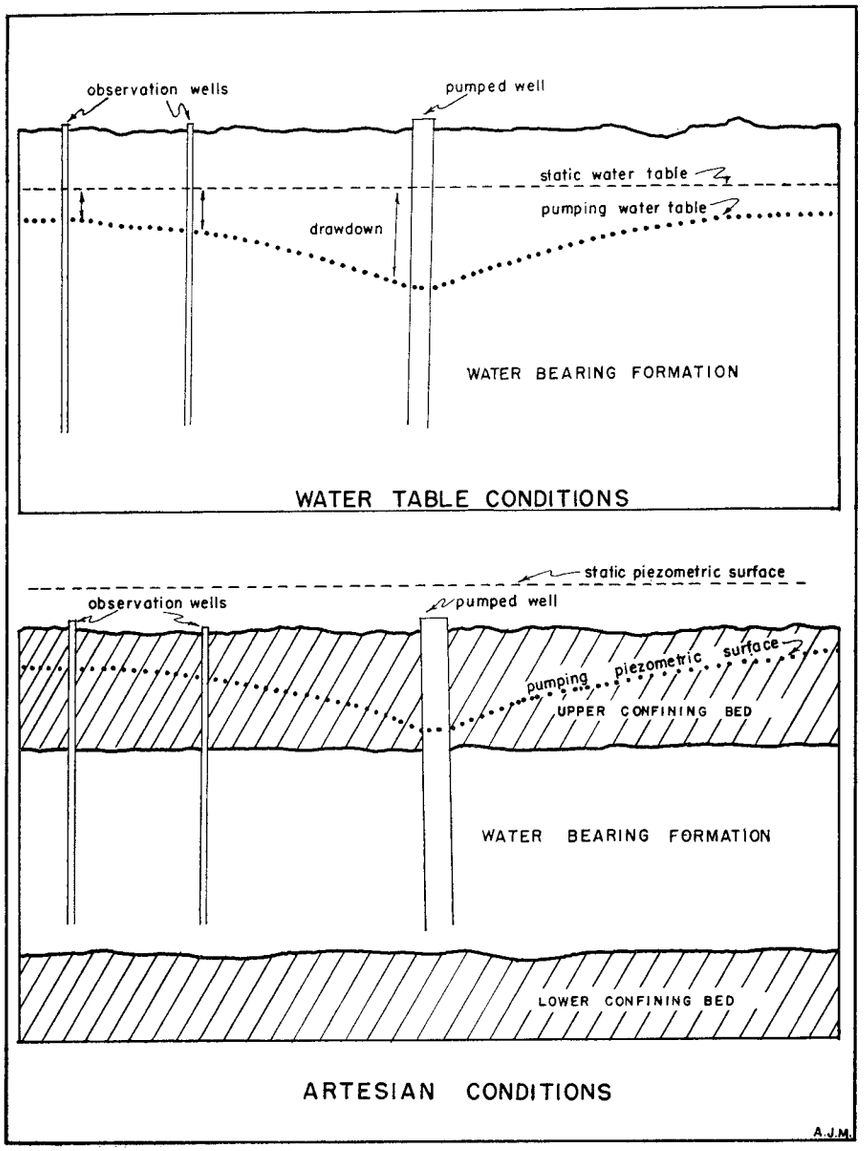


FIGURE 10

the total water content and the amount that is retained (specific retention) by the substance after it is drained. Under artesian conditions water is removed from storage not by unwatering of the formation but by the compaction of the water-bearing formation and associated beds as the piezometric surface is reduced. The squeezing out of water by compaction initially delays the formation of the "cone of pressure relief" in much the same way that a "cone of depression" is delayed by the unwatering of a formation under water-table conditions. In addition to the coefficient of storage a water-bearing stratum must possess the property of permeability, that is, capacity to transmit water under pressure. Thus, consolidated or unconsolidated sediments that yield water in sufficient quantities are termed aquifers. However, a formation yielding 5 gallons per minute may be considered an aquifer for domestic or farm use, but would not be suitable where large yields are needed for municipal or industrial supplies. Unconsolidated sediments like well sorted sands and gravels generally are characterized by large and interconnected voids and thus yield water more freely than material containing smaller voids such as clays and silts. In consolidated sediments such as shales, sandstones and limestones, the permeability may be increased by secondary openings—joints, bedding planes, and solution channels. Decrease in permeability, on the other hand, may result from cementation or other forms of clogging of the interstices. It should be kept in mind that under most natural conditions the permeability of earth materials, whether consolidated or not, varies from place to place horizontally and vertically, but that natural earth materials are seldom totally impermeable.

GROUNDWATER RECHARGE

Groundwater recharge of any water-bearing material in a specific area under natural conditions is derived by direct precipitation (rainfall and snowfall), percolation from adjacent areas, and from stream flow. The amount of recharge that may occur from direct precipitation is dependent upon several factors, which include the amount, kind, and seasonal distribution of precipitation, porosity and permeability of the earth materials, the type and condition of the soil and vegetal cover, and the geology and topography of the area. In Oakland County, the greater part of groundwater recharge usually occurs in the early spring and in the fall when the condition of the soil is most favorable and when plant life is dormant or at its

minimum, thereby reducing loss by evaporation and plant transpiration.

Recharge by percolation from adjacent areas is accomplished by movement of water in the direction of the water-table slope. The buried sands and gravels in the glacial lake plain section of Oakland County are recharged by the percolation of groundwaters from the intake areas to the northwest. Recharge of aquifers by stream flow may be either by flooding of streams over areas where the materials are suitable for water absorption or by infiltration through the stream beds where the water table lies below the stream bed. In Oakland County, the groundwater levels are above stream levels and hence limited recharge by streams may occur for only short periods during times of high stream flow. It is probable that in the Pontiac region, groundwater level in places may be lowered below the Clinton River by heavy pumping of the municipal wells in the vicinity. With a reversal in the groundwater gradients some recharge may be from the stream into the ground, assuming that areas favorable in porosity-permeability relations are along the course of the stream. Recharge of permeable beds may be accomplished artificially by various methods of water spreading, or through the use of recharge wells. Artificial recharge has not been attempted in any part of the county although consideration has been given to the possibilities of such a practice in the Pontiac region.

GROUNDWATER DISCHARGE AND RECOVERY

Discharge of water from the aquifer is accomplished in several ways. In areas where the water table lies near the surface, the water may be directly evaporated from the capillary fringe zone or transpired to the atmosphere by growing vegetation. In addition to these losses, groundwater is also discharged into streams through seepage and springs.

Where no water is pumped from an aquifer, the average recharge over a long period of time is generally equal to the average discharge; that is, the amount of recharge from precipitation and other causes is balanced by the amount lost through evaporation, transpiration, springs and seepage. The withdrawal of groundwater through wells introduces a new factor in the hydraulics of an aquifer. As soon as pumping begins, most of the water is taken from storage within the sediments in the vicinity of the well and temporarily very little water is drawn into the well from greater

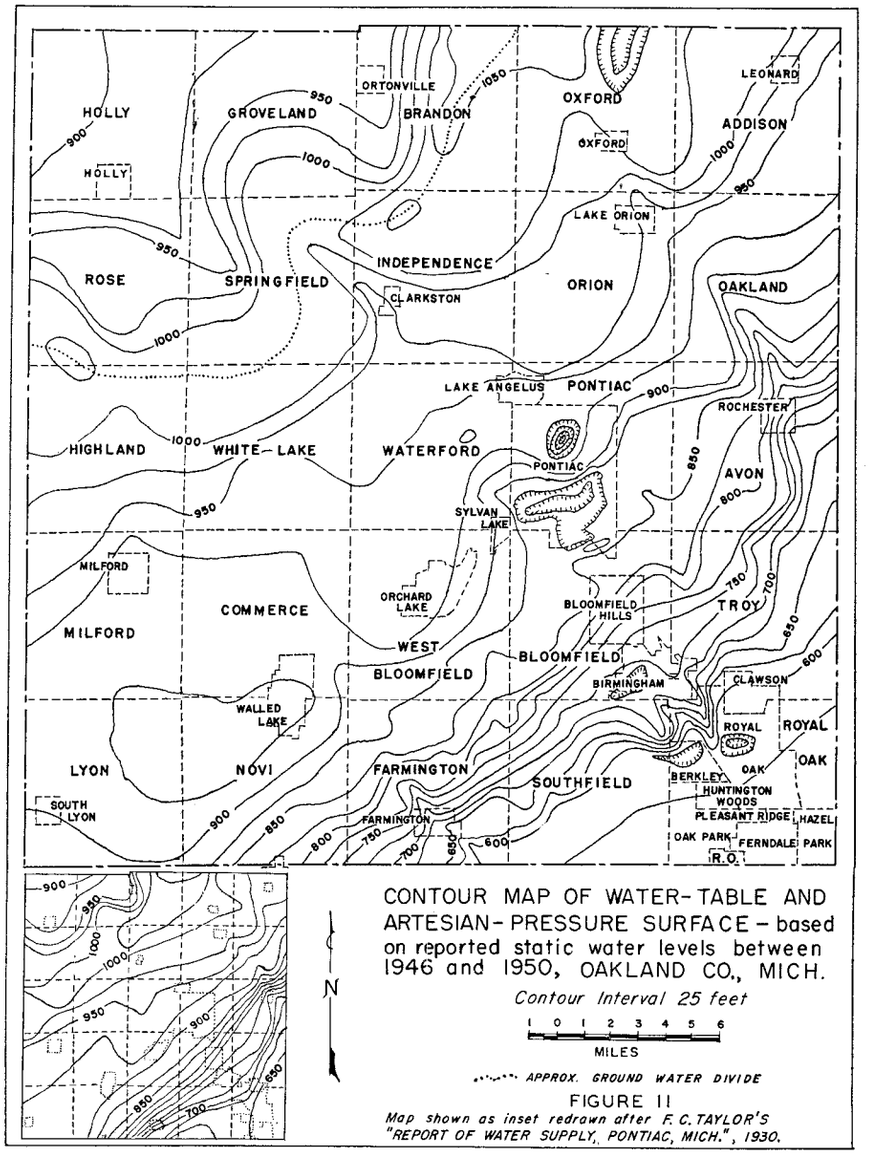


FIGURE 11

Map shown as inset redrawn after F. C. TAYLOR'S "REPORT OF WATER SUPPLY, PONTIAC, MICH.", 1930.

distances. As the pumping is continued, the water table is lowered around the well and a hydraulic gradient from all directions is established toward the well; that is, the water table soon assumes the shape of an inverted cone or "cone of depression." This hydraulic gradient is nearly an equilibrium gradient and is established close to the well so that the water transmitted through the water-bearing material is nearly equal to the rate at which it is being pumped. With continued pumping more of the aquifer will be unwatered and the cone of depression will be extended, thereby resulting in the percolation of water from greater distances. If no water is added to the aquifer through recharge, the water table will continue to decline and the cone of depression will be subsequently enlarged until the limits of the aquifer are reached. Recharge, on the other hand, may retard the enlargement of the cone by furnishing additional water that will become a supply for the pumped well. The consideration of these factors becomes essential in the development and spacing of wells for large municipal or industrial supplies.

Chapter IV

CONFIGURATION OF THE WATER TABLE

GENERAL CONSIDERATIONS

A map showing the configuration of the water table and/or the piezometric surface is desirable in any groundwater study since it indicates the areas of intake and discharge, the position of the groundwater divide, and the direction of groundwater movement. In the current investigation static water levels were collected whenever available for the preparation of the map included in this report as Figure 11. An ideal contour map depicting the configuration of the water table or piezometric surface is one based on static water-level measurements made during a particular month or season, preferably at a time when water-level fluctuations are at a minimum. This is not always possible when an area under consideration is as large as Oakland County and investigated only by one person. The preparation of such an ideal map would involve expenditures for test holes where wells are lacking and the procurement of personnel to perform water-level measurements over the entire county within a given period of time. The map which is included in this report is based on reported and measured static water levels in wells drilled between 1946 and 1950. The majority of the static levels plotted on the base map are the figures reported by the drillers upon the completion of the wells. Additional levels were obtained by the writer whenever uncapped or newly constructed wells were found while he was in the field. In such wells the water-level depths below the ground surface were made with chalk and steel tape to the nearest foot. The principal municipalities were generally cooperative in this study and thus made additional water-level data available from records on file. An attempt to obtain levels for a particular year was not feasible because of the size of the area and the reluctance of home owners to have wells dismantled in order to take measurements. The static levels obtained were usually reported as the depth below ground surface. These depths were transposed to a sea level datum by subtracting the depth to the water level from the ground elevation of the well. Surface elevations for the various wells were obtained from the U. S. Geological Survey topographic sheets. The pinpointing of wells on such maps was accomplished largely by speedometer checks starting at prominent road

intersections. Whenever the occasion demanded, elevations were obtained by handleveling from some known elevation or with the aid of an aneroid.

In view of the fact that the static levels represent data covering a period of five years, it is apparent that the resulting map departs considerably from the ideal condition. Furthermore, the selection of a contour interval is for the most part arbitrary since no observation wells that are beyond the influence of heavily pumped wells or areas are within the limits of the county. The interval selected was 25 feet for the final construction of the map because of the nature of the data and the inference that the average water level under most natural conditions would not decline 25 feet within a period of five years, especially in an area where the average annual precipitation amounts to 29.94 inches. For the year 1950 groundwater levels in rural and suburban areas rose from several tenths of a foot to two feet, and in industrial areas depending on groundwater the static levels increased up to five feet. The same trends occurred for the year 1951, but with net gains up to two feet for rural and suburban areas and up to three feet for industrial areas. These figures were obtained from the annual summaries of the *Water Resources Review*. The interval selected also would allow for any discrepancies made in water-level measurements and in the determination of surface elevations of the wells involved. In drawing the contours, levels of inland lakes of the outwash areas, as shown on the 1942-43 quadrangle maps, and stream courses were used as additional controls wherever possible for the adjustment of the contour lines. In spite of the handicaps the resulting map constructed by the writer compares favorably with the 1930 map prepared by Taylor (inset, fig. 11) insofar as the major features are concerned.

The principal groundwater divide is in the northwestern part of the county and is approximately coincident with the topographic divide that separates the drainage to the north and northwest from drainage to the south. This divide roughly follows the line of demarcation between the morainic deposits of the Saginaw lobe and the interlobate outwash area. As far as it is possible to determine from the bedrock elevations, the groundwater divide lies slightly to the northwest of the bedrock-surface divide. In general the contours have a northwest-southeast trend, which is in harmony with the glacial topographic features of the county. As shown on both maps, the regional slope of the water table and

piezometric surface is to the southeast, excepting a small area in the northwest corner of the county, where the slope is to the northwest. Another smaller groundwater divide is suggested in the southwestern part of the county, which coincides with the topographic divide separating the River Rouge and Huron River drainage systems. Lack of data prevented a more accurate definition of this feature, which is only suggested on the current map.

UNCONFINED OR WATER-TABLE CONDITIONS

The reported static levels of most of the wells located in the outwash plains and in the till deposits of the Saginaw lobe harmonized with the lake levels of the area. In this area which lies northwest of the Fort Wayne Moraine, the groundwater may be considered as being under "unconfined or water-table conditions" although some reservation must be made since no natural deposits of whatever origin are entirely without structure. This area, particularly the region underlain by the outwash sand and gravel deposits, constitutes the major intake area of the county because it is favored with materials of high permeability in comparison with the morainic and lake plain sediments found to the southeast. The numerous lakes and pits which dot the outwash plains act as reservoirs for any excess slope run-off during times of heavy precipitation. Since the major groundwater divide lies within this area, the movement of the water is to the southeast and northwest. The water table does not have a stationary surface but is constantly changing, its slopes being adjusted in response to the gains or losses of water due to recharge or discharge. Thus the surface configuration of the water table changes from one period to the next. A perfect map of the water-table surface which is drawn on a two-dimensional surface indicates only the horizontal movement of the groundwater at the water table. However, hydraulic gradients are three-dimensional features, and hence it should be visualized that the movement of water is not only along the water table but also to depths below it and upward again at some other place. As water moves downward a corresponding decrease in head with depth takes place, and conversely an increase in head as it moves upward, since the depth below the water table is decreased. From the generalized contour map of this particular area, it is apparent that the water-table surface has slopes which are more gentle in comparison to the slopes of the piezometric surface in the southeastern part of the county.

CONFINED OR ARTESIAN WATER CONDITIONS

Southeastward from the northwesterly limits of the Fort Wayne Moraine, the contours of the water-table map depict a piezometric surface which embraces the entire area of the glacial lake plain and the southerly belt of morainic hills. Generally, the reported static levels of wells in this part of the county are not in harmony with the lake levels. The levels of Sylvan Lake and Dawson Mill Pond (928 feet a.s.l.) in the vicinity of southwestern Pontiac stand 104 feet above the reported head in the Orchard Lake well No. 3 (PO-86) owned by the city of Pontiac and completed in April 1949. Orchard Lake well No. 1 (PO-88), drilled nearby in October 1925, had a reported static level of 894 feet above sea level, thus placing the lake levels 34 feet above the water level in the well. The water level in 1948 of well PO-39 located in section 20, Pontiac Township, and owned by the General Motors Corporation, was 115 to 119 feet below the levels of lakes Osmun (932 feet), Terry (933 feet), and Howard (936 feet) in the immediate vicinity. The cases that have been cited are in areas of heavy groundwater withdrawal, but similar facts obtain in areas of light groundwater draft. In section 18, Bloomfield Township, two wells (BL-24 and 25), drilled on the property owned by the Couzens Estate, have static levels which are not in harmony with the level of Wabeek Lake (922 feet). Well BL-24, drilled in 1936, adjacent to the east margin of the lake has a depth of 215 feet and a static water level of 890 feet above sea level. This would place the water level in the well 32 feet below the level of Wabeek Lake. This well has a performance of 700 gpm[1] and was pumped for several weeks in order to raise the water level of the lake which in 1936[2] declined after a prolonged dry period. Well BL-25, drilled in 1948 for a domestic supply, is 165 feet in depth and has a static head of 870 feet above sea level, or 25 feet below the lake level. These examples of discordance in water levels between lakes and wells, and even between adjacent wells are typical of the area in which the water is under confined conditions in highly variable glacial deposits. Despite probable errors in the data used, it is interesting to note the increased declivity of the piezometric surface; the increased declivity coinciding with the position marked by the contact of the glacial lake plain with the Inner Defiance and Birmingham moraines.

Reconsidering the nature of the glacial deposits of southeastern

[1]Gallons per minute.
[2]Personal communication.

Michigan from the viewpoints of occurrence and distribution of the sand and gravel pockets, lenses, and other bodies, it is evident that the more permeable but buried materials lying below the water level in the intake area are under partial, if not complete, confinement and hence are artesian. This region, particularly the glacial lake plain area, is not composed of a single artesian structure but rather is composed of numerous small and imperfect artesian systems, some of which may be isolated in a sense, but most of which are interconnected in devious and complex manners. Since the individual artesian zones are at various depths and have various interrelations, as well as varying degrees of porosity and permeability relationships, it is obvious that the static levels may differ in wells that are reasonably close to each other. It also adds to the difficulty of preparing a piezometric map since this area includes many artesian aquifers rather than a single zone of large areal distribution, which is more common under bedrock conditions.

Under confined conditions of groundwater, a piezometric or pressure-indicating surface is established which represents an imaginary surface that coincides with the pressure (head) of the water in the aquifer. In this part of the county, many small permeable bodies are involved, and hence the map of the piezometric surface, more or less, represents a composite of them all. The contours of such a surface, like the contours of the water-table surface, are useful because they indicate the approximate source, destination and the general direction of groundwater movement. The principal intake area for this complex artesian system lies to the northwest in the glacial outwash plains of the county. Additional intake areas may well be along the marginal outwash deposits which are between the Inner and Outer Defiance moraines, as well as the southern morainic belt of hills, which are characterized by numerous depressions and inland lakes. Movement of groundwater from the intake areas into this region is more freely accomplished through the most permeable deposits, but the percolation of water is not only lateral, but also up and down in conformity with the "structure or deformation" of the water-bearing zones. The contours of a piezometric surface as shown on the map suggest only a horizontal movement, but since a piezometric surface is also a three-dimensional feature, upward or downward percolation is possible if the confining layers are only partially impermeable. Thus, if the water in the upper confining bed is under a greater head than the water in the confined aquifer, then percolation will be down into the

aquifer. Conversely, if the head of water in the aquifer exceeds the head of the water in the upper confining layer, then escape of water will be upward from the confined aquifer into the overlying bed. The same principle holds true for the lower confining bed. Percolation of water from the intake area into the glacial lake plain of southeastern Oakland County is therefore complex, and the evaluation of groundwater gains and losses for municipal or industrial supplies in this area will require a more complete and detailed study. Much of the difficulty will lie in the determination of the size, shape, and extent of the numerous buried aquifers, which can be ascertained only by drilling numerous test holes at some expense. Such drilling and expenditure will be necessary in order to estimate the amount and rate of groundwater recovery.

The presence of groundwater under water-table conditions in the glacial lake plain section is restricted to the surface deposits of coarser materials in beaches, alluvial deposits, deltas, river terraces, and spits or bars. In the morainic areas groundwater under unconfined conditions is in any surface deposit of coarser clastics.

AREAS OF HEAVY GROUNDWATER WITHDRAWAL

Despite the limitations of the water-table map as prepared by the writer, areas of heavy groundwater withdrawal are apparent (fig. 11). Taylor, in the preparation of his 1930 map, disregarded the static water levels from heavily pumped municipal wells around Pontiac since they would lead to the distortion of the contours. In view of the fact that these wells are closely spaced and in operation for long intervals, complete recovery of head is seldom attained. The writer, therefore, has plotted an approximate average static water level of each of the municipal wells for the latest possible year. Records of static levels for the city of Pontiac wells are not all continuous. The average static levels as plotted in the Pontiac region indicate a depression in the piezometric surface the maximum elongation of which corresponds to the nearly linear distribution of the municipal wells which follow the course of the Clinton River as it passes through the city. The exact size, shape and depth of the depression cannot be accurately evaluated with the information available, but its general trend cannot be disputed. The earliest municipal wells, drilled in 1888 were located at the Walnut Street plant (section 32, Pontiac Township) and the water levels stood at ground level (919 feet a.s.l.). The mean static level of an observation well located near the municipal wells at the Walnut Street

plant was 815 feet above sea level in 1950, or 104 feet below ground surface. This indicates that the static level at the Walnut Street site has declined appreciably since the first wells were drilled for the city.

Another area of heavy groundwater withdrawal, although of smaller areal extent, is indicated by the depression contours shown in sections 16, 17, 20, and 21, Pontiac Township. This depression is attributed to three closely spaced wells, owned by the General Motors Corporation, which are capable of a combined yield of more than 2.5 million gallons per day. All three wells are in the northeast quarter of section 20 and have a surface elevation from 940 to 950 feet above sea level. Two of the wells were drilled in 1926-27 and the reported static levels shown on the records were 45 feet and 30 feet below ground surface respectively. The third well, drilled in 1948, had a static level of 133 feet. No additional records are available to determine the area of influence of each well or the composite area of influence, and hence it is difficult to determine accurately the amount and extent of the decline in the static head. It is reported[1] that the heavy withdrawal of water from these wells influences the static levels of municipal wells located in the western part of the city as indicated by the upsurge in static levels during week ends. While the industrial plant is in full operation, all three wells are used to supplement the water supply furnished by the city of Pontiac, and a permanent depression in the piezometric surface has developed. It is unfortunate that no records have been kept which might indicate the amount of recovery in head while the wells are not in operation. From all contacts in the field, no indications were found that the heavy pumping of the industrial wells has caused a decline in the water levels of Terry, Osmun, and Howard lakes which are located nearby.

In the northwest part of Royal Oak Township the contours indicate two small areas of heavy groundwater withdrawal. These depressions are caused by heavy pumping of municipal wells owned by the cities of Royal Oak, Berkley, and Clawson and by unincorporated subdivisions located in Royal Oak and Southfield townships. These areas trend northeast-southwest. The heaviest withdrawal is centered in the city of Royal Oak. In the area centering about the city of Birmingham only a slight depression is indicated since the municipal wells are more adequately spaced and each well is rested after a period of operation. Since time is allowed for re-

[1]Oral communication, Water Supply Engineer, City of Pontiac, Michigan.

covery, the depression of the piezometric surface is not as overdeveloped and hence is not as apparent on the basis of the contour interval selected.

The depressions shown on the map indicate the areas where groundwater problems have occurred frequently in the past decade, and where these problems must be seriously considered as the region continues to grow in population and in industrial productivity. The size, shape, extent and depth of these piezometric depressions are not to be considered as the actual picture of existing conditions since the data are far from adequate for quantitative evaluation. However, the information gathered for this investigation strongly suggests that certain areas are critical, and hence a systematic collection of data that would permit a quantitative evaluation of groundwater gains and losses is needed. It also appears advisable that the municipalities of southeastern Oakland County should combine their efforts and resources toward a regional groundwater study rather than the individual exploration of possibilities.

DECLINE OF THE PIEZOMETRIC SURFACE

A comparison of Taylor's map of 1930 with the map in this report suggests a regional decline in the piezometric surface in the glacial lake plain section of the county, particularly in Royal Oak and parts of Farmington, Southfield, and Troy townships. Although it is admitted that the static levels used in the preparation of the current map were not obtained from the same wells from which Taylor obtained his data, reasons to accept the indications of a decline in the surface are good. Drillers, established in the county for the past three decades, commented to the writer on several occasions about the decline in water levels in the glacial lake plain area, particularly in Royal Oak Township. A section by section comparison of reported static levels as indicated on Taylor's map with those obtained by the writer for a five-year period seemingly bears this point out.

The earlier map shows the 650-foot contour of the piezometric surface as the lowest contour passing through Royal Oak Township, whereas on the current map the 575-foot contour is drawn. This represents a difference in head of 75 feet for the southeastern extremity of the county. Considering the nature of the data used, this difference should not be construed as the actual amount of decline in head since 1930, but as a record that a noticeable decline occurred, which generally decreased in a northwesterly direction. To determine the actual decline in head more accurately, additional observation wells are needed so that measurements over a period of years may be taken or automatically recorded. Additional static levels for Royal Oak Township could have been used advantageously in the preparation of the current map, but were not available. The general conclusion is that the greatest decline since 1930 has occurred in the southeastern extremity of the county and decreases in the direction of the morainic area to the northwest. The contributing causes for the decline in head are several in number. These are listed and discussed in the following paragraphs:

(1) In the past decade Royal Oak, Southfield and Troy townships have had an increase in population ranging from 61 per cent to 198 per cent exclusive of incorporated cities and villages. Population gains ranging from 29 to 180 per cent were experienced by the cities of Clawson, Birmingham, Royal Oak, and Berkley. With this increase in the number of inhabitants, and the attendant increase in new construction and industry, the number of private wells has correspondingly increased. In municipalities having a public water-supply system, the increase in population has placed an added load on the existing municipal wells, thereby initiating exploration and the construction of new wells, or else has led to more continuous operation of old wells to meet the demand. Individual municipal wells in existence or developed recently in this area have yielded up to 1,500 gpm. Many homes today are equipped with appliances (showers, washing machines, sprinkling systems, and other water-using devices) therefore the trend in the quantity of water used on a per capita basis has been upward. Many privately owned flowing wells have been equipped with pumps in order to meet the demand imposed by added appliances and personal conveniences.

(2) Overdevelopment of individual aquifers is a contributing factor to the decline of the piezometric surface. In three areas known to the writer, and discussed later in the report, artesian zones have been over-pumped as the result of closely spaced municipal wells of high yields. In each case, the operation of one well affected the static levels in the others. Such a practice is neither sound nor economical and should be avoided since a single and larger well equipped with a more efficient pump could produce the same yield as the two closely spaced wells when operating at the same time. During a prolonged dry spell, a heavily pumped or an overdeveloped

aquifer undergoes a pronounced loss in head which becomes greater as pumping continues. Thus the head in confined or partially confined water-bearing zones above the heavily pumped aquifer may decline in response to the downward percolation of water. The downward percolation begins at the moment the head in the upper aquifers exceeds the head in the lower ones. Since it is conceivable that many of the more permeable zones in the glacial lake plain are only partially confined and hence interconnected, the effects produced by overdeveloping a particular zone become more widespread with time.

(3) Recharge of the water-bearing aquifers in the glacial lake plain section may be principally by indirect percolation of water from the intake areas in the outwash plains and morainic deposits immediately to the northwest. However, recharge by precipitation falling directly upon the area should not be excluded since very few natural materials are totally impervious to water percolation. In the past three decades some of this recharge has been lost, particularly in the past ten years when the construction of residential, commercial and industrial buildings reached an all time high. New structures covering the rechargeable area reduce the amount of available surface area for direct recharge, and furthermore, the precipitation falling upon the roofs of such structures is generally lost since it is diverted directly into sewers or drainage ditches.

(4) Urbanization of an area also leads to road construction, much of which is bituminous or concrete. This again decreases the amount of available areas for recharge by direct precipitation, and in addition, provides for greater and more rapid run-off.

(5) Urbanization of an area also has its attendant sewer construction projects and road drainage ditches, which cause some loss of water that is under water-table conditions. Again, water derived from precipitation, which might have been retained for a greater period, and produced more recharge, is rapidly drained. Sewer systems, especially if not watertight, are adverse to groundwater recharge, a specific example of which has been noted in the city of Pleasant Ridge in Royal Oak Township. A ridge of sand, representing the beach deposits of glacial Lake Wayne, extends along Livernois Avenue from the southern boundary of the county (Eight Mile Road) northward as far as the city of Royal Oak. The entire area of the city itself is underlain by fine yellow or gray sand, eight to fifteen feet thick, and resting on blue clay that is free of gravel. Originally the water supply for the community was obtained from

shallow wells constructed in sand in which the water level stood within two feet of the surface. According to the city engineer[1] the water level in the beach sand has been considerably lowered as the result of a sewer installation in 1920-23. The sewer line was constructed of vitrified tile with cemented joints which were not watertight. The drop in the sewer pipe from the point of the highest invert to the lowest invert, where it leaves the city of Pleasant Ridge, is approximately 33 feet. This installation resulted in the gradual drainage of the water in the beach sand, which subsequently caused a stand of oak trees in the vicinity to die.

(6) Many of the original marsh areas shown in earlier reports have been drained during the process of urbanization in the southeastern part of the county. Marsh areas act as reservoirs for excess precipitation and run-off and under proper conditions may contribute to groundwater storage.

All of the factors cited have undoubtedly contributed to the decline of the water levels in southeastern Oakland County, but a quantitative evaluation of each factor is not possible on the basis of the information made available to the writer. Many of the data are scattered, and the records collected frequently have not been continuous for any given period. An evaluation of these factors on a quantitative basis would require continuous records over a period of years, and this in itself constitutes a separate study.

[1]Oral communication, July 21, 1949.

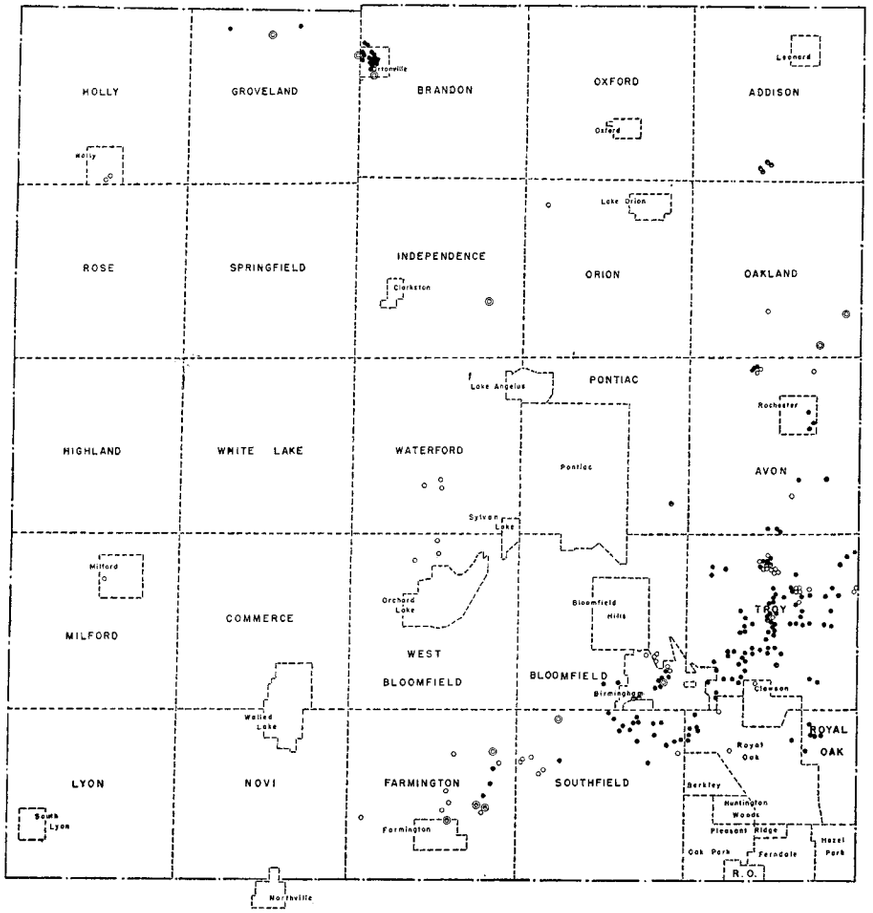
Chapter V

FLOWING WELLS

FLOWS FROM UNCONSOLIDATED DEPOSITS

Glacial Lake Plain

The glacial lake plain of the county is noted for flowing wells in the past and today. As may be seen from the profiles (fig. 12, A-D) constructed across the lake plain section in Troy and Royal Oak townships, the declining topographic slope is in a southeasterly direction, and the confined but permeable materials at various depths give rise to the basic structural conditions needed for artesian flows. Each of the profiles is drawn nearly at right angles to the northeast-southwest trend of the major glacial features, and from them it is also noted that the conditions giving rise to flowing wells are not of simple structure. Instead of well defined aquifers, that might be more generally expected in consolidated sediments, the cross sections indicate the presence of several permeable zones, or lenses, each of which may act as a confined aquifer or may be interconnected by devious courses and give rise to flowing or non-flowing wells if they occur below the level of saturation at the recharge area. The location of such permeable zones and their thickness, shape and extent are difficult to predetermine unless numerous test holes are drilled, which is not always economically practicable. The sections show that lacustrine clays and unassorted till deposits predominate in the area with a greater abundance of coarser sediments in that part of the lake plain which is marginal to the Inner Defiance and Birmingham moraines, that is, in a belt defined roughly by the highest Maumee and the Whittlesley beaches, as is shown on Profile C of Figure 12. From the scattered distribution of the permeable strata flowing wells may be expected anywhere in the glacial lake plain whenever a sufficient head exists to raise the water above ground level. On Figure 13 it is noted that the distribution of flowing wells follows a northeast-southwest trend; they are located principally along the higher part of the lake plain, the northwesterly limit being marked approximately by the highest Maumee beach. Southeastwardly, the flowing wells decrease in number, and their absence in the southeastern part of Royal Oak Township may be owing to insufficient head, or since the area is supplied with water from the Detroit system no records of flowing wells that may have been in the area have been kept.



FLOWING WELL AREAS IN OAKLAND COUNTY, MICHIGAN

LEGEND

- ○ *FLOWING WELLS IN DRIFT.*
  - ● *drilled prior to 1911.*
  - ◓ *1911 – 1930*
  - ○ *1931 – 1950*
- ◎ *FLOWING WELLS IN BEDROCK*

N

1 0 1 2 3 4 5 6
MILES

FIGURE 13

The greatest concentration of known flowing wells, in the past and at present, is in Troy Township. This area is one of the larger flowing-well districts of southeastern Michigan and has been discussed by Leverett (1906-07) in his report on the water supplies of Oakland County. Of 81 wells tabulated in his study for Troy Township, 76 were reported as flowing wells with heads ranging up to 30 feet above ground level. Most of the wells ranged in depth from 80 to 120 feet; the shallowest flowing well being 50 feet and the deepest 220 feet. Approximately two-thirds had reported heads of less than 5 feet, generally averaging between 2 and 3 feet above ground surface. Stronger heads were associated with the deeper wells, 120 to 140 feet in depth, but this feature is a function of permeability rather than of depth. Within relatively short distances the comparative heads between wells varied considerably even though they penetrated to the same depths. This is not an unusual phenomenon since the physical attributes of glacial deposits change markedly both laterally and vertically. Reported yields from most of these wells were less than 5 gpm where the casing diameter did not exceed 2.5 inches. With larger casings the yields generally ranged from 5 to 10 gpm and from one well a flow of 129 gpm was recorded. A notable fact to retain in mind is that prior to 1910, a non-flowing well, particularly in the vicinity of Troy, was the exception rather than the rule.

Since Leverett's study, the static level has declined as noted previously in the discussion of the water-table map. Of 55 wells drilled in Troy Township during the past decade for which more complete data are available, 42 were non-flowing thus indicating that flowing wells are becoming less numerous. In the lake plain of Royal Oak, Bloomfield, Southfield and Farmington townships, the percentage of non-flowing to flowing wells was again greater when compared with the tabulated data in Leverett's work. This decline in head is suggested in Profile C of Figure 12 where the piezometric surfaces are shown for 1928, 1949, and 1950 as well as available data would permit. In comparing the 1910 piezometric level with the level shown for the year 1950, a decline of 50 to 75 feet is shown along the profile. It may be added that in the construction of the profiles an attempt was made to select only those records that fell along the line of profile, though this proved to be insufficient. Thus where the tops of the plotted well logs fall either above or below the topographic profile, it is an indication that the positions of such wells

were shifted slightly from their true positions along a strike at right angles to the line of profile.

The factors contributing to the decline in the head were discussed earlier in the report, but in the glacial lake plain it appears that the increase in the number of wells and the development of municipal wells of high yield may be the most significant. Wells TR-52, 65, and 69, owned by the city of Birmingham, The Bundy Tubing Company and the city of Clawson, respectively, are shown plotted on Profile C of Figure 12 and illustrate the effect of overdevelopment of a particular water-bearing zone. The wells are spaced approximately 550 to 600 feet apart, and the nature of the sediments penetrated and the reported static levels are indicated on the profile. All three wells penetrate the same water-bearing zone, and because of proximity interfere with each other. The static water level of the Bundy well has declined 21 feet since the completion and subsequent operation of wells TR-52 and TR-69 in 1949. During the operation of the Birmingham well at 1,000 gpm, the static level in the Bundy well dropped from 50 to 75 feet. With the pump testing of the new Clawson well, operating at 650 gpm, the static level in the Bundy well dropped below the 91-foot depth,[1] that is, beyond the limits of the gage line. The water level in the Bundy well now has an average static level of 71 feet below the ground surface. Since the three wells are frequently in operation, particularly during the summer months, a composite cone of pressure relief is developed which extends in size with prolonged pumping, resulting in a decline of the piezometric surface over a wider area. Thus any confined water-bearing aquifers higher in the section are likely to be affected, the movement of water being downward if the head exceeds the head of the lower zone. The effect of this overdevelopment is strongly shown by comparing the static level profiles of 1928 and 1949. A similar condition, although not as pronounced, exists in the vicinity of section 16, Troy Township, where a heavily pumped well at the White Chapel Cemetery apparently has caused the lowering of water levels in non-flowing wells or the failure of flowing wells. This change has been most noticeable during the summer months when residents within a radius of 1.5 miles of the cemetery well have complained of flowing-well failures or a decline in the level of their non-flowing wells. Whether the operation of the cemetery well has any direct influence on wells a mile and a half distant is not known, but well owners within that radius were

[1]Personal communication, September 13, 1949.

compelled to deepen their wells or drill new ones after the cemetery well was put into service. Data relating to the cemetery well could not be obtained from any source. However, these two examples serve to indicate the possible effect upon the piezometric surface through local heavy withdrawal. If such withdrawal were repeated many times, the net effect in time would be a decline over a much wider area. Since groundwater percolation, in general, is a slow process, the complete recovery of head cannot occur as long as high producing wells are in operation. Though the decline in head as shown on Profile C of Figure 12 may be as much as 75 feet since 1906, it must be kept in mind that such declines are of local extent. However, a reduction in the piezometric gradient through heavy groundwater withdrawal at one point would naturally lead to some decline in head at points beyond, particularly in the direction of the piezometric slope.

Flowing wells are numerous in sections 3, 4, 9, 10, 15, and 16, Troy Township. A 6-inch well, with a flow estimated at 100 gpm, was recently drilled at Troy. For that area a comparison between the two water-table maps does not show any appreciable change in head since 1930. This may be partly explained by the fact that this area is quite distant from any area of heavy groundwater withdrawal. Nevertheless, the drilling of additional new wells recently within the section listed has had its effects on older wells. Upon the completion of the 6-inch well, an older well on neighboring property less than 40 feet away ceased flowing. This is a natural consequence of urbanization. As new wells are drilled overdevelopment of the artesian aquifer will occur, and flowing wells in this area will become a thing of the past. The flowing wells in sections 3, 4, 9, 10, 15 and 16 are completed at depths ranging from 89 to 115 feet, and all apparently tap the same water-bearing zone.

In and around the overdeveloped areas shown on the water-table map, occasional flowing wells are reported. Well RO-21, owned by the Consumers Power Company, is located in the northwest quarter of section 5, Royal Oak Township. The piezometric contours indicate a head of 650 feet above sea level in that section, but the well, drilled in 1931 and still flowing, has a head of 9 feet above ground level, or 719 feet above sea level datum. This flow comes from a 12-foot layer of gravel between the depths of 238 and 250 feet. Other wells drilled in the vicinity, as reported in 1930 by Taylor, had water levels standing at the top or slightly below the top of the casing. In section 12, Southfield Township, well SO-32, drilled

in 1949 to a depth of 220 feet flowed from a bed of gravel 10 feet thick. In section 8, Royal Oak Township, the location of test hole RO-41 is between two small overdeveloped areas. The 3-inch test hole was drilled to a depth of 147 feet, the last three feet being in shale. A fine sand and gravel bed approximately nine feet thick overlies the shale, from which came a strong flow of salty water. Since the surface elevation of the test hole is 670 feet, the static level is at some height above ground level. Piezometric depressions from 550 to 575 feet above sea level are on each side of the test hole. In the vicinity of the test hole other deeper wells, from 160 to 227 feet in depth, have static levels definitely below the ground-surface elevation. These scattered flowing wells, located in or adjacent to a piezometric depression, suggest two possibilities: (1) that lower gravels in the vicinity have not been affected by the heavy withdrawal of water from higher zones, or (2) that scattered water-bearing zones are more isolated, or at least more effectively confined from other water-bearing zones above or below.

Ortonville District

Leverett in his report (1906-07) described Ortonville as the only village of its size that is supplied almost entirely with domestic flowing wells. The village is in Brandon Township (T 5 N, R 9 E) and located in the northward sloping valley of Kearsley Creek at its junction with Duck Creek. According to Leverett, the upper slopes of the valley consist of a coarse till that has been deposited over a more compact and darker till material which he believes to be of pre-Wisconsin age. The valley, now cut into both tills, is partially filled with fine sediments consisting of sand and silt which in a few places are mixed with gravel. These sediments in turn are capped by a pebble-free, tough blue clay ranging from 15 to 30 feet in thickness. Overlying the clay is a deposit of coarser sand and gravel from 15 to 35 feet in thickness, which now forms the floor of the valley which contains Kearsley Creek.

No records of new wells drilled in this area were obtained, since drillers operating in this part of the county were not in the habit of keeping records. From interrogation of drillers and residents, it was established that the majority of wells in the district are no longer flowing, pumps being required to bring the water to the surface. The decline in head is attributed to an increase in water consumption on a per capita basis and to the number of new wells. The new wells may be of more significance since the population of the village increased from 377 to 686 between 1910 and 1950.

Rochester District

Leverett (1906-07) reports flowing wells in the village of Rochester. Owing to a public water-supply system which furnishes an adequate supply of water, this area has not been extensively developed. The village is situated in the valley of the Clinton River at junction of the Paint Creek tributary. Sandy and clayey lacustrine deposits, with some outwash materials, are along the valley floor of the Clinton River, which in this part of its course is confined between the Birmingham and Inner Defiance moraines. Sediments of a similar nature and origin are along the valley of Paint Creek from its debouchure in the Clinton River northwestward beyond the settlement of Goodison, as the valley is cut into the unassorted tills of the Fort Wayne and Defiance moraines. North and northeast from the village are deposits of outwash sands and gravels with scattered areas of unassorted till, and to the east are some sand and gravel deposits of deltaic origin deposited in glacial Lake Maumee.

The early wells of the district were in the heart of the village and were reported to have heads of 18 to 20 feet above the ground surface. The principal water-bearing formations are sand and gravel beds at depths between 98 and 150 feet. From well records of a more recent date, the artesian conditions result from a gravel deposit which is overlain by a blue or gray clay. The gravel in places is separated from the clay by a layer of hardpan. Since the municipal supply is obtained from wells located in morainic deposits beyond the village limits, records for this district are lacking, but from data on hand and oral exchanges of information with drillers little or no change has been indicated in the static head for the district. Well AV-1, located in the northwest quarter of section 2, Avon Township and drilled in 1949 to a depth of 129 feet, has a reported head of 9 feet above ground surface. In the northwest quarter of section 14 of the same township, wells AV-13 and 14, owned by a paper mill, show but a slight decline in head, which is the effect of heavy pumping. In 1927 well AV-14 was flowing but the amount of head was not reported. Well AV-13, drilled in 1949 on the same property has a reported static level of 12 feet, the actual level being 7 feet below surface, since 5 feet of fill has been added to raise the well mouths above the floor of the valley. This decline of 5 to 7 feet indicates a very local decline owing to heavy withdrawal of water used in the processing of paper.

Morainic and Outwash Areas

In addition to the flowing-well districts just described, additional flowing wells are known throughout the morainic and outwash belts. Each of the known areas represents localized artesian conditions which are generally expected to be in glacial deposits that are highly varied in structure and sediments. These isolated areas are too numerous to treat individually, but the most prominent flows are in the vicinity of Cass and Crescent lakes (moraine and outwash) in West Bloomfield and Waterford townships respectively. The wells are along the steeper slopes bordering the lakes and are 30 to 60 feet deep but some may be deeper. Much of the artesian condition of confinement is produced by a fine beach sand which overlies sediments of a coarser nature. The village of Rochester obtains its water supply from artesian wells finished in gravels that are buried in the sediments comprising the Outer Defiance Moraine.

FLOWS FROM CONSOLIDATED SEDIMENTS

Since the recovery of groundwater from bedrock sources is small in comparison to the recovery from the drift deposits, the available data are extremely meager for a complete discussion of this facet of the investigation.

The records collected show that flowing wells have resulted from penetration of the Coldwater, Berea and Antrim formations. The reported static levels were as much as 15 feet above ground surface and with reported yields ranging from 2.5 to 30 gpm. Of 14 reported flowing wells terminating in bedrock, 7 are in the Coldwater formation, 6 in the Berea and one in the Antrim. Flows from the Berea sandstone have been reported in Independence, Bloomfield, Troy, Southfield, and Farmington townships. Flows from the Coldwater formation have been reported in several townships from the northern to the southern limits of the county.

The underlying bedrock formations dip in a northerly direction at a rate of less than 40 feet per mile except where local rock structures modify the degree of dip. It is suggested that the movement of water is in an up-dip direction along the more permeable strata of the underlying formations, particularly in the Berea sandstone and in the Coldwater shales. The force causing the percolation of water up-dip in the formations may result from the head established by the major groundwater divide in the county, or perhaps from a higher groundwater divide located in the adjacent areas to the

north. Most earth materials are not totally impermeable, and hence percolation of water into the formations could be accomplished by way of voids and fractures of both primary and secondary origin. Since the rock surface of the Thumb Upland is probably dissected by many rock valleys, the vertical distance of water percolation from the overlying mantle into the Coldwater shales and thence into older formations would thus be decreased. Unfortunately the details of this surface are not known, but deep cuts into the rock surface are indicated in places. According to one driller, bedrock was encountered at a depth of 550 feet below ground surface (or 440 feet above sea level) in the southwest quarter of section 28, Oakland Township (T 4 N, R 11 E). This could not be verified by the writer since no record was kept for the well. The owner of the well made a similar claim as to the rock depth. A wildcat oil well (IN-15) located in the northeast quarter of section 26, Independence Township (T 4 N, R 9 E), is some 5 miles to the northwest. When the Berea formation was penetrated in this well at a depth of 970 feet brine flowed over the top of the casing; at depths of 1,028 and 1,105 feet in the same formation, the static level of brine in the casing dropped to 40 and 312 feet below the surface respectively. The probability that gas in the Berea may be the force causing the up-dip movement of water is not excluded from consideration since natural gas is known to be present in the formation in other parts of the state. In this particular well, some gas was reported from near the base of the Coldwater beds and in the Berea formation itself. It is not unlikely that both forces may be involved in the movement of water up-dip in some areas, but the available data do not permit conclusive evaluations to be made. The gas where present could be localized along the crests of the small anticlinal structures and could act as a driving force in the movement of groundwater if pressures elsewhere were reduced in some manner.

Chapter VI

GROUNDWATER RECOVERY

Groundwater is recovered principally from wells which may be either bored, jetted, dug, driven, or drilled. The type of well that is selected is dependent upon such factors as depth of the aquifer, lithologic properties of the aquifer and of the overlying materials, desired yield, and the desired speed and cost of construction. Of the five general types, the drilled well (either by cable tool or by hydraulic rotary drilling) is most commonly used in Oakland County for the recovery of water from unconsolidated and consolidated formations. Driven wells are most abundant in areas where the water table lies near the surface, and the glacial drift is relatively free from large fragments and boulders. Driven wells in the county are located in the outwash sand and gravel areas, in the sandy sediments along the beaches of many inland lakes, and in the beaches and deltaic deposits of the glacial lake plain area. Dug wells are not common but the few noted were 12 to 42 inches in diameter and from 10 to 40 feet in depth. Most dug wells are in the deltaic deposits and beaches of the former glacial lakes in Avon and Troy townships. Yields from dug wells were sufficient for most domestic, stock or farm purposes, though many failures were reported after prolonged periods of drought during the summer months. Jetted or bored wells were not found in Oakland County in connection with the inventory for this report.

RECOVERY FROM CONSOLIDATED SEDIMENTS

The quantity of groundwater recovered from bedrock formations underlying the glacial drift mantle in Oakland County is insignificant in comparison to the total recovery from the unconsolidated sediments. Of the logs gathered from all sources only 168, or approximately 14 per cent of the total, report that bedrock was reached or penetrated and only 38 producing wells have been finished in bedrock. Many records of the rock wells were incomplete, which added to the difficulty in identifying and evaluating the water-bearing characteristics of the individual formations. As an example, a well record indicating that shale was penetrated was not particularly informative regarding position of the shale in the stratigraphic column since all formations from the

Antrim through the Coldwater are shales or formations containing shale zones. Color designation on the log offered some clue since the Antrim and Sunbury formations consist of dark brown to black shales, and the Bedford, Berea and Coldwater formations consist wholly, or in part, of shales that are blue or light gray in color. However, study of the geologic and bedrock-surface maps and the descriptive logs of fifteen deep oil and gas exploratory holes, made possible some assignment of geologic horizons. On such a basis the bedrock wells are tabulated. (Table 6.) This table shows that the greater number of the rock wells are in the Berea or Coldwater formations. The Berea consists of beds of sandstone separated by layers of hard blue shale. No particular bed could be singled out as the principal aquifer on the basis of the records available, but as shown in the tabulation the yields ranged from 5 to 30 gpm. Recovery of water from the Coldwater formation is chiefly from the small sandstone beds or scattered layers of limestone reported to be interspersed within the blue shales. Reported yields varied from 10 to 70 gpm, depending upon the permeability, the depth of penetration into rock, and the number of sandstone layers or lenses which are cut through.

Eleven of the rock wells tabulated are flowing wells with reported heads up to 5 feet above ground level and yields of 2.5 to 20 gpm. The static heads of non-flowing wells were as much as 95 feet below ground level. Yields ranged from 1.5 to 100 gpm with an average yield of 20 gpm for the wells tabulated. In the majority of rock wells the water is more highly mineralized than in drift wells. Drawdowns were reported for several of the rock wells, and from such information "specific capacities" were determined. "Specific capacity" has been defined as the yield per unit of drawdown, expressed in terms of gallons per minute per foot of drop in static level—a crude measure of the water-yielding properties of an aquifer. Specific capacities of the individual formations could not be fairly appraised with such limited data, but as shown in Table 7, the specific capacities of the rock wells range from 0.06 to 10.0 gpm and average 2 gpm per foot of drawdown for all wells. These records show that the yield in most wells is small. Thus, even if the quality of water is disregarded, the quantity is likely to be insufficient to permit utilization as a coolant for refrigerating or air conditioning systems which require large volumes of water.

Recalling the nature and thickness distribution of the drift throughout the county and the occurrence of groundwater therein,

it is not surprising that rock wells are so few in number in the county, excepting possibly in the glacial lake plain area. The greater thickness of the drift and the presence of more sand and gravel zones in the outwash and morainic deposits have been deterrent factors in the development of rock wells in such areas. In the glacial lake plain area, where the mantle may be thin or composed dominantly of clays, more attempts have been made to obtain groundwater from the underlying consolidated formations, but the mineralized quality of the water was immediately recognized, and drilling into bedrock was thus discouraged. The numerous inland lakes which dot nearly two-thirds of the county, show that large potential supplies of surface and groundwater are available, but have not been greatly developed, inasmuch as the major part of population and industry is in the southeastern third of the county.

GROUNDWATER RECOVERY FROM THE GLACIAL LAKE PLAIN SECTION

The glacial lake plain embraces all or parts of Royal Oak, Southfield, Troy, Avon, Bloomfield and Farmington townships of southeastern Oakland County. Several profiles constructed across this section (figs. 12, 14 and 19) show the area to be composed largely of unassorted till, in part deposited as waterlaid moraine, and lacustrine deposits of sandy and clayey sediments. It is probable that some of the buried pebble-free clays are of lacustrine origin and have been deposited by earlier glaciers or perhaps by substages of the Wisconsin ice. Dating these clays is not possible with the data now available. Most of the sediments of the lake plain section are finely textured and, if well compacted with a low permeability coefficient, the percentage of run-off during times of precipitation is high where the slopes are significant. Where slopes are not pronounced, marsh or wet areas may be in the depressions, and permit a limited amount of groundwater recharge. However, the low permeability coefficient of the sediments may cause much loss of the surface water by evaporation and by plant transpiration during the growing season.

The profiles show two zones of the coarse fraction of sediments. The first zone of sand, gravel, or various admixtures is on the surface of the lake plain in the river terraces, beaches, deltas and recent alluvial deposits. The second zone of coarse sediments is beneath the surface as beds, lenses, and pockets, of various dimen-

sions and of irregular distribution throughout. They may be of similar origin to sand and gravel bodies found at the surface but were formed by earlier glacial deposition. Correct identification of the origin of these sands and gravels depends upon information obtained by additional and properly spaced borings. The volume of sand and gravel in proportion to the less permeable clays and tills appears to increase northwestward and is in that part of the lake plain adjacent to the morainic belt of hills formed by the Inner and Outer Defiance moraines. In earlier stages of the Pleistocene probably some deposition of coarse clastics was made against the existing rock slope in the form of marginal outwash. Or perhaps earlier glacial lakes formed beaches, deltas and river terraces, as their lake levels changed in the same manner that the glacial lakes of the Wisconsin withdrawal of the glacier built the formations now at the surface. Most of the buried sand and gravel deposits are water-bearing, and groundwater has been recovered from aquifers which range in thickness from two inches to several tens of feet. It is obvious that the location trends of such bodies of sand and gravel cannot be determined by surface examination, but can be determined by a well planned and directed drilling program that can acquire data relating to the areal extent, shape and thickness of the water-bearing zones. Completion of such a program is necessary in planning for large water supplies demanded by industries or urban centers.

From the distribution of coarser clastics in the sediments of the lake plain area, it is apparent that individual wells may differ considerably in depth even when closely spaced. On the basis of 348 records (Table 8) of wells drilled between 1930 and 1950, the well depths ranged from 10 to 258 feet and averaged 109 feet. The average depth of wells in Troy, Royal Oak and Southfield townships has not increased since the time of Leverett's report, thus indicating indirectly that the bedrock surface limits the depth of penetration. It is obvious from the conditions described and shown on the profiles that groundwater in this section is under both confined and unconfined conditions. The surface deposits of sand and gravel contain water under water-table conditions and buried deposits have water under confined or partially confined conditions. The permeable surface deposits of coarse clastics readily absorb precipitation, which moves downward until the water table is reached and then moves laterally toward points of discharge since the water is held up by less pervious materials. Since few earth

materials are entirely impervious, downward percolation carries some of this water into the lower but confined beds of sand and gravel. This can occur only if the hydrostatic pressure of the water in the buried sands and gravels is reduced by pumpage or some other form of discharge.

The shallow dug or driven wells reported in this section of the county are in the beach, terrace, delta or alluvial deposits that are on the surface. Their depth, generally not more than 30 feet, is limited to the depth of the first underlying stratum of clay or till. The precipitation absorbed by the surface deposits of sand and gravel may be in sufficient quantity for domestic needs, but it is doubtful if large supplies for industrial or municipal purposes can be developed from them since the storage capacity is so limited. The water table under these conditions is near the surface and fluctuates with the seasons, as indicated to some degree by the number of reported failures, most of which occur during the summer after periods of drought. Furthermore, water is lost by seepage from these surface deposits wherever they are intersected by streams, drainage ditches, or by sewer mains that are not of watertight construction.

Buried deposits of sand and gravel in the lake plain are capable of furnishing small to very moderate supplies of water. Because of their complete or partial confinement by clays, the water contained is under pressure, and the movement of water through these aquifers must be complex. Recharge is principally by way of the outwash and morainic areas to the northwest. Flowing wells, as stated previously, may be expected anywhere in the lake plain section, but the largest flowing-well district is within the limits of Troy Township. Leverett tabulated 111 wells (1906-07) within the limits of the lake plain section. Of these 97.3 per cent were reported as flowing with the static levels ranging from 9 feet below to 30 feet above ground surface (Table 8). For the period 1930-1950, 193 wells were reported but only 30 were flowing, or approximately 15.5 per cent of the total. Static levels ranged from 137 feet below the surface to 9 feet above ground surface with an average static level of minus 32 feet for the non-flowing wells. Of the townships included in this section, Royal Oak had the lowest average static level (minus 81 feet) and Avon Township the highest average static level of minus 16 feet.

The reported yields from wells in this section averaged 102 gpm with a range from 0.2 to 1,500 gpm as determined from 167 records.

The average yield appears somewhat high considering the nature of the glacial lake plain deposits, but an explanation for the high average yield is found in the developed, and hence highly productive, municipal wells of Royal Oak, Birmingham, Clawson, and Berkley. A breakdown of the records on the basis of individual yields revealed that 72 per cent of the wells had yields less than 21 gpm, 13 per cent had reported yields between 21 and 100 gpm, 8 per cent between 101 and 500 gpm, and 7 per cent between 500 and 1,500 gpm. For most domestic or commercial wells up to 6 inches in diameter the records indicate the average yield to be approximately 10 gpm without any special development.

The water-yielding properties of the buried aquifers in the lake plain sediments are in part indicated by the wide range of yields, and also by specific capacities determined on the basis of yield and amount of drawdown whenever such data were included in the records. Specific capacities of such aquifers ranged from 0.03 to 166.4 gpm per foot of drawdown or an average of 22.4. In general the smaller diameter wells, for the most part slightly developed, had the lowest specific capacities recorded. Larger diameter wells, which are developed and gravel packed (Table 9) recorded extremely high specific capacities. The data on specific capacities included in this report are not as accurate as might be desired inasmuch as the accuracy of measurement and methods employed in the test, no doubt, varied among drillers. Nevertheless, the data reported on yields and specific capacities do indicate to a degree what yield may be expected and what can be done to increase the quantity of water from a well. In Montgomery County, Ohio, specific capacities of 1,011 and 1,360 gpm per foot of drawdown were reported from two 26-inch wells finished in sand and gravel deposits (Norris, 1948, p. 18). The ranges in specific capacity for each of the city of Birmingham wells are shown in Table 9. In some wells the range in specific capacities for individual wells is considerable. Increases result after a well has been in operation for some time, and decreases are caused by declining static levels, pump inefficiency, or by an increase in screen friction as the result of clogging.

RECOVERY FROM SPECIFIC AREAS IN THE LAKE PLAIN SECTION

City of Berkley

The city of Berkley is within the limits of Royal Oak Township on the northeastern flank of the waterlaid Detroit Interlobate Moraine. Currently, the city has three wells (RO-61, RO-61a, and RO-62) in service. These highly productive wells are drilled in the sediments of the lake plain area that have been deposited along the south wall of a tributary bedrock valley that joins the major bedrock valley to the east. Whether this association of rock valleys with productive wells is of any special significance is not yet determined as data are incomplete and poor, but the relationship is similar to the situation disclosed at the city of Royal Oak by examination of the maps and profiles. The nature of the sediments penetrated by the Berkley wells is shown on Profile F of Figure 14.

The water-supply system of Berkley dates back to 1927 when the first well (RO-61) was drilled at the site of the Department of Public Works building. The depth of the well is 223 feet, and it is cased with 12-inch pipe to a depth of 180 feet. The screen consists of 62 feet of 10-inch casing perforated with ⅜-inch holes spaced one and one-half inches apart and set between depths of 161 and 223 feet. With this arrangement the 12-inch pipe overlaps the perforated casing for nineteen feet, leaving forty-three feet exposed as a screen. The profile shows that the screen penetrates layers of good water-bearing gravel which are separated by layers of clay or admixtures of sand and clay. When tested in 1927, the well had a capacity of 1,000 gpm with a measured drawdown of 7 feet. The static level at the time of the test was 96 feet below ground surface, but declined to a depth of 140 feet reported in 1949. This decline represents a loss in head of about 2.1 feet per year. In 1929, as a precautionary measure against pump failure, a second well (RO-61a) was constructed adjacent to the original well. This well is of similar construction to the original and likewise had a rated capacity of 1,000 gpm. When both wells are operated simultaneously, the measured yield is 2,000 gpm with a drawdown of 10 to 12 feet. The city was thus adequately supplied with water until the rapid increase in population and new construction made it necessary to augment its existing facilities with a new well in 1947.

The new well (RO-62), completed in 1948, has a depth of 205 feet. It penetrates mostly sand from 125 to 184 feet and sand and gravel between 184 and 204 feet. It is finished with a 10-inch screen, 15 feet long, consisting of No. 40, No. 60, and No. 80 mesh screening variously arranged to meet the character of the water-bearing sand and gravel. When tested in 1948, its yield was 650 gpm with a measured drawdown of seven feet. The water level stood at 137 feet, and when compared with the 1949 levels of wells RO-61 and

61a it appears that all tap the same water-bearing zone and are perhaps within influence of each other. The new well is located approximately 300 feet west-southwest of the old wells.

Berkley is primarily a residential community. Its water consumption has steadily increased from 80 million gallons in 1930 to 400 million gallons in 1949. As of 1950, the per capita consumption of water averaged 60 gallons per day. Monthly and annual pumpage, static levels and population growth are shown in Figure 15. The

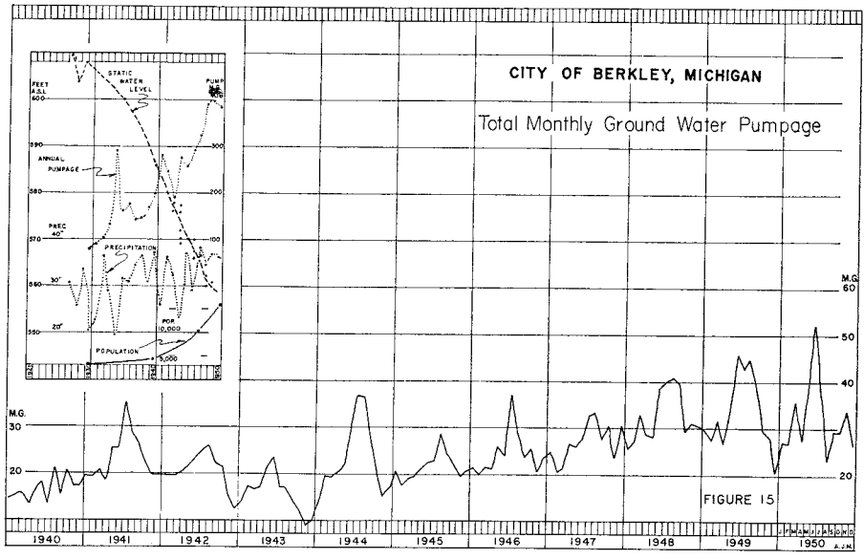


FIGURE 15

extremely high pumpage for 1934 was caused by an exceptionally dry year during which only 19.68 inches of precipitation fell upon the area, compared with the average annual precipitation of 29.94 inches (determined for Pontiac). This represents a negative departure of slightly more than 10 inches from the normal rainfall. The fluctuations of the water-production curve, if carefully analyzed, can be also correlated with the economic and business activities of the area and of the nation as well. The upward trend in groundwater pumpage since 1945 is the result of postwar rise in population and the construction of new homes in the area.

The hydrograph (fig. 15) recording the static levels in the Berkley area is based for the most part on sporadic water-level observations, except in later years when measurements were taken more

frequently and the averages plotted. A progressive decline in the static level for the Berkley area is clearly shown, and no doubt the continuing increase in groundwater consumption contributes dominantly to this decline. The decline, however, does not necessarily mean depletion of supply, as the progressive increase in the amount of groundwater withdrawn annually prevents stabilization of the water level. Since the entire area of the glacial lake plain will probably have further population growth, it is not certain just when or where stabilization will be reached. Therefore, comprehensive tests are necessary to determine if this particular area is overdeveloped or is being overdeveloped.

The declining static levels and the increase in groundwater consumption have given cause for concern to Berkley and other communities in southeastern Oakland County. The problem of meeting demands has not only resulted in the construction of new wells but has also initiated a program of curtailing groundwater lossage. The difference between the amount of water pumped and the total amount metered at all establishments represents unaccounted lossage. Lossage consists of all unmetered water used by the city, individuals or of loss through pipe leaks. Berkley's water lossage for the fiscal year 1947-48 was 35 per cent,[1] thus placing the city seventh among the eight neighboring communities. When compared with the generally accepted maximum normal lossage of 15 per cent, the quantity of water lost is high in terms of gallons per day. Pumped but unmetered water not only contributes to the decline of static levels but also to a loss in revenue. For the fiscal year 1947-48, Berkley's unaccounted water lossage was 124.6 million gallons, which represents a revenue loss of $232,000 to $300,000.

The financial loss to the city resulting from unaccounted water lossage is sufficient to warrant corrective action for the conservation of water. Corrective measures may generally include the location and repair of leaks, increase in water rates for construction purposes (the rate to be determined on the volume of building materials used), strict policing of water used on construction jobs to prevent waste through negligence or carelessness, and the checking of master meters for accuracy in delivery.

City of Birmingham

Birmingham is situated in parts of Bloomfield and Troy townships along the upper part of the glacial lake plain at the junction of the

[1]City Engineer's Report to City Manager of Berkley, Michigan, February 3, 1949.

Birmingham and Detroit Interlobate moraines; in a zone defined by the Whittlesey and Maumee beaches. The River Rouge, after crossing the marginal outwash deposits between the Inner and Outer Defiance moraines passes through the city southwestward and across the glacial lake plain. The volume of coarser sediments is greater in that part of the lake plain that lies between the Whittlesey and Maumee beaches, as shown in profiles C and J, Figures 12 and 14. Whether this condition persists all along the zone defined by the beaches is not definitely known since well data are not adequately distributed. The origin of these buried sands and gravels may be attributed to beach deposition of earlier glacial lakes or, as it is not entirely beyond the realm of possibilities, these sands and gravels may represent marginal outwash deposited between the ice front and the higher land to the northwest by an earlier phase of Wisconsin glaciation. At the moment the origin of these coarser sediments is not as important as the relationship of these coarser clastics to the marginal outwash at the surface between the Inner and Outer Defiance moraines. The area covered by the marginal outwash may be the immediate principal area of recharge for the buried sands and gravels of the lake plain. Recharge may likewise be accomplished along part of the River Rouge through induced infiltration into the alluvial deposits whenever a decrease in static head occurs as the result of groundwater withdrawal.

The water-supply system for Birmingham prior to 1910 (Leverett, 1906-07) consisted of five four-inch wells, each approximately 45 feet deep and completed in alluvial deposits of the River Rouge valley in the vicinity of Baldwin and Maple streets in section 26. Each of the wells had a reported flow of five gallons per minute or a daily yield of approximately 40,000 gallons. In 1915 the existing wells were operated by steam-powered pumps and served the needs of 2,000 people in the community, but since the capacity of the village system was inadequate at the time, many private wells were used. The experience of a serious fire loss prompted the community to initiate a program of well development which has continued since. The water-supply system of the city now consists of seven wells which were constructed over a period of years. The earliest well, Baldwin, was completed in 1922; the Lincoln and East were added to the system by 1930; the West and South by 1942, and in 1949 the Redding and Walker wells were added to the system. The wells are from 10 to 26 inches in diameter, range in

depth from 73 to 249 feet and have operating capacities from 200 to 1,500 gallons per minute. All the wells are finished in either gravel, sand and gravel, or fine to coarse sand. Profiles C, I, and J, Figures 12 and 14 contain the plotted logs of all wells except the Redding and South. These were not included because their position was too distant from the selected lines of profile.

The consumption of groundwater, as far as records show, has increased from 455 to 610 million gallons annually in the period 1933 to 1950 (fig. 16). The chart indicating groundwater pumpage

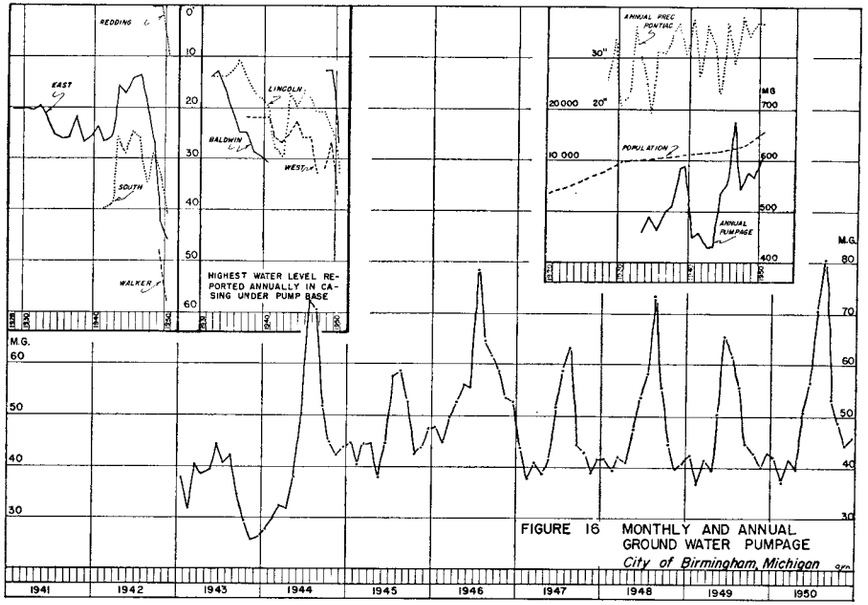


FIGURE 16 MONTHLY AND ANNUAL GROUND WATER PUMPAGE
City of Birmingham, Michigan

is somewhat inconsistent with records of annual precipitation and groundwater levels. The high in pumpage for 1938 and 1939 may be the result of prewar building activity, or the effects of groundwater lossage, which is determined by checking production figures against metered consumption. From the difference obtained, or water unaccounted for, allowances must be made for unmetered water used for ice rinks, for fire fighting, and for construction. The remainder of the water unaccounted for would constitute lossage, assuming that the meters installed on well pumps and in consumers' dwellings were recording properly. In a survey[1] by the

[1]City Manager's Report to the City Commission of Birmingham, Michigan, July 24, 1950.

city manager, it was reported that the 1939 pumpage was 584 million gallons compared to the annual production of 563 million gallons for 1949. This is 21 million gallons less, despite the fact that more construction and a greater population were served in 1949 than in 1939. The reduction in the quantity of water pumped resulted from a continued program of leak repair in the distribution system. The city of Berkley study indicated that water lossage for the city of Birmingham was as much as 39 per cent of the total pumpage.[2] The annual pumpage chart reflects the great activity of postwar construction of new dwellings and restricted building activity during the war years of 1940-1943.

The city today has two elevated standpipes with a combined capacity of 800,000 gallons, and has planned to construct another to meet future demands or emergencies. The city also has acquired sites for additional wells, near surface bodies of water which would permit artificial recharge if necessary. Birmingham likewise has contracted with the Detroit Board of Water Supply to purchase six million gallons of water daily when new transmission facilities, now under construction, are completed some time prior to 1955.

The Birmingham wells, with the exception of the Baldwin (BL-58), are located about the perimeter of the city, and therefore more favorably spaced. The Baldwin well is in the valley of the River Rouge near the center of the city (Profile J, fig. 14). All wells are operated in accordance with an established pumping schedule allowing a rest period for each well and thus permitting some recovery of static level. The effect of proper well spacing and the maintenance of a pumping schedule is reflected in the hydrographs shown in Figure 17. It is evident that the decline in level has not been conspicuous for the Birmingham wells when compared to the static levels of wells in other parts of the lake plain. For some of the older wells, the hydrographs have indicated stabilization for short periods, but in general, the records indicate a decline in head for the period 1940-1942 and an increase for the period 1943-1945. Each shows a decline since 1946 or later. The same trend is shown in Figure 10, in which the curves drawn are based on the highest static levels recorded yearly for each of the wells. In 1950 the highest static levels ranged from 4 to 14 feet below the levels recorded in 1949, and yet, in the period 1947 through 1950, the precipitation was 34 to 38 inches annually, which is well above the annual average. The annual demand for

[2]City Engineer's Report to the City Manager of Berkley, Michigan, February 3, 1949.

water continues to increase and until the demand remains nearly constant, the stabilization of static level in each well is not to be expected.

Of the long term records the hydrograph (fig. 17) for the East, or Derby, well (TR-54) best indicates the stabilization of the static level for the years prior to 1943, after which time the level rose, owing to restrictions placed on the building industry. Since 1946 the static level has progressively declined because of increased construction activity particularly in the northeastern part of the city. The East well (Profile C, fig. 12) is finished in sand and gravel at a depth of 137 feet, has a 26-inch diameter and a rated capacity of 900 gpm. The Lincoln well hydrograph reveals stabilization prior to 1938, but on completion of the West well in 1937, a loss of static head is noted with the period 1940-1942 marking the maximum decline. Both hydrographs show recovery during the period 1943-1945 and a subsequent decline after 1946—again reflecting the building activity of the city. The Lincoln well (BL-65) has a 10-inch diameter and a rated capacity of 400 gpm. In contrast, the West well (BL-64) is 26 inches in diameter with a capacity of 1,000 gpm. Both are on Lincoln Avenue in section 35, Bloomfield Township and are approximately 400 feet apart. Profile J, Figure 14, shows that both wells terminate in sand and gravel deposits 60 to 75 feet deep associated with a southeastward trending bedrock valley. From the conditions as shown, the Lincoln and West wells are favorably situated for either artificial or natural recharge. In the West well induced seepage from the River Rouge could result from a decline in static head owing to excessive groundwater withdrawal, provided the buried sands and gravels penetrated by the wells were interconnected with the alluvial deposits of the stream valley.

The South well (BL-61) (not shown on any of the profiles) is in the southeast corner of section 35, Bloomfield Township. It is 249 feet deep and finished in 16 feet of gravel and sand. The well has a 26-inch diameter and a rated capacity of 1,500 gpm with a drawdown of 23 feet. During the initial pumping test the well produced 2,600 gpm with a measured drawdown of 35 feet. In relation to the Lincoln and West wells, the South well is located approximately 0.7 mile to the southeast, and its depth of 249 feet suggests that it occupies a position along the axis of the same sand- and gravel-filled rock valley. From the maps it is noted that the trend of the River Rouge is such that it cuts across the bedrock

valley (fig. 7) between the Lincoln-West wells to the northwest and the South well to the southeast. The conditions again suggest that the River Rouge may be recharging the underlying aquifers by induced infiltration. Artificial recharge of the Lincoln, South or West wells is favorable in the event future investigations show that induced infiltration from the River Rouge is insignificant because of clay barriers between the aquifers and the alluvial deposits of the river valley.

The hydrograph (fig. 17) of the South well likewise shows a decline in static head, particularly for 1949-50. With reference to the specific capacity of the well, the chart shows a range from 105 to 250 gallons per minute per foot of drawdown. Specific capacity may vary considerably—the variation resulting from pump inefficiency, increase in screen friction due to clogging, or from fluctuations in static head. Since the specific-capacity curve for the South well shows conspicuous and recurrent highs and lows, it is likely that this behavior is caused by losses and increases in static head brought about by the operation of other wells in the vicinity, in this case by the operation of the Lincoln or West wells or both.

From the data available it now appears that the gravel- and sand-filled rock valley is favorable for the development of additional wells. On the bedrock-surface map it may be seen that the rock valley extends southeastward and is a tributary to the major bedrock valley that passes beyond Royal Oak. At the junction of this tributary with the principal bedrock valley, it appears that the buried sand and gravel deposits give way to unassorted till. This relationship may be seen from the bedrock-surface map and profiles H, I, and J, Figure 14. Northwestward from Birmingham the tributary rock valley may extend beneath the Inner Defiance Moraine and the marginal outwash deposits that are between the Inner and Outer Defiance moraines. If this inference is correct, then it seems that the tributary rock valley is well situated for recharge as several streams cross the outwash deposits. Furthermore, since the marginal outwash area is a lowland between the two moraines, it serves as a catchment area for precipitation. The conditions just described are nearly similar to those found for the city of Farmington.

The Baldwin well (BL-58), completed in 1922, is finished in sand and gravel at a depth of 73 feet, and is the shallowest of the Birmingham municipal wells (Profile J, fig. 14). The well has a 12-inch casing and a rated capacity of 200 gpm. It is near the center of the city in the valley of the River Rouge near Baldwin and Maple streets. Records relating to the static level of the well date back to 1932, and the hydrograph made from them shows a progressively declining curve until 1941, when the well was taken out of service after the West and South wells were completed to augment the city's water supply. While out of service, the water level in the Baldwin well recovered to a high of 720 feet (sea level datum). The well was later restored to service. Another decline of the curve for 1950 is indicated on the hydrograph (fig. 17) after the well was restored to service. The logs plotted along Profile J in the vicinity of the River Rouge suggest the possibility that the water-bearing sediments penetrated by the Baldwin well are recharged by induced infiltration from the river. This recharge is also suggested by the changes in the quality of water from the Baldwin well which will be discussed later in the report. The clay zones shown may make this form of recharge ineffective when compared to the amount of water that is withdrawn through frequent or continued operation. Nevertheless, the conditions portrayed by the profile indicate that recovery of head is extremely favorable, but probably slow, if a sufficient rest period is allowed for the well. From all indications the valley of the River Rouge appears a suitable site for additional wells since outwash deposits are all along the river's course where it flows on the lowland between the moraines.

The Walker well (TR-52) at the eastern limits of the city is in the southeastern corner of section 30, Troy Township. It is 193 feet deep and completed in a fine to coarse sand overlain by "hardpan" and blue clay. The well has an 18-inch screen and a rated capacity of 800 gallons per minute. With respect to surficial geology it is located on the Whittlesey beach, and in relation to the underlying rock surface it is completed in sediments deposited along the eastern slope of the major rock valley (Profiles C and I, figs. 12 and 14). The Walker is the most recent well constructed, and its hydrograph is short. Like other wells, the Walker well shows a decline in head. This decline measured for a 3-month period was 10 to 15 feet in 1949-50. The specific-capacity curve (fig. 17) reveals a range from 37 to 118 gallons per minute per foot of drawdown. For such a short history, the range and variation in specific capacity represent an extremely large change to be attributed to pump inefficiency or increased screen friction, and the decline in specific capacity can be attributed to changes in static

levels brought about by neighboring wells. Profile C shows that the Walker well is not too distant from the Bundy Tubing Company well and the municipal well owned by the city of Clawson. All three wells tap the same aquifer mentioned earlier in the report. The static level of the Bundy well[1] is strongly affected by the operation of either of the municipal wells. Since the Clawson well was tested at 1,070 gpm, it is apparent that a decrease in static head thus produced in turn affects the specific capacities of the adjacent wells. The necessity for proper spacing of highly productive wells is certainly demonstrated, although such spacing may not always be feasible.

The Redding well (BL-40), completed in 1947, is a relatively shallow well, 12 inches in diameter and completed in sand and gravel at a depth of 83 feet (Profile D, fig. 12). Like the Baldwin well it has a rated capacity of 200 gpm and is in a valley in the northeast quarter of section 26, Bloomfield Township. The valley is occupied by a stream which connects Endicott Lake in Bloomfield Village with Quarton Lake in the city of Birmingham. The original static level in 1947 was 8 feet above the ground surface but since has progressively declined as indicated by its hydrograph (fig. 17).

From the foregoing discussion it is apparent that Birmingham is favorably situated in respect to a groundwater supply and recharge possibilities. Natural recharge by induced infiltration from the River Rouge and its tributaries may be occurring in places where the static head has been reduced considerably by excessive groundwater withdrawal. However, the rate of induced infiltration may not be in sufficient quantity to meet the demands of the growing community, and recourse to artificial recharge by the use of return wells may be profitable. This can be accomplished by utilizing surface waters from streams or nearby lakes after a study of stream flow is completed.

Birmingham's position on the lake plain is also favorable with respect to the intake areas. The immediate intake area is the outwash deposit between the Inner and Outer Defiance moraines. The more distant intake area is the morainic and interlobate outwash materials farther to the northwest. In addition, the many morainal lakes serve as reservoirs, with abundant supply, although unfortunately the character of glacial materials in this area prohibits a more rapid transmission of water from the lakes into the

[1]Personal communication, September 13, 1948.

ground. From the available data, it strongly appears that additional wells may be developed along the present alluvium-covered valleys, by tapping the sand and gravel in the known rock valley. Test drilling may determine the extent of known rock valleys, or may locate other rock valleys that may be in part sand- and gravel-filled. It would seem advisable to explore for buried rock valleys as new wells developed in the alluvium-filled valleys are likely to have yields similar to the Baldwin and Redding, each of which has a capacity of only 200 gpm. It also may be practical to increase the diameter of future wells having locations similar to the Baldwin and Redding in order to increase the yield. The Lincoln, West, and South wells which are in the sand- and gravel-filled rock valley have rated yields of 400, 1,000, and 1,500 gpm respectively. The yield for the Lincoln well is small because its diameter is only 10 inches as compared to the 26-inch diameter of the other two wells. Though the gravel-filled rock valley appears to be a favorable site, overdevelopment should be avoided because more highly mineralized waters are likely to enter the wells not immediately, perhaps, but at some future time when excessive lowering of head may induce infiltration of mineralized water from the underlying bedrock formations. Offsetting this probability, however, is the fact that induced infiltration from the River Rouge is likely to occur in greater degree if the loss in static head becomes appreciable.

In the development of future wells either along the stream valleys or the gravel- and sand-filled rock valleys, it will be important to consider the factor of well spacing in order to avoid such interference as is shown by the extreme variations in the specific capacities of the South and Walker wells. A pumping schedule is a practice that should be retained since it permits a partial, if not a complete, recovery in head. It may be worth the effort to study the behavior of static levels more thoroughly while the different wells are in operation in order to improve the pumping schedule. The main purpose of such a study would be to avoid, whenever possible, the simultaneous operation of any two wells that interfere with each other. This procedure is especially applicable to the South well when it is operating concurrently with the West well.

The perimeter location of the wells about the city has advantages other than the proper spacing which it brings about. From an economic point of view perimeter location means reduction in size of the necessary transmission mains and in the amount of line pressure needed to distribute the water. Also any line break would

not seriously affect the water distribution throughout the city as would a break in a centrally located well. In this connection it may be pointed out that spacing resulting from a perimeter location of wells may be easily upset by the location of municipal wells operated by neighboring communities as in the Walker-Clawson wells treated earlier in this discussion.

City of Clawson

Groundwater data for the city of Clawson are few, and where available, they are incomplete or for short periods of production. The city now obtains its entire water supply from two wells drilled in the vicinity of the Whittlesey beach in the northwest quarter of section 32, Troy Township. Both wells are finished in gravel at depths of 175 feet. The most recently drilled well (TR-69), completed in 1949, is 12 inches in diameter, 188 feet deep and has a static level of 76.5 feet below the surface. During the initial pumping test upon the completion of the installation, the well showed a capacity of 1,070 gpm, with a drawdown of 20.5 feet, or a specific capacity of approximately 52 gpm per foot of drawdown. This well taps the same aquifer as do the Bundy and Walker wells (Profile C, fig. 12). In relation to the bedrock surface the Clawson wells terminate in water-bearing sediments that are deposited along the east slope of the major bedrock valley shown on Figure 7.

The old Clawson well was constructed in May 1928, and is just off the southeast slope of the Warren beach in the southeast quarter of section 33, Troy Township. It is a 12-inch well, 230 feet deep, at which depth shale rock was reached. Approximately 18 feet of sand, and sand and gravel layers are between the depths of 204 and 206 feet. With respect to the underlying rock surface, the well occupies a position along a tributary rock valley which was carved in the Antrim shale and trends southwestward to join the major rock valley of the area. Profile C (fig. 12) and the bedrock-surface map (fig. 7) show the relationships. Originally the well had a static level of 30 feet and a capacity of 750 gpm but in February 1949, the reported static level and yield were 93 feet and 250 gpm respectively. On the basis of these meager data the decline in static level in this vicinity averaged 3 feet per year. The well, though still serviceable, is currently not in operation but remains as a standby.

Groundwater production figures for the city of Clawson are available only since 1944 when the annual production was 87 million gallons. Like all other communities in the southeastern part of

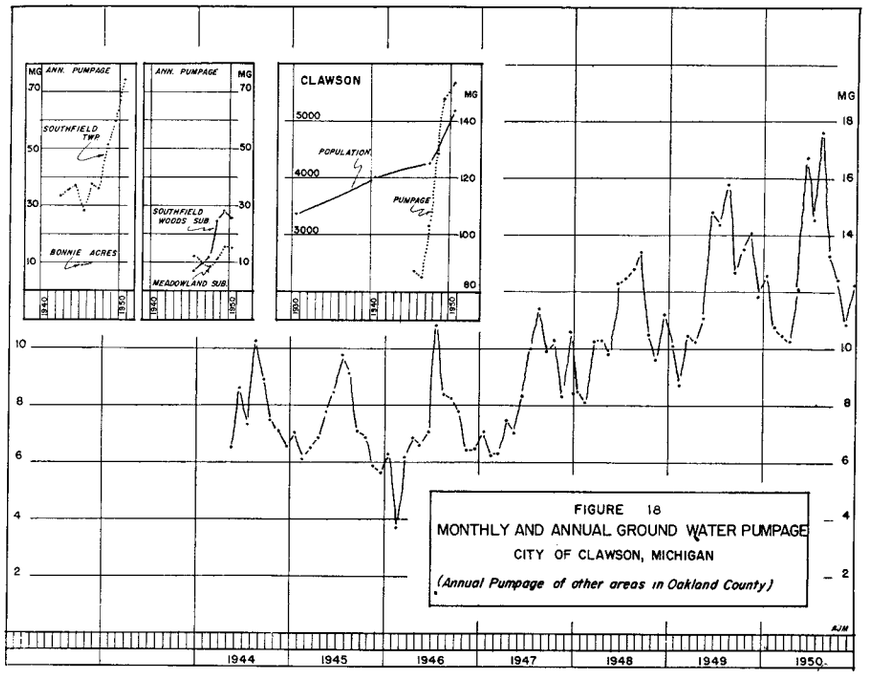
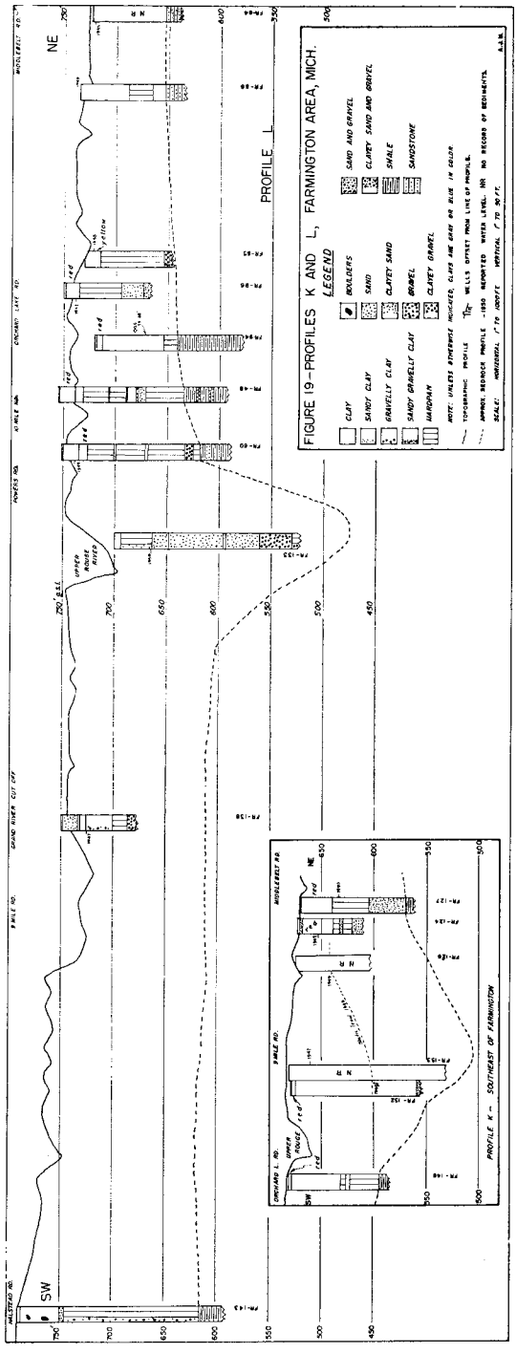


FIGURE 18
MONTHLY AND ANNUAL GROUND WATER PUMPAGE
CITY OF CLAWSON, MICHIGAN
(Annual Pumpage of other areas in Oakland County)

Oakland County, Clawson has grown rapidly in the number of inhabitants and in new dwellings (fig. 18). The demand for water sharply increased yearly so that by 1950 the annual production was 153 million gallons. The wells generally furnish an adequate supply of water throughout the year except during peak demands in summer periods of drought. During such times restrictions are in effect which govern lawn sprinkling, permitting the use of water for such purposes only between the hours of 9 and 12 in the evening. Similar restrictions have been in effect from time to time throughout the various communities of the lake plain area including communities furnished with water by the Detroit system.

City of Farmington

The city of Farmington (Farmington Township) is on the glacial lake plain between the highest Maumee and the Whittlesey beaches. To the south and east of the city are deltaic sediments deposited by streams during Lake Arkona time. From the surficial map (fig. 2) it may be seen that the present upper



River Rouge for a part of its course, is incised into these sediments. The river has its origin in the Fort Wayne-Outer Defiance moraines and flows southeastward and successively crosses the marginal outwash deposits, the Inner Defiance Moraine, and finally the glacial lake plain. The valley of the river consists of alluvial deposits of recent and past origin. The older deposits are now river terraces which were formed by erosion as the base level of the stream became progressively lower during the pro-glacial lake stage (Bay, 1930).

Beneath the mantle in the Farmington area, the rock-surface map (fig. 7) indicates a rock valley passing through the eastern part of the city which approximates, so far as known, the present course of the upper River Rouge which has a northwest-southeast trend in this area. The bedrock-surface elevations available for the vicinity show that the rock valley ranges in depth from 100 to 130 feet. The relationship between the topographic and bedrock surfaces is illustrated by profiles L and K of Figure 19. The profiles show that the upper part of the valley is filled with alluvial deposits. Drillers report "hardpan" when drilling is somewhat difficult, thus much "hardpan" is recorded in the logs of the profile. Such logging is unfortunate since it does not materially help in clarifying the lithology of the areas bordering the rock valley. The term has been variously used by drillers—often loosely applied to any hardened deposits of clay, till, sand and/or gravel.

The city has four municipal wells, rather closely spaced, along the valley of the upper River Rouge in the northwest quarter of section 27. All wells have 8-inch diameters and capacities of 440 gpm. Their depths range from 160 to 172 feet. The first well, completed in 1928, was reported as flowing, but since then the static level has declined to 35 feet below the surface as reported in May 1950. This represents a decline in level of 1.6 feet per year for the 22-year period.

Three of the wells are equipped for operation. During the winter season one well is sufficient to meet the water needs of the municipality, but in the summer two are placed in service to meet the increased demand. In 1950, the city wells pumped an average of 390,000 gallons of water daily with a maximum of 900,000 gallons for any one day. The water system includes a standpipe with a 240,000-gallon storage capacity which maintains a line pressure of 40 to 60 pounds. To date the city has not experienced any periods of water shortage.

On the profiles of the Farmington area the log of only one

municipal well is shown inasmuch as others were not available. Although the Farmington wells are somewhat too closely spaced for maximum efficiency, they are finished in deposits that are in an area favorable for recharge. Part of the recharge may take place by seepage from the River Rouge which can be induced by the lowering of the piezometric surface through pumping. Recharge may also take place by way of the marginal deposits of sand and gravel which lie between the Inner and Outer Defiance moraines. Thus from the conditions as shown on the profiles and maps, any future construction of wells to meet increased water demands could be along the trend of the present River Rouge which in this area roughly coincides with the sand- and gravel-filled bedrock valley.

City of Royal Oak

The city of Royal Oak is built on the lake plain just off the northeastern limits of the waterlaid Detroit Interlobate Moraine. Records relating to the water supply for the city are not complete, but until recently the northern part of the city was dependent upon a groundwater supply and the southern half was served with water by the city of Detroit system. Annual groundwater-pumpage records date back to 1926, and monthly pumpage data are available since 1941 (fig. 20). Annual groundwater pumpage has varied be-

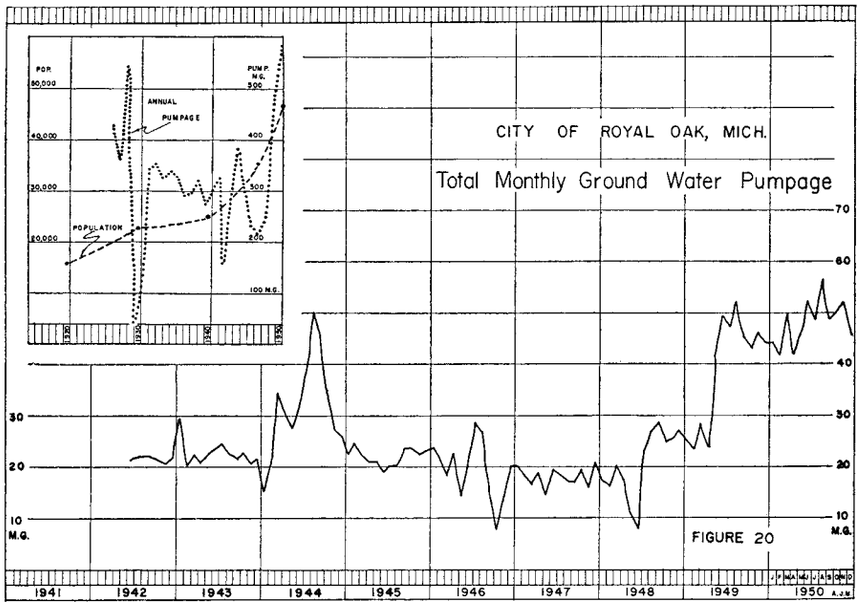


FIGURE 20

tween 120 and 580 million gallons. Although the amount of groundwater recovered annually throughout the years increased, the increase was not gradual but erratic as the quantity of water pumped from year to year depended upon the demands imposed by prolonged droughts, the number of wells in service and by the quality of water. Owing to the strong mineral content of the water, one well was ordinarily out of service except for emergencies. The increased demand for water brought about by the rapid growth of the city in the past decade has resulted in considerable expenditure for test drilling in order to increase its groundwater supply. An economic factor also prompted the test drilling program since water purchased from the city of Detroit was contracted for at $90.00 per million gallons, whereas the cost for groundwater in 1950 varied from $25.00 to $35.00 per million gallons.[1]

For several years the northern part of the city has undergone periodic water shortages brought about by prolonged spells of hot, dry weather. Demands for water during these periods were of such magnitude that water-main pressures were dangerously low and hence ineffective in case of fire. An increase in supply from the Detroit system was not possible at the time since the existing transmission mains were not adequate.

Between 1941 and 1950 the city of Royal Oak completed thirty test holes throughout the city, principally in the area north of Twelve Mile Road and west of Crooks Road where deficiencies in transmission existed. Not all of the test holes are shown on profiles D through H, Figures 12 and 14, thus the plotted results of the tests appear somewhat spotty. Profiles E through H are drawn in a northeast-southwest direction at right angles to the trend of the principal rock valley. Profile D is drawn northwest-southeast in the direction of both the topographic and bedrock slopes. The part of the profile within the limits of the city of Royal Oak shows that the logs of most of the test holes do not record the presence of any permeable water-bearing zones of sufficient extent and thickness to warrant development of municipal wells. In several of the test holes till and clays of lacustrine origin were penetrated. A few test holes (RO-25, 37, and 41) in sections 6 and 8 showed promise regarding quantity, but analyses of water samples drawn after drilling revealed chloride content as high as 900 ppm, and/or contamination by hydrogen sulfide or methane gas.[1] The profiles also show that

[1]Oral communication from George Schmid, Water Supply Engineer, City of Royal Oak, Michigan, June, 1950.

[1]City of Royal Oak, Water Department Interoffice Report to the City Commission, August 9, 1950.

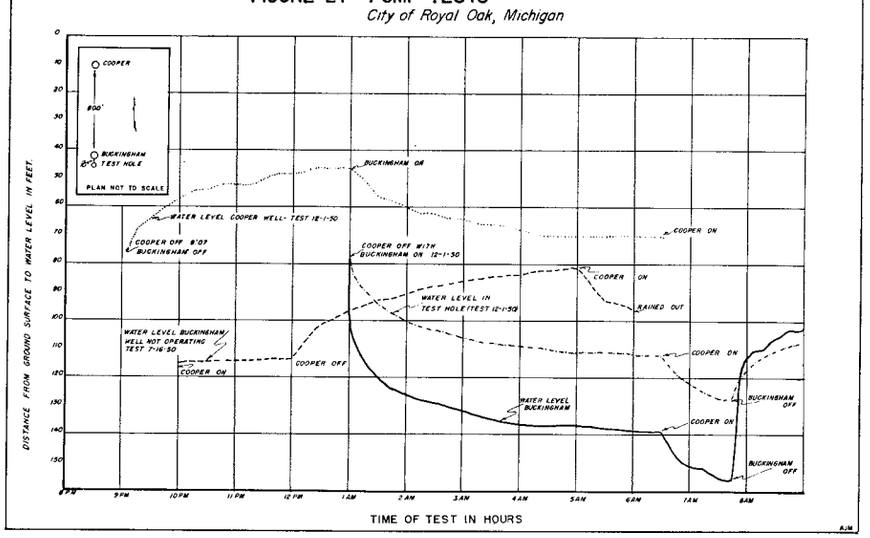
the buried rock valleys in the city of Royal Oak area are for the most part filled with till excepting that part of the major bedrock valley shown on Profile E and in part on Profile D. Considering the nature of the bedrock slope and the location and direction of glacial advance and retreat, it is not surprising that the rock valleys are filled with unassorted till deposits or lacustrine clays. As the result of the various borings only two new municipal wells were developed. One of low yield (150 gpm) is in the southeast quarter of section 6. The other in the northwest quarter of section 6 undoubtedly taps the water-bearing zone that supplies a nearby well.

The city now has five wells of various capacities. The Magnolia (RO-45) and Northwood (RO-46) wells are in section 9. The Magnolia well is 3,000 feet nearly due east of the Northwood. Both wells are completed with large-diameter screens (24- and 18-inch) at depths of 143 and 160 feet, and are apparently finished in the same water-bearing zone, or in separate but freely interconnected zones (Profile E), since the simultaneous operation of the wells results in considerable surging of the Northwood. The cone of depression under water-table conditions develops more slowly than in an artesian aquifer whose storage capacity may be many times smaller. Since the water in the Magnolia-Northwood stratum is under confined conditions, the static level of this artesian aquifer can be lowered by excessive withdrawal below the bottom of the upper confining layer so that the upper part of the aquifer becomes dewatered. Thus the original piezometric (pressure-indicating) surface in the dewatered part would become a water table, and the storage capacity of typical water-table conditions would exist. Any further pumping would create a cone of depression that would develop more slowly with respect to depth and size. If this is the fact, the pump impellers of the Northwood and Magnolia wells could be lowered more in the casing. Surging would be eliminated at present rates of withdrawal, and the wells operated under more or less water-table conditions. Increase in withdrawal of more significant magnitude could not be made in view of the fact that a water-table cone of depression develops in size and depth with respect to the storage capacity and permeability coefficient of the aquifer, which in this case may be limited. Original yields of the Magnolia and the Northwood wells were 1,058 and 700 gpm respectively; the present yields are 1,000 and 500 gpm respectively. With respect to their locations both wells occupy a position along

the major bedrock valley; the valley bottom elevation is less than 470 feet above sea level; each of the wells is completed at a depth of 505 feet below ground elevation or slightly above the rock valley. The records strongly indicate that at this point the rock valley may be filled with coarser clastics as recent test holes drilled in the Magnolia-Northwood stratum show water-bearing gravel and an abundance of water. However, any additional wells in this area would result in added interference with the existing wells, and possibly affect the quality of water through induced flow from bedrock sources.

The Cooper (RO-29) and Buckingham (RO-29A) wells are in the northwest quarter of section 6. The Buckingham is approximately 800 feet south of the Cooper. The Cooper has a 10-inch screen with a reported yield of 900 gpm, and the recently completed 30-inch Buckingham tested at 1,200 gpm. Both of these wells penetrate the same water-bearing zone, and are along the trend of the major rock valley but terminate at around 500 feet above sea level, or approximately 100 feet above the floor of the rock valley. In this area the bedrock valley, as shown on Profile H, is filled predominantly with till, which acts as a barrier against induced flow of more highly mineralized water from the bedrock. The proximity of the wells to each other also results in interference (fig. 21). It

FIGURE 21 - PUMP TESTS
City of Royal Oak, Michigan



has been reported that a yield of 1,400 to 1,500 gpm may be possible when both wells are operated at their maximum rates. Whether the water-bearing zone for these two wells continues southeastward as far as the Magnolia-Northwood stratum is not known, but on the basis of evidence it is doubtful. Thus the wells to each separate stratum may be operated simultaneously without creating interference between the two areas. However, additional wells of high capacity should not be drilled into these water-bearing zones unless thickness and areal extent of the zones are more fully determined by further test drilling. Once these facts are determined, it may be possible for additional wells to be constructed and spaced at such distances as to minimize well interference. Tracing of the Magnolia-Northwood and Cooper-Buckingham zones by test wells may or may not be worth the expenditure. This depends upon whether or not the zones are within the limits of the city. If without the city, additional restrictions might be imposed by other civil divisions of government. Where several communities are adjacent to each other and all are dependent upon a groundwater supply, a joint project may well be a constructive measure.

The Greenfield well (RO-35), completed in 1949, originally had a yield of 150 gpm, which by 1952 had declined to 80 gpm. The well is finished in coarse to medium gravel layers interbedded with silty or muddy sand. It is probable that the decline in yield resulted from the clogging of the coarser fraction by the movement of finer particles into the pore spaces. This is possible if the well is operated at such an excessive rate that flowage is turbulent thereby displacing finer particles around the screen area whenever the well is turned off. Such turbulent flow would be of short duration but effective in clogging the aquifer over a period of time. It also may be probable that the drop in yield has resulted from overdevelopment causing a decline in water level to such a depth that pump energy is expended in overcoming the added lift. Static level data are not available for the well, but it has been orally stated to the writer that the well temporarily recovers after resting for a period of two to three weeks. This suggests poor transmissibility of groundwater into the area and hence a resulting overdevelopment of the aquifer.

Information on the behavior of water levels is lacking, but available data concerning the city of Royal Oak wells are tabulated in the following chart:

WELL NO.	NAME OF WELL	ORIG. WL[1] AND YEAR	SUBSEQUENT WATER LEVELS
RO-45	Magnolia	60 ft. 1923	Feb. 1924— 57 ft.
			Aug. 1949—103 ft.
			Apr. 1950— 45 ft.
RO-46	Northwood	95 ft. 1942	1948—121 ft.
RO-29	Cooper	11 ft. 1928	1950— 36 ft.
RO-29A	Buckingham	37 ft. 1950	
RO-35	Greenfield	49 ft. 1949	

[1]Water level.

The 1949 and 1950 reported levels for the Magnolia well are somewhat enigmatic. It is possible that the 1949 reading was taken while the Northwood well was in operation, or else the 1950 figure may represent the amount of recovery, inasmuch as the Magnolia well is frequently kept out of service, owing to the mineralized quality of the water. If non-use of the Magnolia is the case, recovery would follow, assuming that the Northwood well was not in operation at the time that the 1950 reading was determined. From these meager data it can be assumed that (1) the decline is due to continued increased demands for water with the result that stabilization of the static level has not been reached, or (2) that the Magnolia-Northwood aquifer has been overdeveloped. To determine precisely what has taken place can only be ascertained by means of a comprehensive survey including some pump tests. From the figures that are available, if correct, it appears that the static levels for the Royal Oak municipal wells declined at an average rate of 1.5 feet per year.

The water-supply problem for Royal Oak has been currently improved though by no means completely. Of the five wells, the Buckingham and Greenfield are in operation and the others remain as standbys for emergencies. In 1951, fifty per cent of the water supply was drawn from wells and the rest obtained from the Detroit system. Completion in 1952 of a new transmission main, from the 1.5 million-gallon storage tank in the southern part of Royal Oak to the northern part of the municipality, permits the city to be dependent upon wells for only 20 per cent of its total demand. The storage tank is connected by a transmission main to the Detroit system. Thus only the northwestern part of the city of Royal Oak (area north of Webster Road and west of Crooks Road) is dependent on groundwater.

Southfield Township

The Southfield Township water-supply system serves only a small area near its single well (Pierce well SO-1) on Pierce Avenue in the northeast quarter of section 1. The well has a 12-inch diameter, a depth of 196.8 feet and is finished in coarse sand and gravel between 153 and 196.8 feet. It is rated at 444 gpm with a drawdown of 116 feet. With reference to the surficial geology, the well is just north of the Southfield spit (sections 1, 2, 12, and 13, Southfield Township), and with respect to the rock surface it occupies a position along the same tributary rock valley as the Lincoln, West and South wells of the city of Birmingham. The bottom-hole elevation of the Pierce well is 548 feet above sea level, which places it nearly at a level with the upper limits of the rock valley (550-foot contour). Since the log of the Pierce well ends in gravel at an elevation of 548 feet no data are available to show whether the sand and gravel continues to the floor of the bedrock valley. At this point, the rock-surface map indicates that the floor is 400 to 450 feet in elevation. Approximately 0.7 mile to the southeast from the Pierce well, and in line with the trend of the tributary rock valley, is a test hole (RO-27) drilled by the city of Royal Oak which penetrates 345 feet of drift before bedrock is reached. In the total depth of the test hole no sand or gravel stratum of any significant thickness was penetrated which might be suitable for development. The drift penetrated is principally clays and various mixtures of clay with sand and gravel. From the data it appears that the tributary rock valley at its junction with the main rock valley of the region is choked with sediments which are a part of the waterlaid Detroit Interlobate Moraine.

Data relating to the original and subsequent static levels of the Pierce well are not available since records have not been kept. Groundwater pumpage from the Southfield Township well has varied between 28 and 74 million gallons annually. Since 1947 the recovery of water has been increasing rapidly as indicated by the pumpage chart shown in Figure 18.

Troy Township

The Troy Township water-supply system serves a small area embracing parts of sections 20, 21, 28, and 29. Information regarding this water-supply system is either lacking or else was not made available to the writer during the course of field investigation. As far as it is known, the system consists of three wells; the latest

was drilled in 1950. Two of the wells are in the southeast quarter of section 20, one of which (TR-30) is on the Whittlesey beach. The well casing passes through 15 feet of sand and gravel, 90 feet of clay and till, and is completed in a gravel stratum between 105 and 123 feet. The water level in 1940 was reported at a depth of 36 feet below the surface. The most recent well (TR-50) is in the northeast quarter of section 29, approximately 1,700 feet southwest of well TR-30. Shale was penetrated from 145 to 200 feet, but the well was completed in good water-bearing gravel between 126 and 143 feet. The gravel was overlain by 126 feet of soft to hard blue clay. Static level and yield were reported as 60 feet and 500 gpm respectively. It appears that all wells are located in the same gravel stratum that is immediately above the bedrock surface which, in this particular area slopes to the south and southeast toward the tributary rock valley in Clawson.

Data relating to changes in static level are not available, but the two known reported water levels show a decline of 15 to 20 feet. Available figures show an average daily consumption of 32,000 gallons in 1940, increasing to 40,000 gallons daily by 1944. Since the overall population of Troy Township increased by 61 per cent, it is estimated that this system recovered approximately 55,000 to 60,000 gallons of water daily in 1950.

Bonnie Acres, Meadowland and Southfield Woods Subdivisions

Data relating to water levels, recovery, etc., for water-supply systems of subdivisions within the glacial lake plain area are lacking or incomplete. Data are not maintained because the responsibility of operating and maintaining the water-supply system frequently changes hands among the residents of the subdivision. The subdivisions listed are along the eastern half of sections 12 and 13, Southfield Township. Little is known regarding wells of the subdivision other than that they are in the area between the Whittlesey and Arkona beaches and with reference to the rock surface they occupy a position along the northern slope of a tributary rock valley which trends northeastward and joins the main valley. Annual groundwater recovery for the subdivision wells are shown plotted in Figure 18. The well for Bonnie Acres failed shortly after its construction, and by arrangement the community is now temporarily hooked to the Southfield Woods water-supply system. In recent years the demand for water has increased to such a point that officials of Southfield Woods have directed Bonnie Acres to

develop a separate supply, and a program to accomplish this is now under consideration.

Summary of Groundwater Pumpage

From groundwater production records maintained by five principal municipalities, two subdivisions and one township in the lake plain area, approximately 5.4 million gallons of water were recovered daily in 1950. This represents an annual recovery of nearly 2 billion gallons of water from the 24 municipal, subdivision, or township owned wells. It is apparent that the total groundwater recovery figure for the lake plain area is even considerably greater, since pumpage estimates for privately owned wells and other subdivision wells were not available and hence have not been included in the figure cited.

RECOVERY OF GROUNDWATER FROM OUTWASH AREAS

Outwash deposits of sand and gravel underlie one-third of Oakland County and are found in 21 of its 25 townships. The largest outwash area is between the morainic deposits of the Saginaw and Erie-Huron lobes, or more specifically in the interlobate area of the county. Scattered within this area are patches of morainic materials which form isolated hills, clusters of hills or ridges that rise slightly above the level of the outwash plains. The interlobate tract serves as the principal intake or recharge area for groundwater in the county. The principal water-table divide is in the more northwesterly part of the outwash where it merges with the unassorted till deposits of the Saginaw lobe. In addition to the interlobate tract of sorted drift other smaller areas of outwash materials are between the Inner and Outer Defiance moraines, and as patches scattered within the morainic tracts of the county. The data available record that yields from most of the wells drilled in the marginal outwash between the Defiance moraines are small, more than half of the wells having reported yields of 10 gallons per minute or less.

Wells completed in the outwash areas ranged in depth from 18 to 320 feet, the average depth being 92 feet. Approximately 68 per cent of the wells were less than 100 feet in depth, and had yields ranging up to 50 gpm. The casing diameters of the wells reported are from 2 to 12 inches; nearly 50 per cent of the wells are two inches in diameter. In general, 2-inch wells less than 100 feet in depth had yields up to 20 gpm, and 3- to 4-inch wells of

equal depth generally furnished yields up to 50 gpm. Six-inch wells had reported yields from 20 to 300 gpm, and wells having 8-, 10-, and 12-inch casings ranged in yield from 100 to 925 gpm. Depth was not of any particular significance since the large producing wells ranged from 50 to 320 feet.

The static level, on the basis of 146 records, averaged 33 feet and ranged from 1 to 192 feet below ground level. The groundwater in the outwash area is generally under unconfined or water-table conditions. Static levels of many wells harmonize with the levels of the inland lakes in the outwash plains. The majority of these lakes are in depressions that intersect the water table. The contour map of the water table in this area shows a more gentle slope of the water-table surface, which reflects the more permeable nature of the outwash deposits. In highly permeable sediments the water-table surface is less steep since a lesser hydraulic gradient is necessary to cause groundwater movement. A more highly inclined water-table slope develops in sediments of lower permeability. Thus, if a log of a well drilled in the outwash deposits records a water level at considerable depth below the surface, one can be fairly certain the well is on high ground that is underlain by very permeable materials. This fact is very clearly shown by well AD-6 the log of which reports a depth of 216 feet, all in gravel and boulders, and a water level of 192 feet. In checking this record in the field, the elevation of the well was determined to be approximately 1,200 feet, and hence its static water level was 1,008 feet above sea level. With respect to local topography, the well was near the crest of the Grampian Hills in the northwest corner of section 32, Addison Township. The static water level of this well stands approximately 20 feet higher than the water level of Indian Lake (988 feet a. s. l.), on the outwash plain near the edge of the Fort Wayne Moraine. The nearest shore of the lake is 0.7 mile south-southwest of the well. This difference in levels may be considered to represent the slope of the water-table surface for the distance between the lake and the well. The level (1,055 feet a. s. l.) of an unnamed lake within the Fort Wayne Moraine and about 0.3 mile southeast of the well is 47 feet above the static level of the Grampian Hills well. If all the data are correct, two explanations of the seeming discrepancy are possible: (1) that the steep slope of the water surface from the unnamed lake to the well indicates materials of low permeability that require a steeper hydraulic gradient for water movement, or (2) that the lake may be perched

over less permeable materials. Since natural materials are rarely totally impermeable, the condition described strongly suggests that many of the morainic lakes are reservoirs that help recharge the underlying sands and gravels. This form of recharge would be accomplished slowly and the lakes at the same time would maintain constant levels by surface drainage and by delayed run-off from the saturated materials that are at higher elevations or have perched water-table conditions. It is impossible to discount the significance of recharge by slow percolation from the morainic lakes to the buried aquifers of the moraines and glacial lake plain because of the volume of water that is involved. The course of water percolation to the aquifers must be somewhat complex since it follows lines of least resistance.

Although the groundwater in the outwash deposits is nearly everywhere under water-table conditions, emergence of flowing wells in this area is by no means surprising. Entirely structureless uniform materials are extremely rare under most natural conditions. Lateral changes in the physical characters of the sediments and vertical changes in various porosity-permeability relationships give rise to artesian conditions. Locally in the outwash areas confined structures may be produced merely by finer sands above and below a layer of coarse sand, a not unusual feature in stratified drift deposits. If such stratification is inclined, then artesian systems on a small scale result. This appears to be the situation for the flowing wells located along the slopes adjacent to Crescent Lake in Waterford Township. One of the flowing wells (WA-66) has a total depth of 120 feet and its log shows 60 feet of gravel overlain by fine sand. Since these conditions are very local the static levels of flowing wells were discarded in the determination of the average depth to the water table in the outwash area.

On the basis of 129 records the average yield from wells in the outwash deposits is 70 gpm with a range from 1 to 925 gpm. A breakdown of the reported yields indicates that 64 per cent of the wells have yields up to 20 gpm, 21 per cent from 21 to 100 gpm, 12 per cent from 100 to 500 gpm and 2 per cent from 500 to 1,000 gpm. The 15 records show a range in specific capacities from 1.5 to 27 gpm per foot of drawdown and an average of 13 gpm per foot of drawdown. Proper development of most of the individual wells would result in greater individual yields. In a comparison of the data relating to depths, yields, specific capacities and water levels between the wells in the outwash with wells of the lake plain, no

marked differentiation is apparent. In fact, the determined averages show that the lake plain section is more favorable for groundwater recovery than the outwash. However, in evaluating the averaged results, consideration must be given to the number of wells drilled, their diameter size, yield and development. Since the lake plain section is highly urbanized, well drilling activity has been directed toward large-diameter screened wells many of which are gravel packed or otherwise developed. These conditions tend to increase the average yield and specific capacities for the wells in the lake plain area. The reported diameters of wells reported in the outwash section never exceeded 12 inches, and nearly 50 per cent of them were two-inch wells with yields up to 20 gpm. In the lake plain many 6-inch wells reported yields considerably less than 20 gpm, and the number of dry holes was definitely greater.

A comparison of the static levels between the two areas also may be misleading unless consideration is given to the confined or unconfined occurrence of the groundwater. No significant decline of the water-table surface in the outwash area has been indicated since 1930, as comparison of the two water-table maps will show. The lake plain, on the other hand, has had a decline in the piezometric surface, indicated by the increase in the number of new wells drilled between 1940 and 1950 that were non-flowing in an area which prior to 1910 generally produced flowing wells.

RECOVERY FROM SPECIFIC AREAS IN THE OUTWASH PLAINS

Village of Oxford

The village of Oxford is on a broad plain of outwash sand and gravel between two well defined morainic ridges left by the retreat of the Saginaw ice lobe. The western and more distant morainic ridge rises to elevations of 1,100 feet, and the ridge to the east attains elevations between 1,150 and 1,200 feet above sea level. The average elevation of the plain where the village is situated is 1,050 feet. Within this broad gravel plain surrounding the village are a number of inland lakes, several of which are without surface inlets or outlets and hence represent exposed portions of the water-table surface. North and east of the village a few abandoned gravel pits have been filled by groundwater and formed new lakes. The bluffs of the abandoned and water-filled gravel pits have been graded and the resulting lake frontage subdivided into plots for real estate development.

The water-supply system for the village is near its eastern limits on slightly higher terrain adjacent to a broad, shallow, partly marshy, depression. In the marshy area several small lake basins, developed in sand and gravel, extend to the water table. The old water-supply system for the village (Leverett, 1906-07) consisted of five wells, each six inches in diameter and driven in gravel to a depth of 85 feet. The reported water level prior to 1910 stood at 8 feet below ground level and was not materially affected under ordinary pumping conditions. Under a pumping rate of 650 gpm a drawdown of 10 to 12 feet was reported, giving a specific capacity of 54 gpm per foot of drawdown.

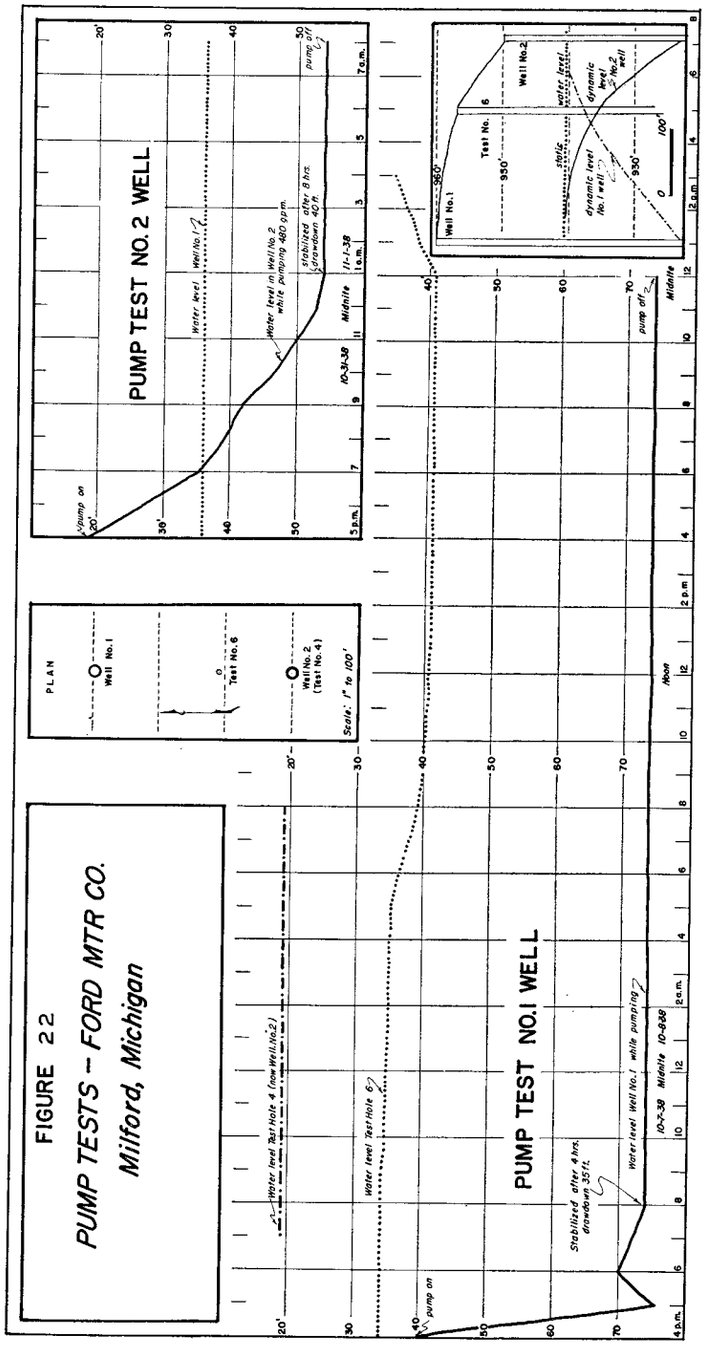
Records relating to the present village water-supply system show that it consists of five wells, six to eight inches in diameter and 90 feet deep with a static level of two feet below the ground surface. The individual wells have reported yields up to 300 gpm. Recovery for 1950 was approximately 98 million gallons or an average of 265,000 gallons per day. Depending upon the season and the climatic variations during each season, the pumpage for the village has varied between 225,000 and 512,000 gallons daily. As far as the writer knows the inhabitants of the village have never experienced a water shortage, and from all apparent indications the available supply is very good.

Village of Milford

Milford is along the banks of the Huron River at its junction with a tributary stream which flows from the north. The village is underlain by deposits of interlobate outwash and morainic materials. The outwash for the most part is along the east-west trend of the Huron River and north-south trend of Pettibone Creek valleys. The morainic deposits form hilly terrain on the northeast, northwest and south sides of the village. In 1895 the village obtained its water supply from a series of shallow wells located along the bank of the Huron River. The present day system consists of two 10-inch wells drilled in the outwash along the north side of the river in the southeast quarter of section 10, Milford Township. In addition to these wells the village has an elevated standpipe added to its system with a capacity of 150,000 gallons. The present wells (MI-6 and 7) are 117 and 124 feet deep and penetrate sand and gravel deposits throughout their entire depth. Both wells are completed in very coarse to pebbly or pea-size gravel. The reported static level in 1950 was 7 feet for the shallower well and 2 feet below ground surface for the deeper one. The deep well was flowing in 1937. The wells are capable of 500 gpm each and are operated alternately. Both are ideally situated for natural recharge by precipitation and by induced infiltration from the Huron River in the event excessive pumpage lowers the water table below the level of the stream. Conditions within and adjacent to the village are adequate for additional supplies of water to meet any future demands imposed by a growing community.

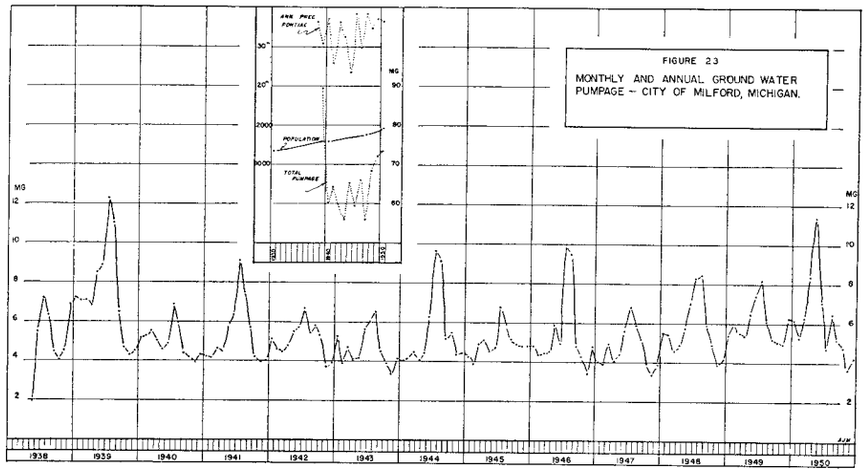
A test hole (MI-2), drilled by the village in 1938 on a morainic hill to the northeast at an approximate elevation of 1,000 feet, was reported as a dry hole. The test hole has a reported depth of 127 feet; the upper 80 feet logged gray clays and silts and the remaining 47 feet logged sands and gravels of various admixtures and coarseness but with very little clay. West of the morainic hill the outwash-filled valley of Pettibone Creek has an elevation of 940 feet. The water table in this vicinity lies between 900 and 925 feet above sea level, which is considerably above the bottom-hole elevation (873 feet) of the test hole. The log of this test bears no reference to any water-bearing stratum, nor is any static level indicated. If the ground elevation of the test hole is correctly determined, it appears logical to assume that the water table was penetrated and that the test hole was reported dry because the desired yield for a municipal well could not be obtained from the sands and gravels penetrated. It is possible that an incorrect location is given for the well and that the correct location might report the mouth of the test hole at a higher elevation. If so, it is conceivable that a dry hole resulted because drilling was halted before the water table was reached. This discussion is included in order to bring out the importance of extending any test through coarse sediments rather than stopping at a predetermined depth.

In the northeast quarter of section 10 within the limits of the village two industrial wells (MI-4 and 5) serve the carburetor plant of the Ford Motor Company. Both are in the outwash deposits confined between morainic hills on either side. The wells penetrate sand, gravelly in places, to a depth of about 80 feet before clay or clay and boulders are reached. The wells are spaced 300 feet apart and are capable of producing 500 gpm each. Well No. 1 (MI-4) has a reported static level of 39 feet and a stabilized drawdown at 74 feet below surface after four hours of pumping. The No. 2 well (MI-5) has a static level of 19 feet and a stabilized drawdown at 54 feet after eight hours of pumping. As shown



by the pumping test (fig. 22), the operation of either well does not affect the water level of the other. The cone of influence about Well No. 1 has a radius between 190 and 300 feet. Recovery of the static level for each of the wells was not determined after pumping was stopped. The water pumped from both wells is used for air conditioning and general plant purposes but not for drinking and sanitation.

Groundwater recovery for the village of Milford has varied between 56 and 89 million gallons annually. In general the increase has been gradual. The peaks of the groundwater-pumpage curve correspond to the troughs of the precipitation curve. The high



pumpage of 89 million gallons in 1939 (fig. 23) may include a considerable quantity of water used by the Ford plant during its construction or prior to the installation of its own private wells used for air conditioning purposes. In the latter part of the 1940-1950 decade an annual increase in groundwater pumpage is noted, which is attributed to the increase in village population and new construction. To date, no ban has ever been in force on the excessive use of water during the summer months for any purpose. Average daily pumpage fluctuates between 135,000 and 368,000 gallons, depending upon the season of the year.

Village of Lake Orion

The village of Lake Orion is on outwash deposits of the interlobate tract adjacent to the Fort Wayne Moraine. The water-supply

system consists of 2 wells and a standpipe which are in the southeastern part of the village. Well No. 1 (OR-9) is 12 inches in diameter, 137 feet deep and completed in coarse to pea-size gravel between 108 and 137 feet. Excepting two layers of clay from 3 to 5 feet, the materials penetrated by the well consist entirely of sand and gravel. The static level reported in 1930 stood at 13 feet with a stabilized dynamic level at 52 feet below the ground surface while the well was operated at its capacity of 925 gpm. The No. 2 well (OR-8) was completed in 1938. It is an 8-inch well, 172 feet deep and finished in water-bearing gravel between 100 and 172 feet. The static level in 1938 was 8 feet with a reported yield of 650 gpm and a stabilized pumping level at 35 feet below ground level.

Groundwater-pumpage data are not available as records have not been maintained. On the basis of the village population it is estimated that an average of 240,000 gallons of water are recovered daily. Like the village of Oxford, this community is favorably situated in the event that a greater supply of water is demanded. Within and adjacent to the village are a number of water-table lakes. As far as the writer knows, the village has never imposed restrictions on the use of water for any purpose.

Village of South Lyon

The village of South Lyon is underlain by interlobate morainic and outwash deposits. Its water-supply system consists of two wells (LY-4) approximately 50 feet apart and an elevated standpipe, all of which are in the southwest quarter of section 20, Lyon Township. The wells, drilled into morainic deposits, are approximately 82 feet deep and are completed in 24 feet of coarse to medium gravel. Both are 10 inches in diameter and are pumped at 350 and 450 gallons per minute.

Recovery of water is estimated at 480,000 gallons daily. This figure may seem exceptionally high for a village of slightly more than 1,300 inhabitants. However, an average of 300,000 gallons per day is utilized by the Michigan Seamless Tube Company. No restrictions have ever been placed on water consumption in this community. No lakes are in the immediate vicinity of South Lyon, but marshes are in the valleys and in low areas of the outwash deposits which surround the isolated patches of moraines and till plains.

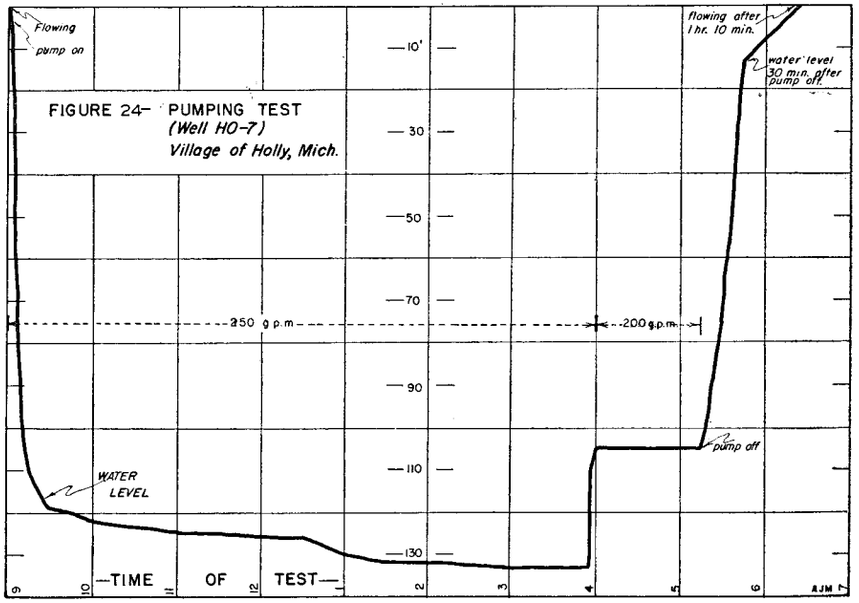
Village of Holly

The village of Holly is built on a sandy-gravelly plain traversed by the Shiawassee River which flows northward through the western part of the village, and thence swings sharply to the west just beyond the northern limits of the village. To the southwest, south and east are moraines and till plains deposited by the retreat of the Saginaw lobe which formed the higher land now surrounding the village on three sides. Small lakes are on the outwash and unassorted till deposits, and several lakes are along the major stream courses, showing the imperfect drainage in the area. The surficial map (fig. 2) shows that the village of Holly occupies a position along a former marginal drainage channel where the Saginaw lobe halted in its northerly retreat. This southwest-northeast channel, underlain by deposits of sand and gravel, is now traversed in part by the Shiawassee River, Swartz and Thread creeks. Because a higher terrain borders the marginal outwash, recharge by direct precipitation, slope run-off, delayed run-off and induced stream infiltration is possible. Hence the physical conditions of this area are very favorable for a large recovery of groundwater.

According to Leverett (1906-07), the original water-supply system consisted of 9 or 10 flowing wells, each 6 inches in diameter and from 23 to 47 feet in depth. The wells were in the southern part of the village at the edge of a marsh near the site of the present waterworks. Owing to contamination by seepage, the incrustation of the screens and the inflow of sand, the wells gradually became unfit for operation and were abandoned. At the time of Leverett's investigation the shallow wells were being replaced by others having depths of 140, 155, and 180 feet. In addition, a deep well (HO-5) was drilled to a depth of 670 feet; rock was penetrated at 265 feet and below that level the well was drilled through the Lower Marshall formation and into the Coldwater shale. The mineral quality of the water rendered it unsuitable for a public supply. The casing was withdrawn to 180 feet, where a 10-foot layer of water-bearing sand and gravel had been previously cased off during drilling. The remainder of the hole was plugged. The log of the well also shows the presence of a 35-foot layer of sand and gravel overlying the bedrock, but this water-bearing zone was abandoned because of the infiltration of highly mineralized water from below.

The present water-supply system consists of three 10-inch wells

located in the same area—the northwest quarter of section 34, Holly Township. Two of the wells (HO-6 and 6A) are approximately 50 feet apart, and though originally drilled to a depth of 200 feet, were completed at a depth of 105 feet. The water-bearing strata consist of layers of fine gravel and coarse sand fifteen feet thick which are underlain by clay and hardpan. When completed in 1938 both wells were flowing, but in 1950 the static level was reported between 6 and 8 inches below the ground surface. The wells are currently equipped with 250-gpm pumps although initial pump tests indicated a capacity of 470 gpm each. The third well (HO-7) of the present series was constructed in 1947. The original hole was drilled to a depth of 220 feet, but the well was finished at a depth of 170 feet. The water-bearing zone is 15 feet thick between 155 and 170 feet and consists of a layer of sand over a layer of gravel. It is underlain by a mixture of clay, sand, and gravel 50 feet thick, and overlain by a stratum of blue clay 78 feet thick. Between the top of the clay and the surface the materials are outwash gravels. The log does not describe the nature of the clay, and it remains undetermined whether the clay is of glacial or lacustrine origin. The occurrence of outwash materials above and below the blue clay may be accounted for by a fluctuating ice front.

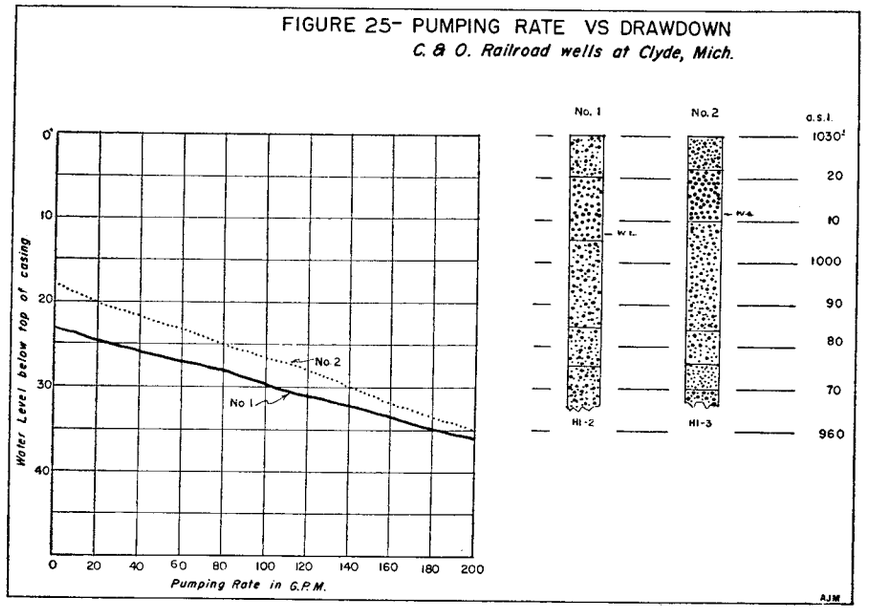


The well has been flowing since its completion, its yield being 250 gpm while pumped. Figure 24 illustrates the decline in the static head while the well is in operation. The graph shows that the head drops considerably within the first 10 minutes of flow and then declines gradually until stabilization is reached at 133 feet. Recovery of head is rapid after pumping has stopped, being 14 feet below surface after 30 minutes and flowing after one hour and 10 minutes. The rapid decline and recovery shown in the curve are typical of confined groundwater conditions. The artesian condition in this area is not at all unusual, since minor variations in the movement of the ice front may have caused the deposition of clays and till over coarser waterlaid sediments, thus creating local conditions of confinement. The high land to the south, east and west and the lakes thereon provide the necessary head.

Exact groundwater pumpage data were not available, but the average daily pumpage in 1949 was estimated at 300,000 gallons. In the last decade no shortages were experienced, and the present system adequately supplies the 2,644 inhabitants of the village.

Chesapeake and Ohio Railway Water Station

The Chesapeake and Ohio Railway maintains two shallow wells (HI-2 and 3) 64 feet deep near Clyde, Michigan. The location of



the wells is in the northwest quarter of section 10, Highland Township. Both are 12-inch wells drilled in the interlobate outwash deposits. The static levels are 18 and 23 feet below the surface and harmonize with the lake levels in the immediate vicinity. The wells are operated at 200 gpm, and the water is utilized in boilers of steam locomotives. The nature of the outwash sediments is shown by Figure 25, which also shows the relation of yield to drawdown. The trend of the curve suggests that the materials are of favorable permeability and that a greater recovery is possible.

Summary

From the conditions described in the preceding paragraphs it is evident that additional large supplies of water can be developed from the outwash deposits within the county. The amount pumped by the principal communities within the outwash area is estimated at 1.6 million gallons of water daily, which represents but a small recovery compared with recovery from the glacial lake plain or the moraine-till areas.

RECOVERY OF GROUNDWATER FROM THE MORAINE-TILL PLAIN SECTION

The moraine-till plain areas are two ranges of hills trending northeast-southwest and separated by interlobate deposits consisting primarily of outwash and some scattered patches of unassorted till. With respect to the bedrock surface, a morainic belt of hills has been deposited on opposite sides of the bedrock divide. The nature of the morainic deposits is revealed by a series of northwest-southeast and northeast-southwest profiles (M through P) drawn through the Pontiac region where the data are most abundant (fig. 26). The drift in places exceeds 300 feet in thickness and consists of unassorted till with interbedded layers of coarser clastics, which are of diverse distribution and dimension. The topography of the moraine-till areas may be described as hilly, pitted with numerous depressions many of which contain lakes or marshes which serve as reservoirs for the surface run-off water. If one bears in mind the position of the groundwater divide and the relationship of the hilly morainic ridges to the outwash, it is apparent that the groundwater in the buried sands and gravels of the morainic belts is under confined or artesian conditions. Groundwater under water-table, or possibly perched, conditions is restricted principally to the coarse clastic sediments deposited at the surface.

In contrast to the lake plain section, the recovery of groundwater from the moraine-till plain region is more favorable for several reasons. The average drift cover is considerably thicker, it contains a greater number of interbedded sand and gravel strata, and its topography and nearness to the interlobate outwash provides more adequate recharge directly by precipitation, or indirectly by percolation from the major intake area. Wells of moderate yield are very common in this region. Greater yields for industrial or municipal purposes are possible, but generally a test-drilling program is necessary to locate large deposits of favorable water-bearing materials. The profiles show a number of sand and gravel strata containing some clay and silt which may be potential aquifers if the finer sediments are removed by proper well-development techniques.

On the basis of 284 records the depth of wells in the moraine-till areas ranges from 24 to 330 feet and averages 129 feet. Such wide range in depth is to be expected in areas covered by glacial deposits. The profiles illustrate clearly the diverse deposition of coarser clastics with depth and areal distribution. The shallow wells of the area reveal water that is more likely to be under water-table or perched conditions. The deeper wells that reach buried aquifers yield water under artesian conditions. Of the total number of wells, 50 per cent are less than 100 feet in depth, 34 per cent are between 100 and 200 feet, 14 per cent are between 200 and 300 feet, and 2 per cent are more than 300 feet in depth. As a rule, the most productive wells are more than 150 feet in depth and most of them are in the urbanized areas of the moraine-till plain region.

In wells tapping confined sand and gravel beds, the static water level averages 43 feet below ground surface and ranges from 17 feet above to 165 feet below ground surface. The wide range in reported static levels is in part attributable to the topographic differences in elevation, and in part to the fact that a number of confined aquifers, rather than a single aquifer, are involved. Since there may be an appreciable change in permeability between aquifers, the variation in the static water level is a natural consequence of such change.

From 208 records, the average yield of wells regardless of size is 99 gpm with a range from 2 to 1,225 gpm. In contrast to the lake plain section the range and average yield do not strongly indicate that recovery of groundwater is more favorable from the areas of moraine and till deposits. However, 52 per cent of the reported yields were up to 20 gpm, 35 per cent between 20 and 100 gpm,

4 per cent between 100 and 500 gpm and 9 per cent between 500 and 1,300 gpm. The number of dry holes in this area is nearly negligible in comparison to the lake plain section. Wells from 2 to 4 inches in diameter had reported yields up to 200 gpm but generally produced between 10 and 30 gpm. Six-inch wells varied in yields between 10 and 300 gpm, eight-inch wells between 40 and 900 gpm, and 10- to 14-inch wells from 200 to 1,300 gpm. Specific capacities of 23 wells for which data were obtained ranged from 0.1 to 110 gpm per foot of drawdown and averaged 11.8. The high specific capacities generally were reported for the larger diameter wells.

RECOVERY FROM SPECIFIC AREAS IN THE MORAINE-TILL PLAIN SECTION

City of Pontiac

The city of Pontiac is on the Fort Wayne-Inner Defiance moraines and hence most of the city is underlain by non-stratified drift, excepting the southwest, northeast and northwest corner areas where outwash or lacustrine deposits are at the surface. A series of profiles was constructed through the Pontiac area and shown on Figure 26, but only Profile M reveals a large and significant aquifer. On the map of the region this profile roughly follows the trend of the Clinton River which winds its way through the city from west-southwest to east-northeast. Other profiles, constructed to the north and having nearly the same trend as Profile M, fail to reveal any other large potential aquifer, but show a juxtaposition of smaller bodies of coarser clastics within the more abundant till. The profiles constructed along a northwest-southeast trend likewise do not reveal any continuous body of coarse clastics except where the individual profiles intersect Profile M. It appears that the narrow belt of coarse clastics, as defined by the profiles, probably represents a buried marginal outwash that was deposited between the higher southeastward sloping terrain immediately to the northwest and the ice front to the south. Such an inference would account for the confinement and continuity of the outwash in a narrow belt. With available data, the outwash can be traced for nearly 4.6 miles —from a point in the southeast quarter of section 31 to the northeast quarter of section 22, Pontiac Township. As indicated by the profile, the outwash along the principal axis of the deposit is predominantly composed of gravel, or gravel and sand admixtures, but probably becomes more sandy northwestward, as suggested by the

logs of test holes drilled elsewhere. The depth to the buried outwash is from 80 to 175 feet (or at elevations of 735 to 815 feet above sea level) depending upon the irregularity of the topographic surface and of the upper surface of the deposit. The thickness of the outwash deposit as shown by the wells and test borings ranges from 10 to 120 feet, but 40 to 70 feet seems to be the average depth of penetration. Many borings did not reach the lower limit of the deposit, nor was bedrock penetrated by any borings that were drilled through the outwash. Apparently till is beneath the outwash and over the bedrock surface. In the southwest area the buried outwash is overlain by a "hardpan" which was either not recognized or not present elsewhere along the line of profile. The width of the marginal outwash deposit is difficult to ascertain, but it varies at least between 1,100 and 2,100 feet as approximated from the profiles and from the areal distribution of the wells and test holes in the vicinity of the profile. Not all logs shown are exactly along the line of profile, a number of them being offset from their true position to the line of profile. The maximum linear distance measured in a northwest-southeast direction is 2,100 feet between the most distant wells on opposite sides of the profile line. The known width may be increased as additional data are made available. The age of the outwash is not definite, since it is difficult to determine whether the coarse clastics separate Wisconsin from pre-Wisconsin till, or whether the sediments in question represent a substage (Cary-Tazewell), or a minor fluctuation within a substage, of the Wisconsin. The only evidence indicating an older surface of glacial deposits is a few scattered oxidized zones of different depths as shown on the profiles. From available data only a pre-Fort Wayne age can be ascribed for the buried marginal outwash, but more data may determine a more exact age.

The buried outwash is the largest known aquifer of the region and is currently tapped by eighteen municipal wells. Eight of the wells have been drilled at or near the site of the Walnut Street filtration plant (NW¼ sec. 32) in the southwestern part of the city. For record keeping purposes, the city of Pontiac has designated this group as the "Low Service" wells and lists them by number. The remaining ten wells constitute a group designated as the "Outlying" wells inasmuch as the individual wells were drilled beyond the limits of the filtration plant area and roughly along the course of the Clinton River. Wells of this group bear street names. Most of the municipal wells are plotted along Profile M. Additional wells for

municipal or industrial supplies are of possible development in the more promising sand or gravel zones that are elsewhere in the area, particularly north of the Clinton River. Such possible development is indicated by the three wells (PO-39, 40 and 41) owned by the General Motors Corporation located northwest of the buried outwash in the northeast quarter of section 20, Pontiac Township. All three wells tap water-bearing sands, or sands and gravels at depths below 200 feet, and have a combined capacity of 2.6 million gallons daily. Many places have potential water-bearing zones that are admixed to some degree with silts and clays, which reduce permeability and therefore reduce the yield of the aquifer. These aquifers may be developed by properly sampling the zone for mechanical analyses of the sediments in order to determine the effective grain size and therefore to make selection of a proper screen. By installation of the correct screen the well could be properly developed by the surging method. The effective grain size determines the slot of the screen to be used so that during surging operations grains smaller in diameter than the effective grain size are removed from the water-bearing sediments in proximity to the well screen. Surging increases permeability and an increased yield results. Where deep test holes reveal more than one potential aquifer, it may be profitable to screen and develop each of the zones penetrated.

From the conditions shown by the profiles and from the data collected on reported yields, it is reasonable to conclude that moderate to large supplies of water are possible from many zones in the morainic belts, and that dry holes are uncommon in contrast to the lake plain section. Additional large supplies are possible in the areas underlain by moraines, but test drilling will be necessary to locate and define the limits of the larger bodies of coarse clastics. Although the volume of water-bearing sands and gravels may appear much less in contrast to the volume of till, it must be appreciated that the till is capable of an immense storage of water which slowly but surely finds its way into the more permeable zones.

The area, from its relation to the interlobate outwash, is favorably situated for recharge by percolation of groundwater from the northwest and by direct precipitation falling upon the area. The nature of the topography (lakes, depressions) retards loss by direct run-off. The profiles of the area lead to the inference that percolation of water through the tills is most rapid in the coarser fractions, and that the path followed by any particle of water is very complex.

Records on groundwater pumpage for the city date back to the year 1913, but have not been maintained consistently on a monthly basis. For the period 1913-1930, the pumpage is graphically shown in an earlier groundwater report of the Pontiac region (Taylor, 1930, p. 69). For the period 1927-1950, the total monthly pumpage is graphically represented on Figure 27 with other data relating to monthly precipitation, temperature and static water level. Taylor's chart reveals a gradual increase in groundwater pumpage from a daily average of two million gallons in 1913 to eight million gallons in 1929. The only decrease in groundwater pumpage prior to 1929 took place in the period when the city was dependent upon a surface-water supply. For the period covered by Taylor's report, the recovery of groundwater up to the year 1924 was entirely from wells in the area of the Walnut Street plant, but as demands increased, additional wells were gradually drilled in the outlying areas. The pumpage curve shows a steep upward trend from 1924 until 1929. Total pumpage from the outlying wells quickly exceeded the combined pumpage from wells at the Walnut Street plant.

On the pumpage chart included in this report a progressive decline is shown from 1930 until 1932—the worst year of the business recession. Since 1932 the quantity of water recovered has progressively increased from an average pumpage of 4.4 mgd in 1932 to 12.2 mgd in 1950, or an annual total of 1.6 to 4.5 billion gallons of water respectively. The occasional interruptions in the upward trend of the pumpage curve are clearly related to historical and hence economic events of the past two decades. The business recession is clearly shown by the pumpage curve from 1929 through 1930; the increase in pumpage from 1934 through 1937 reflects the economic activity initiated by the passage of such federal measures as the W.P.A., H.O.L.C., C.C.C. and the payment of the Soldiers' Bonus in 1937. A minor recession is shown in 1938, after which the pumpage curve continues upward into the year 1945. This particular trend reflects increased production resulting from unstable world political conditions and the advent of the second world war. The termination of World War II, in Europe and in Asia, is marked by the sharp decline of the curve between August and October 1945. The conspicuous low in the curve, appearing in late 1945 and early 1946, is the effect of the record-breaking strike of General Motors Corporation employees, which lasted 113 days, commencing November 21 and terminating March 13 of the following year. From the spring of 1946 through 1950, the trend of the curve rises sharply

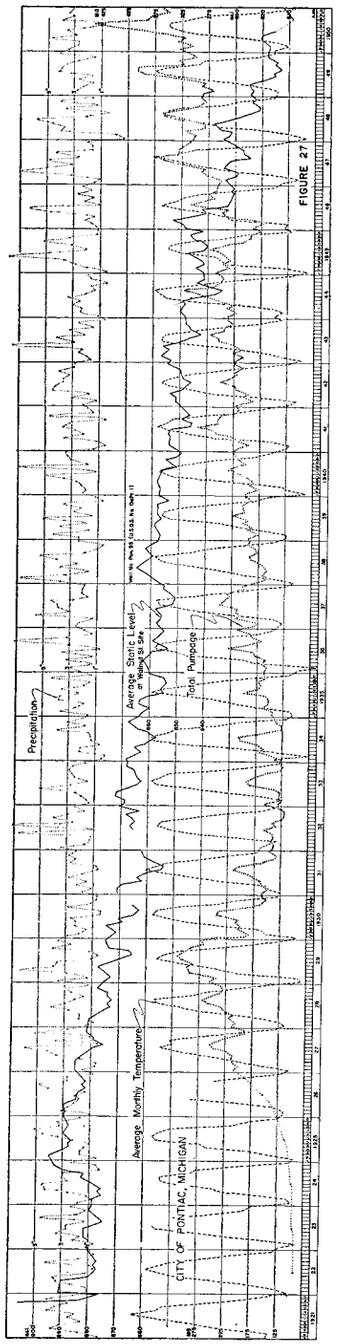


FIGURE 27

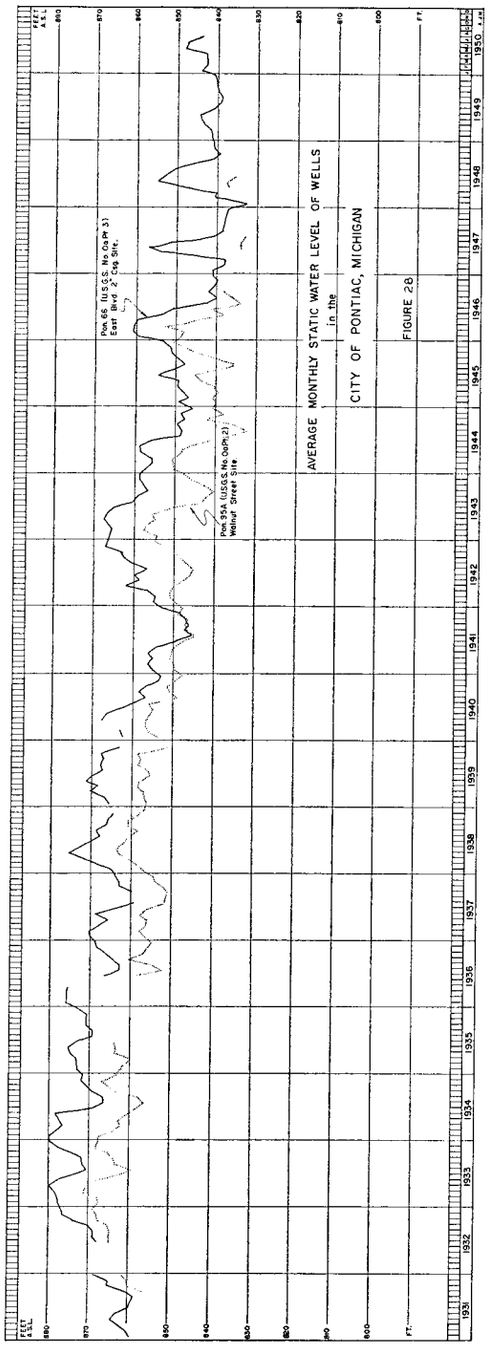


FIGURE 28

and reflects the effects of increased population, postwar construction, and increased production of civilian goods.

From the examination of the water-pumpage curve for each year some specific trends or patterns become evident. Maximum pumpage is generally in July or August and minimum pumpage in February. The peak as a rule correlates with the driest month, and its magnitude is dependent upon the amount of precipitation that fell upon the area during the month for which the high is registered. In general, heavy groundwater withdrawal is from June through September. The pattern of the curve for the years 1929, 1937, and 1941 is somewhat unusual in comparison to the pattern for other years since the trend is in the form of broad inverted U's rather than V's. In each year a sharp increase in pumpage was somewhat earlier than usual (March or April) and then declined abruptly in November. The nature of the curve for these years is suggestive of more than usual activity, and appears to correlate with activity in building and employment. The detailed study of pumpage curves should prove interesting in revealing the habits of a community.

The water-table map of Oakland County indicates a depression in the piezometric surface which corresponds with the trend of the buried outwash in the city of Pontiac. The depression represents an area in which the static head has declined because of heavy groundwater withdrawal. The rate of decline is usually represented by means of hydrographs constructed from static-level data collected systematically over a period of years. For this area, such data have been collected more or less continuously since 1921. The first wells drilled for the Pontiac water-supply system date back to 1888 and were located at the site of the present filtration plant in section 32. The wells, all approximately 175 feet deep, tapped the same water-bearing outwash, and the static water level at the time stood at ground surface, or at an elevation of 919 feet above sea level. According to Taylor (1930, p. 1) water from these wells was pumped by direct suction, and as the head gradually declined, owing to increased demands, a lowering of the pumps was periodically necessary to maintain suction. Static-level data are not available for this early period, but by 1917 the situation demanded new wells completed with an air-lift system. By 1918, the static head stood at 886 feet, at which time a decision was reached by the city officials to abandon groundwater as a source of supply, and to develop the surface waters of the Clinton River. The filtration plant was completed and in use by 1921, but because of high tempera-

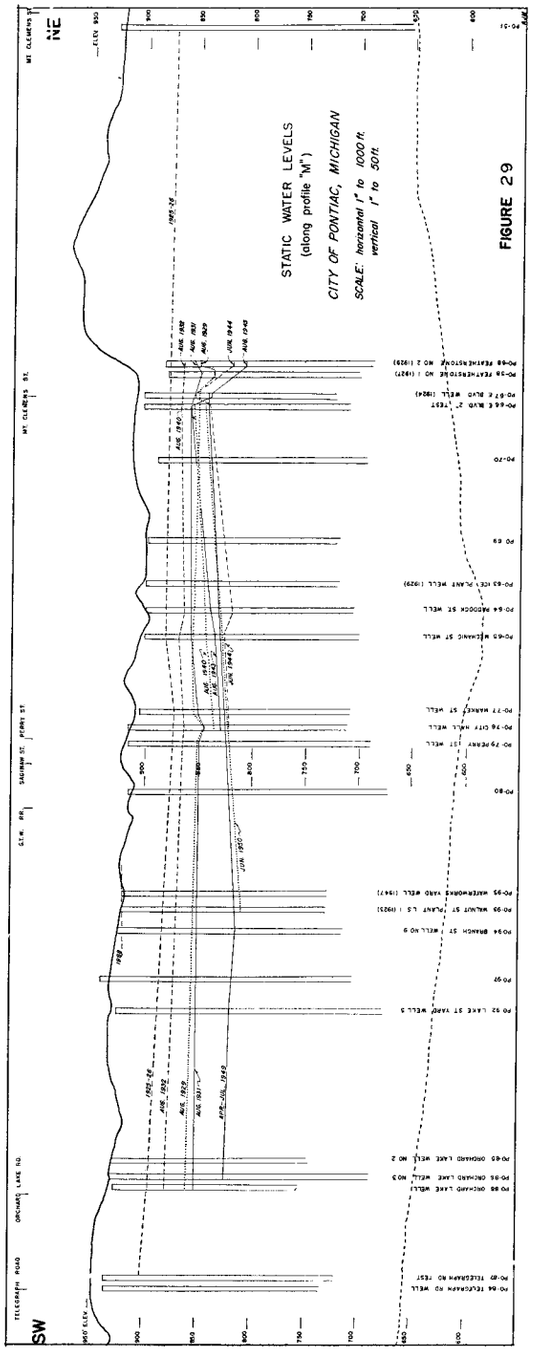
tures and the unfavorable taste and odor associated with the surface water, use of surface waters was shortly discontinued. Since then the city has been entirely dependent upon a groundwater supply.

The static water level at the site of the filtration plant from 1921 through 1930 is shown on the hydrograph (PO-95) contained in Figure 27. This part of the graph has been extracted from Taylor's report (1930, p. 69) and appended to the hydrograph constructed from data obtained by the writer for the same area. In 1921, at the time surface waters were utilized, the static head stood at 906 feet, after which a rapid decline is noted and a level of 875-880 feet established for 1922-1924. This drop is attributable primarily to heavy groundwater pumpage after the city reverted to a groundwater supply. In part, the decline was caused by a deficiency of precipitation, as annual precipitation ranged from 4 to 9 inches below normal for a period of years. The rise in head shown in 1924 was partly owing to increased precipitation and partly due to the fact that new wells were in service in the outlying districts, thereby spreading the pumpage demands over a larger area. From 1925 the head continued to decline until the water level at the Walnut Street site in 1930, according to Taylor (1930, p. 1), represented a total decline of 50 feet since 1888. The mean elevation thus stood at 869 feet, and the loss in head spread over the period of 42 years represents an average decline of 1.19 feet per year. For the period 1931-1950, the static water level of the confined stratum of buried outwash is shown by the hydrographs PO-95, 95A, and 66 (figs. 27 and 28). The hydrographs are for wells PO-95 and 95A located at the Walnut Street plant. Hydrograph PO-66 is for a test well which taps the same buried outwash as the others, but is located approximately 2 miles northeast of the filtration plant. The hydrographs are also designated as OAPt-1, 2, and 3, respectively, so that reference can be made to water-supply papers published annually by the U. S. Geological Survey that contain data on water levels and artesian pressures in the United States. It will be noted that the trends of the curves in all three hydrographs are remarkably similar. Hydrographs PO-95 and 95A, may serve as checks against each other. As a rule, the peaks and troughs of the hydrographs correspond to the troughs and peaks of the pumpage curve. When such a relationship is not evident, then its absence may be attributable to such factors as a more equitable distribution of rainfall throughout the year, an exceptionally cool but wet summer, and a pronounced variation in groundwater pumpage as the result of

economic conditions, or any combination of the factors. From the pattern shown on the hydrographs recharge is greatest in the early spring, a time coincident with mild temperatures, fairly low groundwater pumpage, and small loss of water through plant activity. Recharge is also possible during the early fall season when losses by plant transpiration are again at a minimum, provided that sufficient precipitation occurs and the ground surface is not frozen. Both seasons of recharge may occur since precipitation in this region is not seasonal, periods of heavy precipitation being possible at any time of the year.

Excepting a slight recovery in head coincident with the business recession, the trend of the curve for each of the hydrographs has been continually downward even though precipitation in later years has been at, or above, the annual average. The minor upward trends correlate with the pumpage chart and reflect again the major economic and historical events of the past two decades. In comparing the hydrographs with the pumpage chart it is evident that equilibrium of the head has not been established since 1888, and particularly since 1932, except possibly for extremely short periods.

The mean static level at the Walnut Street plant stood at 815 feet in 1950, or 54 feet below the mean of 1930. In the twenty-year period this change represents an average decline of 2.7 feet per year, which is more than double the rate for the period before 1930. This higher rate reflects greater pumpage; the maximum month in 1930 averaged 8 mgd in contrast to 16 mgd for the maximum month in 1950. Thus, at the Walnut Street area the static level has declined from 919 in 1888 to 815 feet in 1950. This is a difference of 104 feet which if prorated over the interval represents an average decline of 1.68 feet per year. It may be of interest to note that the static level of 815 feet places the head approximately 30 feet above the uppermost limit of the confined aquifer at the filtration plant site. It might be well to point out again that if withdrawal of water continues to increase, the static head of an artesian aquifer can be reduced below the bottom limits of the upper confining bed. Thus the upper part of the confined aquifer is then unwatered, and the plane of saturation within the aquifer becomes a water table. The storage capacity of the saturated part of the aquifer becomes typical of unconfined water conditions. Under these circumstances the rate at which the water table declines will be reduced, but the cone of depression will continue to develop until it diverts enough water into the pumped well or wells. The size and extent of the



buried outwash is then important since it will determine the storage capacity of the aquifer and control the rate at which the cone of depression will develop. Thus it is very possible to rapidly dewater the Pontiac stratum (buried marginal outwash) if additional wells that tap this aquifer are completed. During the period covered by the hydrograph of well PO-66, the static level declined approximately 21.5 feet or at a rate of 1.19 feet annually. It is again brought to the attention of the reader that the decline in head has not been continuous since 1888, as the hydrographs of the wells and the static water levels plotted in Figure 29 indicate. The occasional upward trends, however, are primarily attributed to a decrease in groundwater withdrawal rather than to an increase in the amount of precipitation.

In May 1930, a test of the Pontiac stratum (Taylor, 1930, p. 127) was made to evaluate the relationship between the average lowering of the static head with the yield obtained. All but four of the twelve municipal wells were pumped simultaneously. Two tests of the stratum were made. The first continued for a period of 24 hours in which the yield of the individual wells ranged from 1.05 to 1.95 mgd and the drawdown ranged from 5 to 11 feet. The combined pumpage of all wells included in the test amounted to 10.15 mgd with an average drawdown of 8.8 feet, or an average specific yield of 1.15 mgd per foot of drawdown. The second test, conducted for a 12-hour period, indicated a combined pumpage of 8.29 mgd with an average drawdown of 6.4 feet. From the plotted results of the two tests it was believed that equilibrium was reached by all wells in the first test and practically reached in the second. Recovery of head was most rapid in the first hour and was complete within six hours. According to Taylor, this indicated that the pumpage rate did not approach the rate of infiltration into the stratum. Thus, Taylor (1930, p. 130) concluded that the Pontiac stratum is safely capable of yielding 30 mgd with a lowering of head between 25 and 30 feet, allowing some modification of water levels due to seasonal or secular trends in precipitation.

It will be recalled that the mean static level at the Walnut Street plant stood at 869 feet in 1930 (OAPt-1), and at the site of well PO-66 (OAPt-3) the mean static level stood at 864 feet in 1931. Thus, accepting the figures determined by Taylor, the static level should stand between 839-844 feet at the Walnut Street site, and between 834 and 839 feet at the site of well PO-66, if recovery from the stratum reaches 30 mgd. The average daily recovery of water

from the stratum in 1950 was 12.2 million gallons and averaged as high as 16 mgd during the maximum month. The 1950 mean static level at the Walnut Street site stood at 815 feet or 24 to 29 feet below the predicted level. At the site of well PO-66, the hydrograph indicates a mean level of 841 feet compared with the predicted 834-839 feet, but here it is necessary to consider that records permitted the use of levels only for 1930 and 1949 since data were incomplete or else lacking for 1930 and 1950. The loss of head therefore has been greater than predicted even though the withdrawal rate of 30 mgd has not been reached.

Since the demand for water continues to increase in Pontiac, it appears that a new series of pump tests is needed to determine the safe daily recovery of water from the Pontiac stratum. It is suggested that if such pump tests are made, the formula by Theis (1935, pp. 519-524) to determine the drawdown of the water level in the vicinity of a discharging well be used. This formula takes into consideration the removal of water from storage and is generally called the non-equilibrium formula since it does not depend upon the hydraulic system to attain a condition of steady rate of flow or equilibrium. By determining the position of the static level on the basis of anticipated water demands of the community, the amount of safe recovery can be established for the stratum. If the anticipated future water requirements exceed this rate, as seems possible, then recourse to artificial recharge may be necessary. The Pontiac stratum may be recharged by surface waters of the Clinton River particularly during the November-May interval when unfavorable tastes and odors are at a minimum, the temperature of the water is low, and the daily discharge of the river at Pontiac averages more than 100 cubic feet per second, as indicated by the stream hydrograph for 1929-1930 (Taylor, 1930, p. 80). This discharge represents an approximate stream flow of 45,000 gpm or 64.8 million gallons per day from which some percentage may be diverted into recharge wells. Before such recharge, a survey of the rate and direction of groundwater percolation should be made by utilizing either sensitive organic dyes or radioactive salts which could be introduced into the proposed recharge wells. The direction of groundwater percolation could be determined by the detection of the dyes or salts in the water from pumped wells in the area, and the rate established by noting the time elapsed since the introduction of the dyes or salts.

Village of Rochester

Rochester is in the lowland channel between the Defiance and Birmingham moraines. However, its water supply is obtained from wells on a high, hilly moraine approximately 2.3 miles to the northwest of the village in the northwest quarter of section 4, Avon Township. The three wells are at elevations between 892 and 900 feet above sea level. All wells are 79 to 81 feet deep and penetrate at least 40 feet of medium to coarse gravel. Currently two wells furnish the total water supply for the village of 4,300 inhabitants. Well AV-5 is 12 inches in diameter, is completed with a 40-foot screen, and has a flow of 300 gpm. During summer months this well is operated at 750 gpm. Well AV-6, which is 6 inches in diameter, has no screen but penetrates 40 feet into the aquifer and flows at 200 gpm. Water from both wells is diverted into two reservoirs (2.5 million- and 77,000-gallon capacities) which are at an approximate elevation of 880 feet above mean sea level. From the reservoirs the water flows by gravity directly to the village which has an average elevation of 750 feet. The established head results in an average pressure of 60 pounds throughout the village mains. During peak demands the daily consumption averages 700,000 gallons, of which 33 per cent is utilized by industries. The water supply is more than ample, and as far as known the village has never experienced a water shortage during prolonged periods of drought when demands are apt to be excessive.

Summary

From metered and estimated pumpage data at least 4.7 billion gallons of water are recovered annually (or 12.9 mgd) from municipalities and villages situated on the moraines. No doubt recovery is somewhat greater since production from subdivision and private wells throughout the morainic areas is not included in the figure just cited. However, it should be noted that daily recovery from the principal civil divisions within the morainic areas is nearly two and one-half times greater than the recovery from cities and villages of the lake plain section and that it is eight times greater than the combined pumpage of the cities and villages situated on the interlobate outwash deposits.

TOTAL RECOVERY OF GROUNDWATER FROM THE UNCONSOLIDATED DEPOSITS

A minimum of 29.6 million gallons of groundwater is recovered daily from the unconsolidated rock (glacial drift) mantle of Oakland County. This minimum has been determined by adding the estimated water requirements of the rural population, and of the livestock in the county, to the total metered and estimated groundwater production for the villages and cities throughout the county. On a per capita basis the groundwater consumption for the urban population varied from 60 to 167 gallons daily. The 60-gallon figure represents the daily per capita consumption of a residential community (Berkley), and the 167 gallons the per capita consumption for the most industrialized area (Pontiac) of the county. For the majority of communities the consumption determined from population and pumpage records available ranged from 80 to 120 gallons per day per person. The estimate of water recovered in the rural areas was obtained by subtracting the population served by water-supply systems from the total population of the county, and assuming for the remaining (rural) population a per capita consumption of 60 gallons daily. Consumption by livestock was determined by using data furnished the writer by the county agricultural agent, and the data on daily water requirements of farm animals as published by Norris (1948, Table 7, following p. 21). The daily demand for groundwater is therefore given as follows:

URBAN POPULATION	19,920,661 gpd
RURAL POPULATION	9,169,020 gpd
STOCK REQUIREMENTS	479,400 gpd
TOTAL	29,569,081 gpd

It may be of interest that approximately 85.4 per cent of the total water recovered daily (or 25.3 million gallons) is from the southeasternmost nine townships of Oakland County, which contain 84 per cent of the total county population.

The daily recovery of groundwater represents but a fraction of the total amount of water that is contributed to storage by precipitation falling within the county. The amount of annual or daily recharge was not determined by the writer since such a study is a separate project in itself. However, some concept of the magnitude of recharge in Oakland County may be obtained from Taylor's work (1930, p. 43) on the hydrology of the Clinton River watershed. This

study embraced the watershed area of the Clinton River above the Dawson Pond stream-gaging station at Pontiac and represents an area of 124 square miles, or 200 square miles if the village of Auburn Heights, 1.3 miles to the east of Pontiac, is included. This part of the watershed as defined is developed principally over outwash and some morainic deposits. The method employed by Taylor follows generally the one used by Meinzer and Stearns (1929, pp. 73-146) in their study of the Pomperaug Basin of Connecticut.

The source of all water is rainfall. Its exchange between the lithosphere, hydrosphere and atmosphere is commonly known as the "hydrologic cycle." The exchange of water between the three "spheres" is affected by many complexities, many of which are interdependent upon each other. The cycle, however, is generally represented by the equation $P=R+E+I$, where

- P = Precipitation
- R = Run-off—both surface and delayed groundwater discharge
- E = Evaporation—from water and land surfaces and losses due to plant transpiration and interception
- I = Infiltration—or groundwater increment

Taylor modified the formula to $P=R+E_w+E_l+T+U$, where

- E_w = Evaporation from water surfaces
- E_l = Evaporation from land surfaces
- T = Plant transpiration
- U = Underflow or groundwater increment

The last factor of the equation represents the intake or increment to the groundwater supply, and its value is obtained by the equation $U=P-(R+E_w+E_l+T)$. Taylor applied this equation to observed and interpolated data covering a 17-year period from 1913-14 through 1929-30. This interval was somewhat drier since the annual precipitation for most years was at or below the annual average of 30 inches. The values obtained by Taylor for each of the factors in the formula are given as follows:

P	$-$	$(R$	$+ E_w$	$+ E_l$	$+ T)$	$=$	U
28.04 in.		5.4 in.	4.4 in.	5.8 in.	3.4 in.		9.04 in.
100%		19.3%	15.7%	20.7%	12.1%		32.2%

On the basis of Taylor's results, nearly one-third of the annual precipitation falling upon the watershed area of the Clinton River represents the groundwater catchment of underflow contributory

to parts of the moraine and lake plain section. Thus, the annual increment of 9.04 inches represents a daily recharge of approximately 430,000 gallons of water per square mile. This represents 53 million gallons daily for the watershed area of 124 square miles and 85 million gallons daily for the watershed area of 200 square miles (p. 247.)

From previous discussions in the report it was pointed out that the interlobate area represents the major intake area of the county. It is approximately 353 square miles in area, of which only 32 square miles lie northwest of the topographic divide. The characteristics of the entire interlobate area resemble more or less the upper reaches of the Clinton River watershed. Hence, if Taylor's daily recharge figure of 430,000 gallons per square mile is applied to the total area of the interlobate tract of 353 square miles, then the total groundwater increment is in the neighborhood of 152 million gallons daily. Of this amount 14 million gallons would be contributory to the area northwest of the topographic divide, and 138 million gallons daily contributory to the area southeast of the divide. This increment to groundwater storage represents only increment contributed by precipitation falling upon the interlobate tract and does not include the unknown amount of recharge that results from the precipitation that falls directly upon the moraine-till and lake plain sections. Thus the total annual increment must be considerably in excess of 152 million gallons daily.

Although this manner of evaluation is far from being entirely satisfactory, it does indicate that annual recharge is greater than the total recovery of groundwater—for Oakland County the recharge is approximately five times greater. It appears that the declining water levels, experienced by communities in southeastern Oakland County, are not caused by a lack of water in storage, but principally by the continuing annual increase in groundwater pumpage. The depressions shown on the water-table map and the regional lowering of the piezometric surface in Royal Oak Township since 1930 suggest a deficiency in transmission of groundwater from the major intake areas into the buried sands and gravels of the moraine-till and lake plain sections. In other words, the known buried aquifers may be overdeveloped to the extent that groundwater withdrawal exceeds the rate of percolation into and within the aquifer. Using the term proposed by Thomas (1951, p. 98), a pipeline problem exists in the southeastern part of Oakland County.

Chapter VII

QUALITY OF GROUNDWATER

Data relating to the chemical and physical characteristics of groundwater supplies are useful in planning the location of future water-using industries, and for the economical and satisfactory treatment of water for domestic, industrial and municipal consumption. When the properties of water are known precisely, then the selection of suitable equipment for water treatment can be thoughtfully planned and unnecessary equipment eliminated.

The analyses of groundwater samples in connection with this study were obtained from the Michigan Department of Health and from private sources. Through arrangements with the superintendent of the Sewage Treatment Plant, city of Birmingham, the writer was furnished monthly analyses of each of the municipal wells for two years so that changes in the quality of the water could be noted in an area of heavy groundwater withdrawal. In all, approximately 346 complete or partial analyses were made available for study and a selected number of these are given in Table 10.

Gases and minerals in groundwater are those that have been absorbed or taken into solution by water as it fell through the atmosphere as rain and as it percolated through the soil and rock. Variations in the quantity of dissolved mineral matter present in the different waters depend upon such factors as the quantity and kind of gases dissolved in the water, the chemical composition of the rock or soil materials and the duration of contact with them, the temperature, pressure, and the rate of percolation. Generally speaking, the character and amount of the minerals and gases in water derived from a given source remain relatively constant throughout the year, although gradual changes may be made over a period of years. The dissolved constituents in water from shallow wells or from channeled bedrock formations, such as limestones, may show greater fluctuations owing to variations in the rate of intake or discharge of the aquifer. Also, if wells draw water from alluvial aquifers that are subject to recharge by infiltration from a nearby stream, the chemical composition of the well water may change in accordance with the changes in the rate of inflow or in the composition of the river water.

The physical and chemical classification of Michigan waters, according to the Michigan Department of Health, is shown in Table

11 for purposes of comparison. Water classified "excellent" constitutes very good water for practically all purposes. Water rated "satisfactory" includes palatable waters that are suitable for most domestic and many other uses usually without treatment. Water rated "objectionable" is definitely unsatisfactory for most purposes and usually unsuitable without some treatment.

QUALITY OF WATER FROM THE UNCONSOLIDATED SEDIMENTS

Hydrogen-Ion Concentration (pH)

The acidity or alkalinity of water is indicated by the hydrogen-ion concentration that is expressed by the symbol pH. It represents the negative logarithm of the number of molecules of ionized hydrogen per liter of water. A neutral water has a pH factor of 7.0, water above that value is alkaline, water with a pH factor below 7.0 is acidic. The determination of the hydrogen-ion concentration is important in studying the corrosiveness of the water. In the proper treatment of contaminated water, the pH factor aids in the proper regulation of coagulation at water-treatment plants.

The groundwater in Oakland County is alkaline with an average pH factor of 7.5 and a range between 7.3 and 7.9. Some pH determinations seem to indicate that the groundwater within the limits of the glacial lake plain is slightly more alkaline than the groundwater of the rest of the county. The number of pH determinations was insufficient to permit a more positive statement.

Taste and Odor

The taste and odor qualities of groundwater in the county can be rated as "satisfactory to excellent" excepting some small areas within the glacial lake plain section. The taste of water in most of these areas is impaired by the presence of chlorides, iron, and hydrogen sulfide in somewhat higher concentrations than elsewhere in the county. Odor is caused largely by hydrogen sulfide or natural gas which has been noticed in waters derived from wells in the lake plain section, particularly in those areas where the sediments penetrated immediately overlie the Antrim shale formation. The occurrence of natural gas in the drift is restricted to the lake plain section, which will be discussed later in the report. It may be stated generally that poor taste and odor qualities of groundwater are more likely to be encountered in the glacial lake plain section than elsewhere in the county.

Silica (SiO_2)

Silica may be dissolved from nearly all rocks, and its presence in natural waters is generally between 10 to 30 parts per million[1]. Very few natural waters contain less than 3 or more than 50 ppm of silica. Its presence in large amounts contributes to the formation of boiler scale. On the basis of 47 determinations, groundwater of the county averaged 10.4 ppm of silica and ranged between 1.7 and 23 ppm. The selected analyses did not show any distinct difference in the amount of silica in the groundwaters from the various glacial deposits of the county.

Iron (Fe)

Iron in varying quantities is in nearly all naturally occurring materials of the earth and hence is dissolved from them. Water containing as little as 0.3 ppm of iron upon exposure to air becomes tinted with an insoluble compound produced by oxidation. Iron in excessive amounts produces stains on porcelain and enamel wares and fixtures, and also on fabrics when they are washed or processed in such water. Iron imparts a color and disagreeable taste to water. It favors the rapid growth of iron-depositing bacteria, whose activity in deposition may eventually lead to clogged pipes. Iron-bearing waters are likewise unsuitable for food processing, baking or canning. Most acid waters contain larger quantities of iron than alkaline waters. The removal of iron from water is simple and relatively inexpensive in public water-supply systems, but is not usually within economical limits for domestic supplies.

Much of the groundwater within the limits of Oakland County contains an excessive amount of iron. Of 55 selected determinations, the analyses indicated a range from 0 to 6.2 ppm of iron and averaged 1.2 ppm which is considerably above the acceptable tolerance of 0.3 to 0.5 ppm for water classified as acceptable. Iron is the most widespread and objectionable characteristic of groundwater in Oakland County. The difference in the quantity of iron in the groundwater throughout the various glacial units of the region is not significant.

Calcium (Ca)

Calcium is an element that is dissolved from nearly all rocks, but principally from the sedimentary rocks—limestone, dolomite, and gypsum. Inasmuch as the Pleistocene glaciers moved over and

[1]Parts per million (ppm) is a measure of the concentration of a dissolved constituent by weight in a million parts of the water by weight.

eroded sedimentary rocks which underlie the greater part of Michigan, it is not surprising that the resulting drift mantle is partially composed of calcium-rich fragments. The calcium and magnesium in water contribute to its hardness and, in addition, make it very active in forming boiler scale. Much of the water obtained from granitic areas is low in calcium in comparison to water in areas that are underlain by sedimentary formations.

The analyses of samples from Oakland County show that calcium is present in amounts ranging from 8 to 139 ppm and averages 70 ppm. In the outwash and moraine-till areas the calcium in groundwater averages 78 ppm and only 59 ppm for the lake plain section. If the outwash and till deposits contain a higher proportion of fragments of limestone, dolomite and gypsum, then a higher average calcium content of the groundwater is to be expected. The lake plain section has a preponderance of clay, a part of which is of lacustrine origin with the calcium leached away. More rapid percolation of groundwater in the outwash and till areas may also explain the difference in the average content of dissolved calcium. However, a difference of only 19 ppm is not significant enough to warrant further discussion.

Magnesium (Mg)

Magnesium is likewise dissolved from many rocks but particularly from dolomites and magnesian limestones, or from drift deposits that are in part composed of such rock materials. In bicarbonate form, its effects are similar to calcium. Waters containing magnesium and chlorides in appreciable amounts may also become corrosive especially to boiler equipment. In soft water the magnesium content for the most part is very low, but water from areas underlain by dolomites and magnesian limestones may carry from 20 to 50 ppm of magnesium.

Its origin in the groundwater of the area is the same as calcium. The analyses of 50 groundwater samples show a range in magnesium between 3 and 37 ppm with an average of 26 ppm. In the breakdown of analyses with respect to the outwash, moraine-till and lake plain areas, no appreciable difference was noted.

Sodium and Potassium (Na and K)

Sodium and potassium are two of the more abundant constituents of the earth's crust and are consequently dissolved from nearly all rocks. In most natural waters sodium and potassium constitute only a small fraction of the dissolved mineral matter. When these elements are in water in very small amounts they are nearly everywhere in nearly equal proportions. As the total amount of these combined constituents increases, the proportion of sodium is generally the greater. These elements in small quantities can be disregarded, but when present in amounts exceeding 50 to 100 ppm, they produce foaming of water in steam boilers. Water containing sodium salts in extremely large amounts may become unfit for most purposes.

In the analyses of water samples from Oakland County, sodium and potassium have been combined. The 49 selected determinations show a range from a trace to 239 ppm with an average of 43 ppm. The range of these elements for water from the outwash area is from 1 to 45 ppm; from the moraine-till plain areas, from a trace to 43 ppm; and from the glacial lake plain 20 to 239 ppm. On an average basis, this would be 18, 23 and 68 ppm respectively. The higher average and greater range in sodium and potassium in groundwater of the glacial lake plain make it somewhat distinctive from the other glacial units of the county.

Carbonates and Bicarbonates (CO_3 and HCO_3)

Carbonates and bicarbonates are in natural waters largely through the effect of dissolved carbon dioxide (CO_2), which permits the water to dissolve carbonates of calcium and magnesium. In general, the carbonate is not present in significant quantities in natural waters when compared to the bicarbonate present. Groundwaters in areas of relatively insoluble rocks have a low bicarbonate content, but water recovered from limestones and dolomites may contain several hundred parts per million. Large quantities of bicarbonate in groundwater make it unsuitable for use in steam or condensing equipment since heating of the dissolved bicarbonates of calcium and magnesium changes them into insoluble carbonates through a loss of carbon dioxide. The insoluble carbonates thus formed make a hard scale or precipitate when deposited.

The bicarbonates in the groundwater of the county averaged 355 ppm with an indicated range of 262 to 482 ppm. Carbonates are not always reported in the analyses, but when reported, they range from 0 to 80 ppm.

Sulfates (SO_4)

Sulfates can be dissolved in large quantities where water is in contact with gypsum beds or gypsum-bearing sedimentary rocks. Since such rock formations are at or near the surface in parts of