might also have penetrated the bedrock surface.

Second, the bedrock underlying well RO 8 may be more permeable than the rocks which underlie well RO 20. If this condition prevailed, the mineralized rock water could more readily infiltrate the basal drift in the vicinity of the permeable connection.

In Birmingham, water from the Baldwin (BR 1), Derby (BR 3), and Redding (BR 6) wells show greater chloride contents than water from the Lincoln (BR 2) and West (BR 4) wells. The withdrawal rates per unit area are larger in the Lincoln and West well area than at the other three sites and proximity to the underlying bedrock is comparable at each site. It would be expected that larger withdrawals at the Lincoln-West site would tend to cause greater chlorides, but the reverse condition occurs. This lower chloride content points to the possibility that the Lincoln-West well group lies in the general direction of a recharge source. Properly planned aquifer tests could confirm this possibility if the source is of principal magnitude.

The relatively large amounts of chlorides reported for wells Tr 3 and 4 and RO 11 as shown by tables 7 and 8 are of particular significance. The recent intensive development by several communities of the buried-outwash aquifer, near the southwest corner of Troy Township, has resulted in marked water-level declines in this area and has created the potential condition for equally marked rises in chloride content. Chlorides in this area in 1945, before much of the present development existed, were already appreciable as shown by well Tr 3, and confirmed by well BR 3 to the west. The marked declines of water level in the area suggest a small aquifer and a considerable distance to the source of recharge. If development is further intensified water quality may deteriorate appreciably. Therefore, immediate steps should be taken to establish adequate programs of water-quality, pumpage, and water-level observation to provide a basis for forecasting trends in the area.

POTENTIAL YIELD OF GROUND-WATER RESERVOIRS

The work of Taylor (1930) and the present small cooperative program of surface-water, ground-water, and water-quality data collection comprise the only basis for analysis of the water-resource potential of southeastern Oakland County. The paucity of water-resources data in this area greatly limits quantitative appraisal of its total water potential.

Ground-water recharge

Taylor in his study of the Pontiac area developed a water budget (1930, pp. 105-11) for the 124-square mile area of the Clinton River watershed that lies above the Orchard Lake Avenue crossing of the river. Using the method of water-table rise developed by Meinzer (1929, pp. 140-141), he estimated (1930, p. 105) ground-water recharge as 21.4 inches or 76.5 percent of the 27.63-inch rainfall during the 1930 water year. The hydrographs of ground-water level used as a basis for the application of this method were developed from weekly observations of ground-water stage in 9 observation wells on the upland of permeable outwash west and north of Pontiac. Four wells were in Waterford Township and the others were in Orion, Independence, and Springfield townships, which adjoin the area on the northwest.

The validity of Taylor's estimate of ground-water recharge may be checked from independent data which he collected at the time. Over any extended period, the total discharge from an aquifer must equal the total recharge to that aquifer after allowance is made for gains or losses in storage. The total discharge from an aquifer includes seepage to streams or lakes, leakage to overlying and underlying rocks, man's diversion by wells, and losses by evapotranspiration. In the 124-square mile control area used by Taylor no significant diversions were caused by wells other than wells of the Pontiac municipal supply. Leakage from the glacial drift to the underlying Coldwater shale would be relatively small. Thus, most of the natural ground-water discharge from the control area was by evapotranspiration and by seepage to the Clinton River.

In moving to the streams and lakes, ground-water must pass through the streamside and lakeside lands where depths to water are small and consequently the evaporation opportunity is large. Evapotranspiration demands have first priority and only residual of ground-water flow reaches the streams. In summer, evapotranspiration rates are large and if much of the drainage basin consists of lands of shallow depth to water table, the residual of ground-water flow, which provides the base flow of the streams, will be small. In winter base flow will be large if air temperatures in the region are low enough to kill vegetation and reduce evapotranspiration to a minimum.

Generally, January and February temperatures in Michigan are low enough that evapotranspiration losses become small and errors in their estimation are not of great consequence in effecting estimates of total ground-water discharge. Although stream flow during these months is augmented by snow melt, temperatures are often low enough to limit this contribution and base flow can be determined. The latter part of January and the fore part of February 1930 was a period of subfreezing weather and flow from the control area declined slowly but steadily (Taylor, 1930, p. 80). The latter part of this period may be used for estimating ground-water discharge from the control area.

From November 1928 through August 1930, the discharge of the Clinton River from the control area was measured by weirs and by current meter. The discharge determined by current-meter measurement was invariably larger than discharge computed from the weir observations. Taylor was inclined to discredit the current-meter measurements, but from his description of the weir station (1930, p. 74) it seems more probable that the weir data are in error. Gage heights at the weirs were measured from piers only a few feet upstream from the weirs and were probably influenced by drawdown which would result in recording too little discharge. Leakage through or around the dam would bypass the weirs. The contraction effects of the piers would result in too small a flow computed for the weir observations unless appropriate corrections were made. Thus, the cumulative result of these several influences would tend to appreciable error in the direction of too little discharge and may account for the discrepancy noted by Taylor.

The average flow from the control area during the interval February 6-19 inclusive was 147 c.f.s. as determined by current meter gagings (Taylor, 1930, p. 11). From Taylor's estimates (1930, p. 107) with appropriate adjustment for lower temperatures, the evaporation losses in this interval are computed as 0.4 inch per month or 44 c.f.s. from the control area. Snow cover in the basin was thin and most of the evaporation came from the lakes and adjacent lands. These lakes and lakeside lands represent areas where the ground-water table is at or near the surface and all of this evaporation is added as part of the ground-water discharge. Underflow diversion from the area included the 6.3 m.g.d. withdrawal by wells of the Pontiac municipal water supply and smaller withdrawals by industrial, domestic, and rural supplies in the area. It is estimated that total ground-water withdrawal by all wells in the area probably did not exceed 8 m.g.d. at this time or about 12 c.f.s. from the area. All water was returned to the stream below the control area. Available hydrogeologic evidence indicates that natural underflow into and out of the gaged area probably canceled out and vertical seepage into or out of the area was probably small compared to the other discharge influences. Thus, the total ground-water discharge from the 124-square mile area is estimated from the sum of these influences as 203 c.f.s. or 1.64 c.f.s. per square mile. Similar computations for periods in January and February of 1928 and 1929 indicate comparable values for ground-water discharge, but distribution of the several discharge influences varies and in 1929 changes in ground-water storage must be accounted for.

Seasonal fluctuations of water table in the area are of the order of 2 to 4 feet as compared to total saturated thickness of water-bearing deposits of a few hundred feet and total relief on the water table of 50 feet or more. On a regional scale, the profile of the water table from upland to lowland is not greatly different in over-all slope from seasonal low to seasonal high or from year to year. Over a long period of time the position of the water-table profile is the result of the effective average rate of recharge which prevails. Hence, the rate of total ground-water discharge estimated for February 6-19, 1930 is indicative of the effective average annual rate of ground-water recharge. This concept of gross reservoir action was utilized by Theis (1937, pp. 564-568) and by Jacob (1945, pp. 564-573, 928-939) for similar evaluations of ground-water recharge in other areas. An effective average discharge of 1.64 c.f.s. per square mile would require an effective average annual rate of ground-water recharge of 22.2 inches. This rate of ground-water recharge represents 74 percent of the average annual precipitation and compares favorably with the value of 77.5 percent determined by Taylor using the method of water-table use. Taylor reported 76.5 percent, but recalculation of his percentage data shows 77.5 percent.

Ground-water runoff

It is of interest to examine the distribution of annual discharge from the ground-water reservoirs in Taylor's study area to appraise the relative magnitudes of ground-water runoff, evapotranspiration losses, underflow, and diversions. Stream flow records for the Clinton River at Dawson's Pond were discontinued after Taylor's 1929-30 investigation and only fragmentary records were available prior to his work. However, since May 1934 records of flow are available for the Clinton River at Mt. Clemens, Michigan. For study purposes flow records for the water years 1942 to 1950 inclusive were selected. This 9-year period is a fair representation of average hydrologic conditions for the Clinton River drainage at Mt. Clemens. In this period the total annual runoff from the Clinton River basin at Mt. Clemens averaged 10.4 inches or 31 percent of the 33.34-inch average precipitation observed at Pontiac during the same period.

Annual hydrographs of daily discharge were used as the basis for separating total runoff into ground-water runoff and overland or storm runoff. For practical reasons this separation cannot be exact and is intended only to show relationships in the general order of magnitude. Ground-water runoff averaged 4.4 inches annually or 42 percent of the average total runoff and 13 percent of the average precipitation over the 9-year period. Overland or storm runoff averaged 6.0 inches annually or 58 percent of the total runoff and 18 percent of the average precipitation over the 9-year period.

Records of flow of the Clinton River at Pontiac versus Mt. Clemens do not overlap. Accordingly, it was necessary to estimate runoff at Mt. Clemens for the 1930 water year. The average percentage relationship between total runoff and precipitation at Mt. Clemens was determined for the 9-year study period. Within this study period the 1946 water year was very similar to the 1930 water year in rainfall amount and in general climatological conditions, and it was found that the percentage runoff compared favorably with the average for the study period. An estimate of 8.6 inches of total runoff at Mt. Clemens was obtained for the 1930 water year.

The distribution of total runoff at Mt. Clemens determined for the 9-year period was 42 percent ground-water runoff and 58 percent overland or storm runoff. For the 1946 water year, the distribution was 36 percent ground-water runoff and 64 percent storm runoff. These estimates are rounded off to 40 percent ground-water runoff and 60 percent storm runoff. On this basis, storm runoff at Mt. Clemens is estimated at 5.2 inches for the 1930 water year and the balance of 3.4 inches represents ground-water runoff.

Nearly half of the precipitation during the 1930 water year was during several regional storms over the basin and under storm conditions it is probable that overland runoff at Pontiac was comparable to runoff at Mt. Clemens or 5.2 inches for the year. Total runoff at Pontiac for the 1930 water year was 11.7 inches as determined by current-meter measurements rather than the 8.5 inches computed by Taylor from the weir observations. As pointed out, the validity of the weir data is questionable and the several potential sources of error would combine to make the computed discharge over the weirs smaller than the actual discharge. Accepting the current-meter data and subtracting the estimated overland runoff, the ground-water runoff at Pontiac is calculated as 6.5 inches for the 1930 water year.

A check on the total runoff at Mt. Clemens and the estimate of ground-water runoff at Pontiac may be made from independent sources of data. Analyses of stream flow records available for the Clinton, Rouge, and Huron basins for the 1935 to 1950 water years inclusive were made and flow-duration curves were developed by the Surface Water Branch of this Survey. From these data it was determined that, excepting the extreme low flows, the lower and median flows of the Clinton at Pontiac are about one-third larger than flows at Mt. Clemens. Inasmuch as the 1930 water year was comparatively dry, much of the flow was in the median and lower parts of the duration curve and the relation between the duration curves for Pontiac and Mt. Clemens may be used to check the total runoff at Mt. Clemens. Increasing the estimated 8.8-inch total runoff at Mt. Clemens by one-third yields 11.7 inches at Pontiac, which not only checks the discharge measured by current meter as opposed to the weir data, but also confirms the estimate of total runoff at Mt. Clemens.

The flow-duration data indicate that runoff per unit area from the North Branch and Middle Branch of the Clinton River above Mt. Clemens is much smaller than the contribution from the Clinton River through Pontiac. The mantle of glacial drift on the Clinton River basin above Pontiac is much more permeable and is of greater average thickness than on the North Branch or Middle Branch basins. Thus, it is to be expected that ground-water flows per unit area at Pontiac will be considerably larger than at Mt. Clemens. The ratio of flow-duration curves at Pontiac and Mt. Clemens provide supporting evidence and an index for appraising the hydrogeologic differences. The ratio of ground-water runoff to total runoff at Mt. Clemens, when applied to the total runoff measured at Pontiac, yields 4.7 inches of ground-water runoff for the 1930 water year. To adjust for hydrogeologic differences between the two areas, the estimate of 4.7 inches is increased by one-third in accord with the flow-duration index noted above and the ground-water runoff at Pontiac becomes 6.3 inches. Subtracting 6.3 inches ground-water runoff from the total runoff of 11.7 inches, there

Table 9.-Water budget for 1930 water year in the 124-square mile drainage area of the Clinton River above Dawson's Mill Pond at Pontiac, Mich.

Recharge or Discharge	Gain or loss in inches			Total gain or loss (percent)
	Subsurface	Surface	Total	
Recharge	21.4	-	27.63/1	100
Discharge				
Evapotranspiration	13.5	0.9	14.4	52.2
Runoff	6.4	5.3	11.7	42.4
Diversion by wells	1.5	-	1.5	5.4
Total			27.6	100

/1 Total rainfall for 1930 water year

remains 5.4 inches of overland runoff as compared to the previous estimate of 5.2 inches. All estimates of total runoff and its distribution are in good agreement for the several methods employed.

Water budget

It is of interest to apply the estimates of ground-water recharge and ground-water runoff to an examination of the over-all water budget for Taylor's control area on the Clinton basin above Pontiac for the 1930 water year. The estimated ground-water recharge was 77.5 percent of the 27.63-inch precipitation or 21.4 inches, which leaves 6.2 inches to be accounted for as overland runoff and as evaporation not related to the ground-water reservoir. The average of estimates for overland or storm runoff was 5.3 inches. The remaining 0.9 inch of precipitation excess over ground-water recharge was lost by evaporation from transient storage on the surface or from the zone of aeration. The value for evaporation from transient surface storage and from the zone of aeration may appear unusually small, but it should be noted that only a small part of the control area is represented by lands of appreciable depth to water table. Many, if not most of the lakes and marshes, are surface expressions of the ground-water table and much of the area consists of lands of shallow water-table where the soil belt merges with the capillary fringe or the water table. Thus, most of the precipitation on these lakes, marshes, or shallow water-table areas becomes an immediate part of the ground-water storage and is readily discharged therefrom by evapotranspiration.

Of the 21.4 inches of ground-water recharge, 6.4 inches were discharged as ground-water flow by the Clinton River. Average annual ground-water diversions are estimated to be not more than 9 m.g.d., or 14 c.f.s., or 1.5 inches from the basin. The remainder of 13.5 inches represents evapotranspiration losses from the ground-water reservoir. These data are summarized by table 9.

Since 1930, the average annual withdrawal of ground water by wells in Pontiac and in the townships of the Clinton basin above Pontiac has increased to about 35 m.g.d. or 54 c.f.s., or 5.9 inches from this basin. A large part of the increased ground-water withdrawal represents a net diversion of water from the control area. Unfortunately, gaging of the Clinton River at Dawson's Pond and other hydrologic data collection were discontinued after Taylor's investigation. Consequently, no basis is provided to determine how the increased diversion by wells has affected the distribution of other water losses from the basin.

At present, the stages of the chain of lakes to the west of Pontiac are affected by regulation and on the average are 2 feet lower than the 1930 stages reported by Taylor (1930, plate 1). The lower stages would result in smaller areas of water surface and a comparable lowering of the adjacent water table which would reduce somewhat the evapotranspiration discharge. Thus, a large part of the increased diversion of ground water by wells may have been accomplished by salvaging water formerly lost by evapotranspiration. Salvage of storm or overland runoff, as a result of lowering of the water table ordinarily would be expected to occur, but in this basin the storm runoff does not appear to have decreased. Diversion of subsurface flow from adjoining basins and the salvage of former underflow from the Clinton basin may also represent an important part of the water captured by the increase in withdrawal from wells in the area.

The present lack of meterologic and hydrologic data in southeastern Oakland County rules out extrapolation of the knowledge gained from Taylor's basinwide hydrologic study in the Pontiac area. Only the northwest corner of the area covered by this report contains any appreciable expanse of the highly permeable outwash deposits that typified Taylor's area in the Clinton watershed. Elsewhere, these nine townships are mantled by moraines and lacustrine deposits. It seems that in these less permeable areas the average annual rate of ground-water recharge would be smaller and the surface or overland runoff would be larger.

Management of water resources

The following discussion of principles and methods for solving water-resource problems through effective planning and management is presented as a source of information and a basis of discussion by interested water users in Oakland County and in Michigan as a whole. They are not intended as recommendations of specific methods for development or management of water resources, because these are the responsibilities of individual water users and of local and state governmental bodies.

The ground-water and the total water-resource potential of any area are subject to change under the continually changing influences of man's development or nature's modification of the hydrologic regimen as a result of erosion and deposition, climatic change and other factors. The forces of nature operate inexorably but are exceedingly slow in terms of man's time and to a great extent they probably compensate over any large region. That is down-cutting of streams may remove the confining cap over an artesian stratum and permit escape of much of the water or it may cut through surficial aquifers and drain them. But elsewhere, streams may build extensive deposits of permeable alluvium and add to or create new reservoirs. Lakes and streams may silt their bed and decrease percolation from or into ground-water reservoirs, but at the same time in other places silts may be removed and recharge to ground-water reservoirs may be accelerated.

Man's land-use practice and development pattern may either increase or decrease the water resources of an area. Some types of flood-protection measures accelerate runoff and thereby reduce the opportunity for subsurface percolation. Other measures may provide for extended surface storage and increase percolation opportunity. Land-drainage structures designed to remove surface storage and lower local water levels during the spring peaks of soil moisture may be allowed to operate at the same peak draft during the summer when moisture should be conserved. Lakes may be dammed to retain water in the summer season of minimum flow, but continue closed through the winter and spring seasons of overflow. Extensive drainage systems may be built to lower water levels and equally large irrigation systems may then be constructed to replace the depleted soil moisture on the drained lands. Thus, lack of perspective in the solving of water problems may result in the paradox of water shortage in the midst of plenty.

At present the most prevalent form of water-resource economy follows the policy of laissez faire. Since 1940, however, increasing attention has been focused on the regulation of water resources and to some extent on management of the resource. In arid and semiarid states considerable attention (Robinson and others, 1952, pp. 57-80) is now being given to the possibility of salvaging a part of the ground water now discharged by vegetation that borders watercourses and covers areas of shallow water table. In the area covered by this report, the discharge of water by evapotranspiration represents about two-thirds of the total precipitation and is equivalent to a water use of about 300 m.g.d. For Oakland County the annual evapotranspiration discharge is about 920 m.g.d. The total withdrawal of ground water from the nine township area for all uses in 1952 is estimated at 50 m.g.d. or equivalent to less than 17 percent of the water discharged by evapotranspiration. In comparison, the total ground-water use for Oakland County does not exceed 7 percent of the water now discharged by evapotranspiration.

Overland runoff during periods of intensive precipitation represents a considerable water loss from most watersheds and in several states steps have been taken in local areas of intensive use to salvage these waters by diverting them to permeable detention basins and thereby recharge underground reservoirs. Extensive use of recharge basins for the artificial replenishment of underground reservoirs and for the removal of storm-water runoff is now made in Nassau County (Welsch, 1949, pp. 708-710, 741-746) on Long Island, New York, where the geologic conditions are peculiarly favorable for this practice. Among agencies practicing such artificial recharge are the County Department of Public Works, the towns of Hempstead, North Hempstead, and Oyster Bay, and numerous private concerns. In 1952, there were 86 recharge basins in operation in Nassau County. Basin area ranged from several acres to nearly 2,100 acres. Many of these pits have been in operation for more than 5 years without overflow or bypass of water during any storm. Infiltration rates range from a few hundred thousand to several million gallons per acre per day.

Although public opposition was met at the first proposal of recharge basin construction in the highly urbanized areas of Nassau County, landscaping of the basins and development of parks on their periphery has resulted in popular acceptance. As important as the conservation phase, has been the considerable saving in the cost of storm-water drainage structures. Photographs of the locale and some of the features of the Rockaway Road recharge basin of the County Department of Public Works at Garden City, New York are shown by figures 43 and 44.

The basin method of artificial recharge and other surface spreading methods are restricted to areas where the aquifer to be recharged is overlain by moderate to highly permeable formations with sufficient unsaturated depth available to recharge water at acceptable rates. For artesian aquifers, the

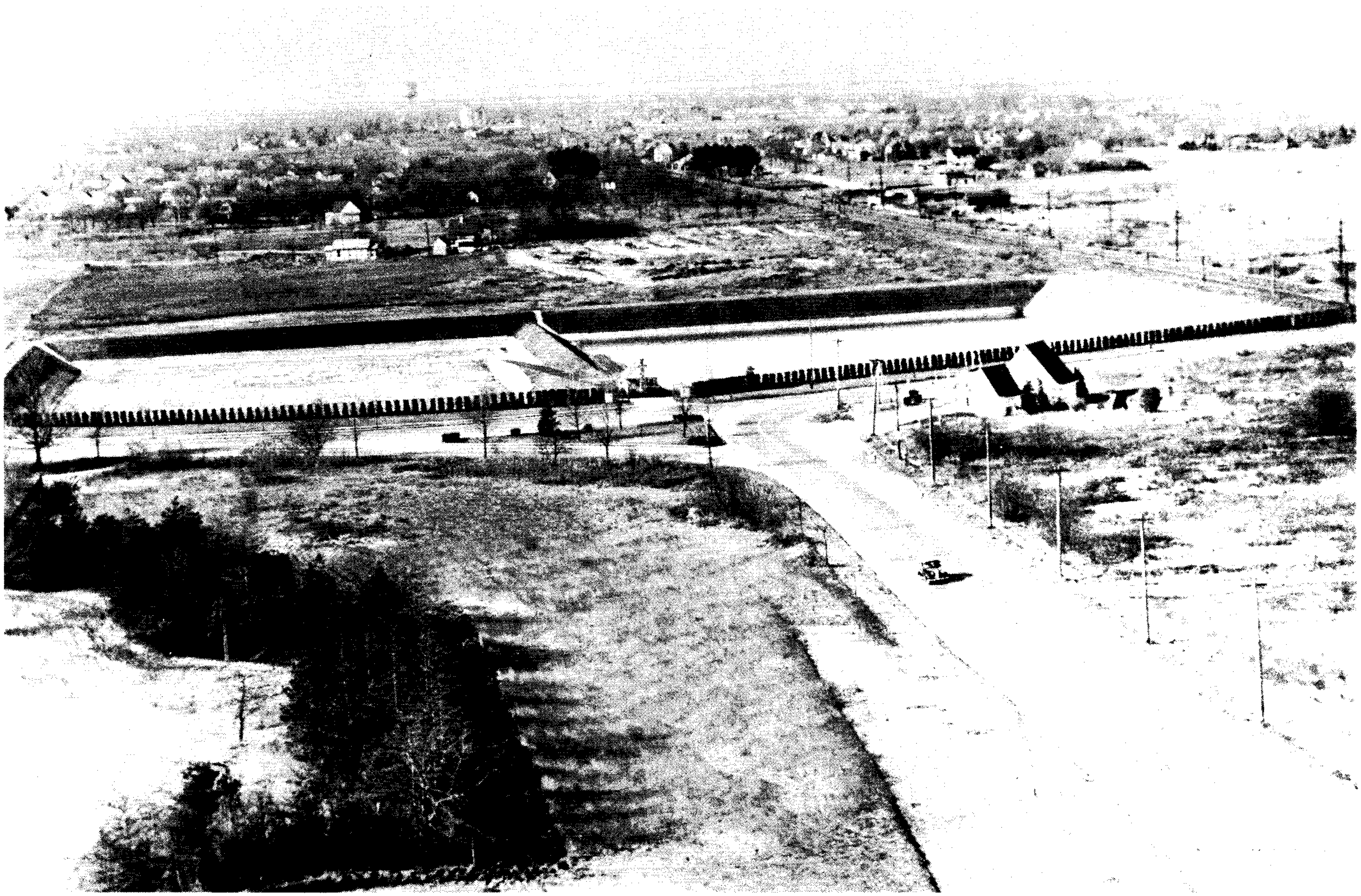

FIGURE 43. - PHOTOGRAPH SHOWING ROCKAWAY ROAD RECHARGE BASIN, GARDEN CITY, NEW YORK
(Courtesy of Department of Public Works, Nassau County, New York)

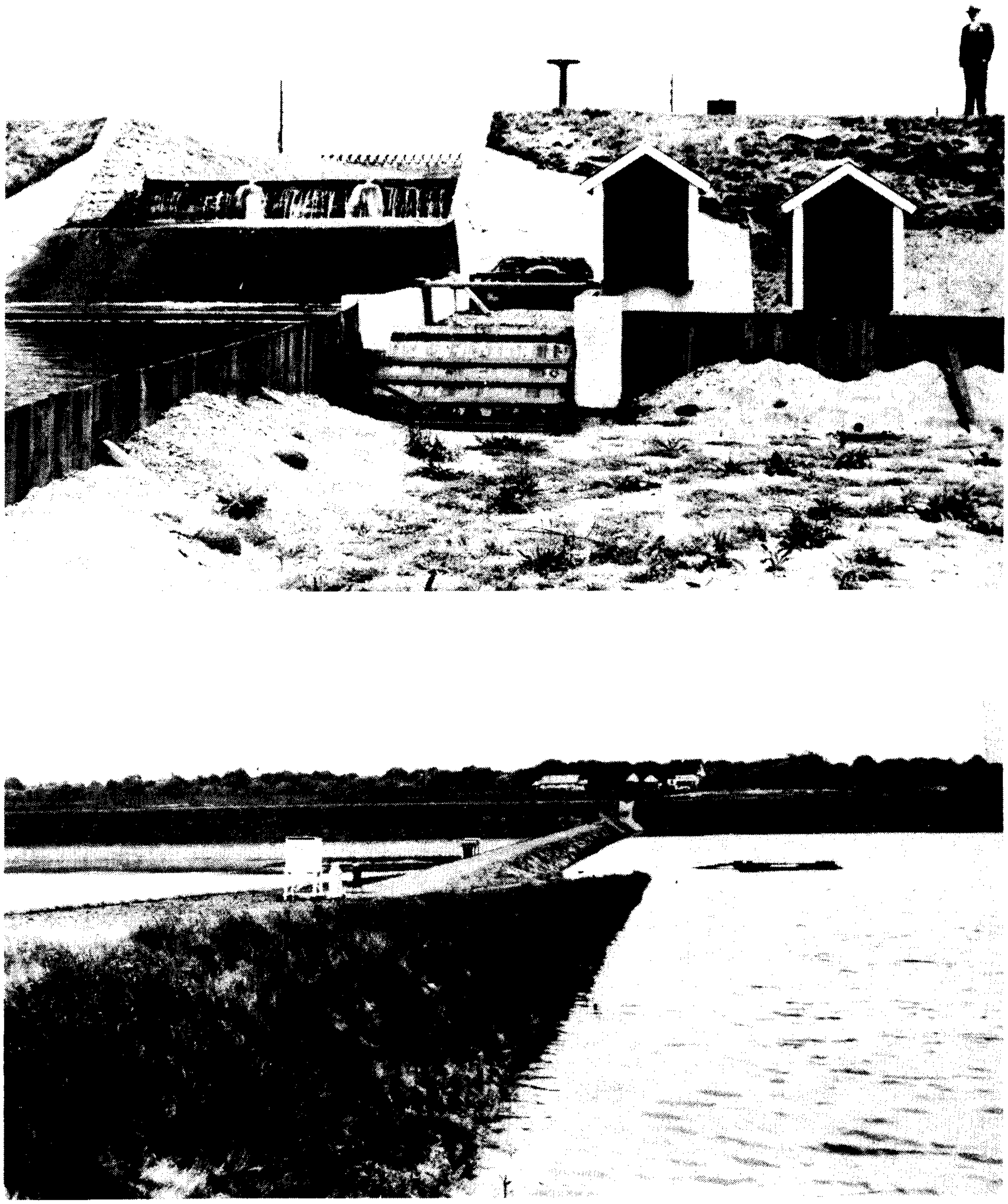

FIGURE 44. - PHOTOGRAPHS SHOWING THE OVERFLOW SPILLWAY AND THE EMBANKMENT BETWEEN THE NORTH AND SOUTH UNITS, ROCKAWAY ROAD RECHARGE BASIN, GARDEN CITY, NEW YORK. (Courtesy of Department of Public Works, Nassau County, New York)

capping formations limit benefits from surface application of recharge unless the confining beds are removed or are pierced by wells or shafts. If the artesian strata crop out within moderate distance of the area of use, surface methods of recharge may be used on the outcrop area and the gradient produced by withdrawals at the focal centers of use will induce migration from the recharge area to the centers of use.

Artificial recharge through wells has increased markedly throughout the United States in the past twenty years. The most extensive use of wells for artificial recharge is on Long Island, New York, where the State Water Power and Control Commission requires that wells used for cooling water at capacities of 100,000 g.p.d. or more, be supplemented by recharge well installations to return this water, warmed but uncontaminated, to the aquifer. In summer, about 300 recharge wells return an aggregate total of more than 60 m.g.d. to the aquifer (Brashears, 1946, pp. 503-516). Many references to artificial recharge installations in the United States were tabulated by Klaer (1948, pp. 1-36). In Michigan, artificial recharge of cooling water through "diffusion" wells is practiced by banks, theatres, and department stores at Flint, Grand Rapids, Lansing, and Kalamazoo. State wide, it is required practice to return brine waters from oil or gas production through disposal wells to the subsurface formations below fresh water strata.

Storm runoff in the nine township area averages about 4 inches annually or enough to furnish 60 m.g.d. continuously. For Oakland County, the average annual storm runoff is equivalent to a continuous supply of more than 180 m.g.d. Addition of the discharge by evapotranspiration to the discharge by overland runoff gives annual water losses from the nine township area of about 360 m.g.d. and from the entire county about 1,100 m.g.d. It is of course impractical to recapture all water lost by overland runoff or by evapotranspiration, but these losses are so great that the need to explore all feasible means of salvaging some part for beneficial use is obvious.

The salvage of storm or overland runoff in many urbanized areas of this county is ruled out because sewer systems now in use are of the combined type and mixing of sanitary waste with the storm water eliminates use of any water from these systems for recharging purposes. Some of the streams in the area may be of quality suitable for recharging, but little information is available concerning the physical, chemical, or bacteriological quality of these waters. In periods of storm runoff, the surface waters would be quite turbid. However, this would not be a great handicap if surface spreading or basin methods of recharge could be used. Hydrogeologic studies of the area are a prerequisite to any consideration of artificial recharge whether by surface spreading or by subsurface injection.

Perhaps the most immediate means of salvaging additional water for wells in the area is to move well installations closer to the recharge and to the evapotranspiration areas. The principal area of recharge is the western upland of permeable outwash. The substantial dry-weather flow of streams crossing the upland outwash plains indicates that the permeable outwash must be of considerable thickness to maintain such large ground-water flows during extended dry weather. However, this outwash plain is also a