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A SURVEY OF GROUNDWATER RESOURCES IN OAKLAND COUNTY, MICHIGAN

by

ANDREW J. MOZOLA, PhD.
Wayne University

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INTRODUCTION

PURPOSE AND SCOPE OF THE REPORT

This report summarizes the occurrence of groundwater in the consolidated sediments and in the unconsolidated glacial deposits of Oakland County, Michigan. It may be used as a guide for the future development of municipal, industrial, and private water supplies of the region.

Field investigations of the groundwater resources for this region were started in June 1949, and were continued through the spring of 1952. In the course of the field work, records were collected regarding the availability and the quality of the groundwater, the trend in groundwater levels, the occurrence of gas and salt water in the drift deposits, and information relating to the geologic and groundwater conditions of the county. The results contained in this report are based on the qualitative evaluation and analysis of these records.

ACKNOWLEDGMENTS

The writer is greatly indebted to the Michigan Geological Survey for providing the grant which made this investigation possible. Mr. Norman Billings, formerly hydrogeologist of the State Geological Survey, now hydrologist with the Michigan Water Resources Commission, was most helpful with suggestions as the occasions demanded, and in making available the initial well records and other facilities that were needed from time to time.

Special acknowledgments are due to Ivan Fosheim, Superintendent of the Water Department for the City of Pontiac; George Schmid, Water Supply Engineer, City of Royal Oak; and L. R. Gare, City Engineer, City of Birmingham, for providing a wealth of well records and related data of their respective municipalities. The writer is also indebted to many officials of industries, cities, and villages who furnished additional information about their wells and water supplies. The writer expresses his appreciation to the well drillers, especially Harvey Tracy, James Price, Elmer Russell, Leon Berg, R. C. Hessler, C. W. Kinsey, The Dunbar Drilling Company, and the Layne-Northern Drilling Company, for furnishing logs and/or other related well data. Mr. Leary L. Oberlin contributed data on

wells which reach or penetrate bedrock.

The majority of chemical analyses of groundwater samples included in this report were made available to the writer by the Michigan Department of Health. Additional analyses were collected during the course of the investigation directly from the various municipalities, industries, and private sources within the county. The writer is deeply grateful to Mr. Russell Grinnell, Superintendent of the Sewage Disposal Plant, City of Birmingham, for the continuing monthly chemical analyses of water samples taken from each of the municipal wells.

Acknowledgment is given to Dr. Earl T. Apfel, of Syracuse University, in appreciation of his guidance and critical review of this study, and to L. E. Dickinson, of Wayne University, and to Miss Helen M. Martin, Research Geologist of the Michigan Geological Survey, for editing the manuscript.

PREVIOUS WORK AND SOURCES OF INFORMATION

The surface geology of Oakland County has been adequately mapped and described by Leverett and Taylor (1915), and a more detailed contribution to the Pleistocene geology of the Cranbrook area, in the southeastern part of the county, has been made by G. M. Stanley (1936). A study of the glacial history of streams of the southern part of Oakland County is included in a bulletin by J. W. Bay (1938). The geology of a small part of the southernmost townships is reported in Folio 205 by W. H. Sherzer (1916).

The earliest discussion on the groundwater resources of the county was prepared by Frank Leverett and others (1906) as a U.S. Geological Survey Water Supply Paper. This report describes the public water-supply systems of cities, villages and other civil districts, delineates areas of known artesian flows and includes a summary of wells by municipalities and townships.

In 1930, the Department of Water Supply, City of Pontiac, Michigan, issued a report prepared by F. C. Taylor (1930) on the ground-water sources in the Pontiac area. This report included a hydrologic study of the Clinton River watershed and a detailed examination of the "Pontiac stratum" from which the city obtains its water supply. In addition, a summary of well logs and a map of Oakland County showing the general water table and artesian head as of 1930 are included in the report.

In 1947, the Michigan Geological Survey in cooperation with the public schools of Oakland County conducted a well-water survey for the purpose of obtaining much needed data on groundwater conditions within the area. Forms were issued to the school children to be taken home and completed by their parents, or by owners of the individual wells. Of the returned forms, many were incomplete and/or inaccurate. However, some information was made available on flowing wells and on the presence of salt water in wells completed in drift deposits.

A report[1] prepared by an engineering firm (Pate and Hirn, 1949) for the city of Berkley, Michigan, contains information on water consumption and local groundwater levels. This study was made for the purpose of predicting future demands upon the groundwater supply. Additional municipal reports, which contained data on water losses, static water levels and quality of water, were made available to the writer by several communities.

METHODS OF INVESTIGATION

The results of this investigation are based on records collected in the period June 1949 through June 1952. The initial well logs and related data were obtained from the files of the State Geological Survey and from published sources, but much additional information was needed because of the size of Oakland County. In view of the fact that the major part of the population is centered in the southeastern part of the county, where temporary water shortages have been experienced by several of the communities and subdivisions, special effort was made to secure as many data as possible for the critical area. Throughout the course of the investigation, contacts were made and interviews were held with nearly all the well drillers operating in Oakland County. For several reasons the information desired from well drillers was not always readily available. Those drillers who maintained detailed records of each well were reluctant to open their files for study either for personal reasons or fear of having such information eventually made available to competitors. A number of the well drillers flatly refused to cooperate or were too preoccupied to unearth old records. Many drillers who offered to cooperate in this project kept no records or at best were able to furnish only partial data.

Municipalities and other civil divisions of local government were the best sources of information, particularly in southeastern Oakland County. Many data were collected in the way of well logs, monthly and annual reports of groundwater pumpage, water-level changes, and estimates on water losses as determined by a comparison of pumpage against metered water consumption. Most industries were very cooperative with this project, but only the larger and older establishments had well-information on file. The newer and smaller plants generally maintained no records and were satisfied in merely having a well or wells that furnished an adequate water supply. In the process of securing well records, many logs furnished by several of the drillers failed to indicate the approximate location of wells, and much time was spent in the field locating the wells in question so that they could be properly spotted on topographic maps of the area. In all nearly 1,138 complete or partial well records form the basis of this report. Their locations are shown on a map filed in the open file of the Geological Survey Division of the Department of Conservation. Since the initial logs for this study were obtained from the Michigan Geological Survey or from previously published sources, only the additional records acquired have been tabulated at the end of the report (Table 1). For purposes of easy reference and general location, all well records are designated by township and then numbered consecutively; the numbering generally begins with wells situated in section one and continues throughout. Each record shown in Table 1 has its location more precisely identified by township and range. Township names have been abbreviated whenever any reference is made to a specific log, and such abbreviations are appropriately indicated in Table 1.

Figure 1. Index map of Michigan

Of the total wells drilled in Oakland County, a surprisingly small number reach or penetrate into the underlying bedrock. As a result, the configuration of the bedrock surface and the pre-glacial drainage system could not be mapped to the degree of finality that the writer had anticipated. Most of the wells that reach or penetrate bedrock are in the more critical area of Oakland County, and thus only a generalized bedrock-surface map for the southeastern part of the county can be shown in this report. A few rock depths were obtained by seismic methods when a seismograph was made available to the writer. The number of determinations was limited inasmuch as a six-trace seismograph required a number of setups where bedrock was in excess of 150 feet. In addition to bedrock depths, data relating to the groundwater levels were collected wherever such information was available. All water-level measurements were calculated from the elevation of the ground surface at the well. The elevations thus obtained were used in the preparation of a map showing the general configuration of the water table and artesian head.

Information was also obtained during the course of this investigation on the quality of water. Analyses dating back to 1923 were obtained from the Michigan Department of Health and were used whenever possible for making a comparison of the quality of water with analyses of more recent samples. In addition, the writer was furnished with monthly analyses of water samples drawn from each of the seven municipal wells in the city of Birmingham. These analyses were plotted graphically to note the changes in the quality of the water resulting from excessive withdrawal or variations with the season of the year. More than 400 records of complete or partial chemical analyses were obtained from these various sources and form the main basis for the conclusions reached on the quality of water in Oakland County.

Throughout the course of this investigation attention was given to evidences relating to glacial deposits of pre-Wisconsin age and to the occurrence of salt water and gas in the drift. These facets of the investigation are discussed in the appropriate sections of this report.

[1]Unpublished.

Chapter I: GEOGRAPHY OF THE AREA

LOCATION AND SIZE

Oakland County is located in southeastern Michigan and includes within its limits an area of 877 square miles as measured from maps just prior to the 1940 Decennial Census (fig. 1). It is square in shape and comprised of five tiers of townships both north and south. The southern limit of the county is marked by the linear survey base line (Eight Mile Road) and its western limit is 42 miles or six tiers of townships east of the principal meridian of Michigan. It is bordered on the north by Genesee and Lapeer counties, on the west by Genesee and Livingston counties, on the east by Macomb County, and on the south by Washtenaw and Wayne counties. Wayne County includes within its civil boundaries the city of Detroit, the county seat, and the largest municipality of the state. The civil divisions within Oakland County include fourteen cities, ten villages and twenty-five townships. The principal cities lie along the Woodward Super-Highway (U.S. 10) which traverses the county in a southeast-northwest direction. Southeastward, the superhighway joins Woodward Avenue, the main thoroughfare of the city of Detroit. The largest city, Pontiac, is the county seat and occupies the approximate geographical center of the county, but 28 miles from Detroit. No part of Oakland County borders any part of the Great Lakes system and hence it is considered inland.

TOPOGRAPHY

According to Fenneman (1930) Oakland County is a part of the Eastern Lake Section of the Central Lowland province east of the Mississippi River. The topography of the county is typical of an area that has been glaciated in the past by the great ice advances of Pleistocene time. Features characterizing the landscape of the area are two hilly belts that cross the county in a northeast-southwest trend, an intervening but extensive and in many places pitted gravel plane and a gently sloping lake plain that lies to the southeast of the more southerly belt of hills. The more northerly of the two hilly belts cuts across the northwest corner of the county, passing through Rose Center, Davisburg and the village of Ortonville in the north. This hilly belt comprises some of the most elevated tracts in the county with elevations generally between 1,000 and 1,100 feet above sea level and many hills and knobs exceed 1,100 feet. The more conspicuous hills in this range are Bald Knob (1,198 feet), Pine Knob (1,221 feet) and Mt. Judah (1,180 feet). The southerly belt of hills, with elevations between 800 and 1,000 feet, is likewise strong and hilly and cuts nearly diagonally across the county, passing through the village of Novi, the city of Pontiac and just north of the village of Rochester at the northeast end. Both the northerly and southerly belts merge in an area northeast of the village of Rochester.

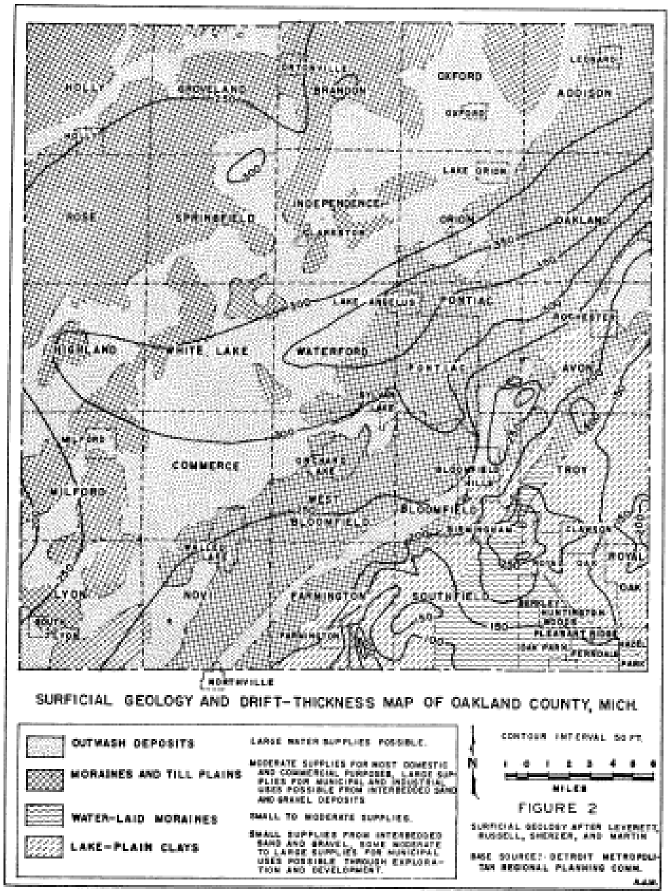

Figure 2. Surficial geology and drift-thickness map of Oakland County, Michigan

Lying between the two belts is a broad pitted flat plain composed of outwash sands and gravels. In places the gravel plain is up to ten miles in width, its flatness being interrupted by a broken group of hills having a general trend similar to the two belts previously mentioned. In a few places a hill of a group of hills rises conspicuously above the level floor of the plain. Scattered throughout the hilly belts and the outwash plains are hundreds of depressions, many of them occupied by inland lakes which range in size from small ponds less than an acre in area to lakes covering one and one-half square miles. Largest of these inland lakes are Cass Lake and Orchard Lake just southwest of Pontiac.

In the extreme southeastern part of the county is the glacial lake plain which slopes gently southeastward. The flatness of the lake plain is conspicuously interrupted by the stream courses and slightly by a series of former glacial lake beaches which often escape the notice of the casual observer. The elevation of this plain decreases from approximately 800 feet in the northwest to 630 feet near the southeast corner of the country.

Examination of the topographic maps of the county reveals a range in elevation from 630 feet to 1,221 feet, or a total relief of 591 feet. The average elevation of the county for the most part is 950 to 1,000 feet. Excepting a small area in the northwest part, which slopes to the north and northwest, the regional slope of the county is to the southeast. The topographic features of the region are reflected in the glacial geology map shown in Figure 2.

Figure 3. Average precipitation and temperature in Michigan

DRAINAGE

The drainage development in Oakland County is poor and hence youthful, as is usual in an area covered by glacial and glaciofluvial deposits. Many stream courses are poorly defined and connect a series or chain of lakes, and the only place where the streams incise (or cut their channels deeply below the general level) is to be observed in the lake plain area. Approximately 425 lakes covering nearly 100,000 acres are within the boundaries of the county. Many of these lakes do not form any part of the river systems but exist as isolated bodies of water with neither surface inlets nor outlets and thus can be considered as exposed parts of the groundwater surface. The fact is an important phenomenon in the study and evaluation of the groundwater hydrology.

The major topographic divide follows along the northern hilly belt and along a portion of the elevated outwash plains area which occupies a position along the “Thumb Upland,” a predominant and elevated tract extending southwestwardly from the tip of the Thumb (Huron County) to the southern boundary of Michigan at the junction of the Ohio-Indiana State like (fig. 1). From this upland divide secondary divides can be traced between river basins that drain into Lake Michigan and Saginaw Bay from those that are contributory to lakes Huron, Erie, and St. Clair. In Oakland County, five river systems have their origin in the hilly belts (moraines) and outwash plains. That part of the county northwest of the upland divide is drained by the Flint and Shiawassee river systems, both tributary to the Saginaw River system which empties into Saginaw Bay. Kearsley Creek and the south branch of the Flint River, in the north-central part of the county, flow northward to join the main branch of the Flint River. The northwest area of the county is drained by the headwaters of the main Shiawassee River and its tributaries, Thread and Swartz creeks. The area southeast of the upland divide is drained by the Clinton, Huron, and Rouge river systems. Both the Huron and Clinton rivers have their origin in the gravel plains and drain the overflow from many of the inland lakes. The Huron River flows south-westward out of the county and eventually swings south, then southeast into Lake Erie at a point several miles south of Grosse Isle. The Clinton River, originating on the eastern side of the Huron-Clinton divide, drains the eastern part of the county and discharges into Anchor Bay of Lake St. Clair. The River Rouge and its upper and middle branches, which have their origin in the southerly range of hills, flow over the glacial lake plain and into the Detroit River just south of Detroit.

Artificial drainage of lakes and marshes has been attempted with varying degrees of success in the hilly ranges and outwash plains. However, artificial drainage has been more successfully accomplished at greater cost in the glacial lake plain area where the rapidly growing communities, and the relatively less pervious nature of the mantle, made artificial drainage practice a necessity in the interest of sanitation and health.

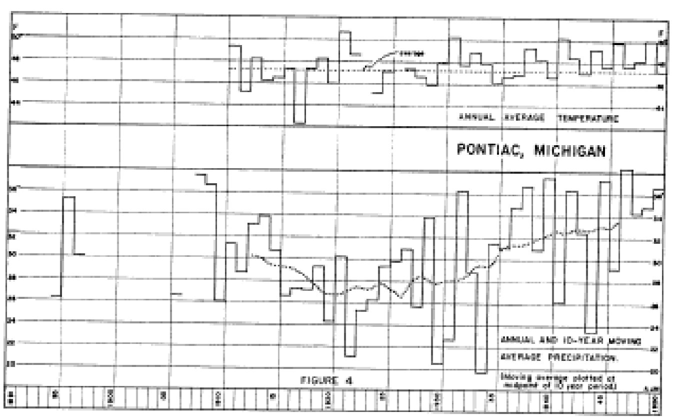

Figure 4. Annual average temperature and precipitation, Pontiac, Michigan

CLIMATE

The position of Michigan in the heart of the Great Lakes Region has given the state the longest lake shore line in the Union. Because of this feature, Michigan is naturally under the climatic influence of these large bodies of water, and thus two distinct types of climate (fig. 3) are observed in the state (Yearbook of Agriculture, 1941). Interior counties of both peninsulas have a climate that alternates between continental and semi-marine depending upon the meteorological conditions. The marine type of climate is brought about by the influence of the lakes and by the direction and force of the prevailing winds. With little or no wind, the weather of the interior counties becomes continental in character—hot in summer and cold in winter. However, quick climate changes may be brought by strong winds blowing from the lakes. Counties which extend in part along the shore of Lake Michigan, Lake Superior and Lake Huron have a modified marine climate for the larger part of the year since the lakes seldom freeze over entirely. Inasmuch as large bodies of water are more uniform in temperature and also less responsive to weather changes, the effect of the lakes is to hold over the winter cold longer in the spring and the summer heat longer in the fall in comparison to the areas surrounded by land.

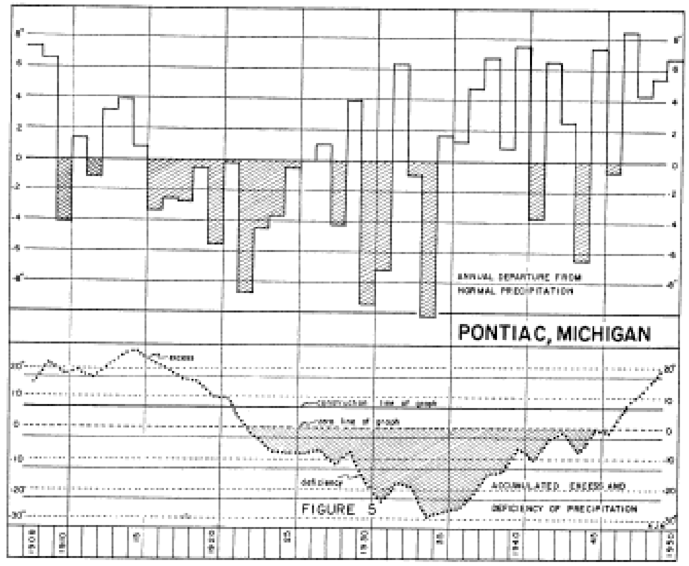

Figure 5. Annual departure from normal precipitation and accumulated excess and deficiency of precipitation, Pontiac, Michigan

Oakland County in eastern lower Michigan, according to the U. S. Weather Bureau, lies in the pathway of storms that move across the Great Lakes Region, and hence its climate is characterized by frequent and rapid changes in weather which such storms produce in their passage. Although the county nowhere touches any of the Great Lakes, the precipitation to a certain extent is modified by the nearness of the water bodies. Temperatures below zero occur in January and February but the winters are not generally severe. Hot and humid weather is frequent during the summer months of July and August. As may be noted from Table 2, the average annual temperature at Pontiac is 47.2°F. The average temperature in July is 71.4° F. and the average temperature for the month of January is 23.1° F. (fig. 3). Highest and lowest temperatures recorded at Pontiac are 104° F. and -22° F. respectively. As a general rule, no extremely hot or cold spells are experienced, and extremes in temperature are the exception rather than the rule. The annual mean temperatures for the past 40 years are shown plotted in Figure 4. It is to be noted that in the past two decades the annual mean temperature has generally exceeded the average annual temperature.

Monthly and annual precipitation records for Pontiac go back as far as 1888 but have not been continuous. However, in the period for which complete and detailed records are available, the records show that 25 years had precipitation above normal, two years had normal or nearly normal, and 23 years had below normal precipitation. From the charts shown in Figure 5 it appears that precipitation in the Pontiac region occurs in cycles—periods of excessive precipitation alternating with periods of deficiency. These cycles are not of uniform length or behavior and may at times be erratic to a considerable degree, as indicated on the chart for the period 1926-1934. This cyclic occurrence has its effects upon the groundwater level of the region.

The average annual precipitation for Pontiac is 29.94 inches computed in 1950 on the basis of the records available. The month of May has the highest average monthly precipitation (3.42 inches) and January the lowest (1.81 inches). Seasonal precipitation does not vary since rainy or dry months can occur any time during the year, as shown on the monthly precipitation chart (fig. 27). Precipitation in the spring and fall months is usually caused by cyclonic disturbances and in the summer by local showers or thunderstorms. The number of days having 0.01 inch or more of precipitation averages 94 per year. Precipitation is recorded for 7 to 10 days each month. Snowfall averages 38.7 inches annually. The first snowfall is late in October or early November and the last snowfall usually in April and occasionally in May. The growing season averages 152 days. The average date of the last killing frost is May 10 and the first killing frost occurs around October 9. Excepting during the months of January and February, the prevailing winds are from the southwest and hence are land breezes. (Table 2).

POPULATION AND GROWTH

The settlement of the area which is now Oakland County was delayed from 10 to 20 years by a false report that the region was an impenetrable morass. The report was submitted shortly after the Revolutionary War (Official Directory, 1949-50) by surveyors who had been bogged down in swamps in the vicinity of the present Oakland-Wayne County line. This report diverted settlement from Michigan toward Ohio, Indiana, and Illinois, until a new survey, ordered by Territorial Governor Cass, rectified the error and the area was declared fit for human habitation. After the first permanent settlement at Rochester in 1817, and at Pontiac in the following year, the region has steadily continued to grow. The opening of the Erie Canal, from the Hudson River to Lake Erie in 1828 provided the greatest impetus to the early growth of Oakland County. The canal offered an all-water route from the Atlantic seaboard to within eight miles of the county's south border. The manufacture of vehicles, wagons, buggies and sleighs during the early decades, and automotive products in more recent decades, at Pontiac and elsewhere in the county, has been the stimulus for continued growth of the region up to the present.

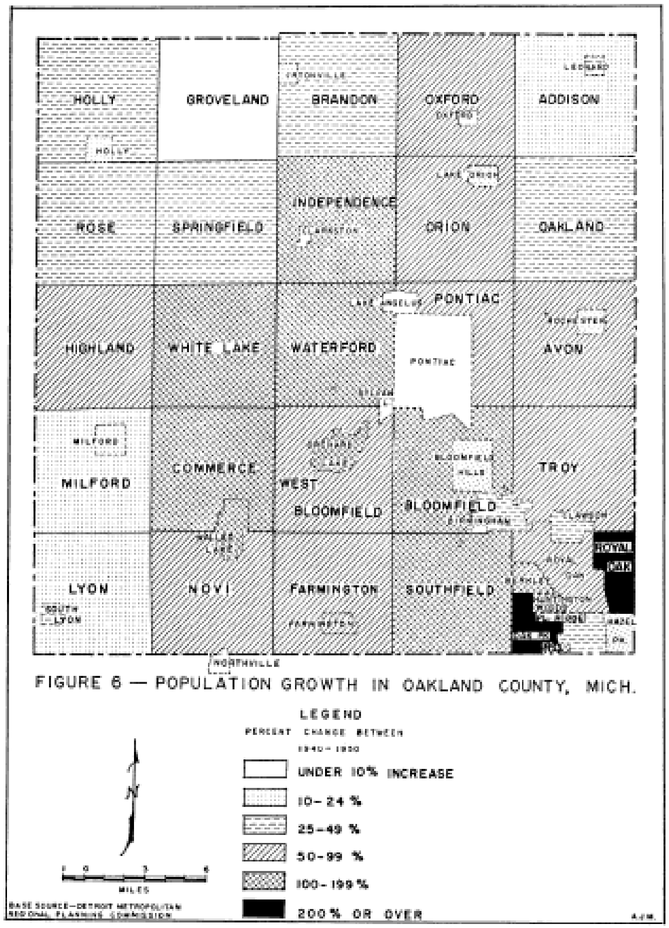

FIGURE 6 — POPULATION GROWTH IN OAKLAND COUNTY, MICH.

Figure 6. Population Growth in Oakland County, Michigan

The population of Oakland County (Table 3) as determined by the Federal Census of 1950 was 393,467 inhabitants (425.9 per sq. mi.), again of nearly 55 per cent over 1940 (289.7 per sq. mi.). Of this number, 241,719 (61.4%) were classified as urban and 151,748 (38.6%) as rural. The breakdown of the rural group into rural farm and rural non-farm classification has not yet been made available by the census bureau. However, the rural population in 1940 was 43 per cent of the total, of which 36 per cent was classified as rural non-farm and only 7 per cent as rural farm. An interesting note is the shift of population from urban to rural areas. In 1930 the urban population of Oakland County was reported as 75 per cent of the total (Taylor, 1930). The percentage declined to 43 per cent by 1940. In the following decade, the urban population increased to 61 per cent, though it still remains below the 1930 figure. Eighty-four per cent of the total population resides within the area of the nine townships of southeastern Oakland County and principally in the cities located along the superhighway (U.S. 10) which traverses the county diagonally. The populations of the several principal cities of this section are: Pontiac, 73,112; Royal Oak, 46,817; Ferndale, 29,670; Berkley 17,913; Hazel Park, 17,791; Birmingham, 15,370; Oak Park 5,243; Clawson, 5,176. Of these cities Oak Park, Berkley, and Royal Oak have shown the greatest gain and Pontiac the least gain in the number of inhabitants for the past decade. It is in the southeastern area of the county that reports of a water shortage have appeared in the public press. Of the twenty-five townships, two had population gains exceeding 150 per cent, five from 100 to 149 per cent, nine from 50 to 99 per cent, five from 25 to 49 per cent, and four townships had reported gains of less than 25 per cent. Largest gains were reported for Royal Oak and Commerce townships, and the least gain was reported for Groveland Township. As indicated on the population growth map (fig. 6), the townships along the principal highway routes figured most prominently in the gains. Since the end of the last war much land bordering the inland lake areas has been purchased by builders for the development of new subdivisions consisting of year-round homes and non-farm estates. The Detroit Area Regional Planning Commission[1] has estimated that Oakland County will have a population numbering 536,000 to 612,000 by the year 1960, and from 709,300 to 846,700 people by 1970. Greatest growth is expected to be in Commerce, Farmington, Lyon, and Novi townships. It appears to the writer that these townships are favored for growth because of their proximity to Detroit, their nearness to a principal thoroughfare (U.S. 16) and the availability of land for future building developments. With this postulated increase in population and the expansion of industry which is also predicted, problems involving water supplies will undoubtedly be of much concern to the communities of these areas.

[1]Detroit News, December 31, 1950.

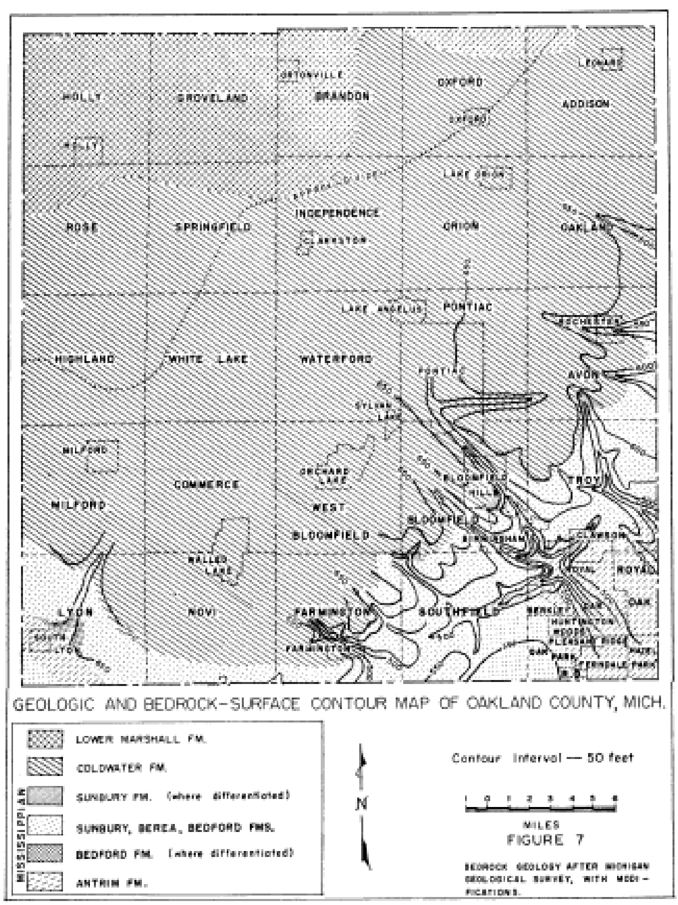

Figure 7. Geologic and bedrock-surface contour map of Oakland County, Michigan

ECONOMIC DEVELOPMENT

Wayne, Oakland, Macomb counties and the easternmost townships of Washtenaw County are included within the limits of the Detroit Metropolitan Area[1] of southeastern Michigan (fig. 1). As a part of this metropolitan area, Oakland County is second only to Wayne County in population and in equalized tax valuation. The 1950 equalized valuation[2] is $966,300,000 and, as confirmed by the State Tax Commission, now exceeds the valuation of Kent County, previously acclaimed the second richest county in Michigan. Wayne and Macomb counties' equalized valuations are approximately $6,067,200,000 and $327,350,000 respectively. The rise in equalized valuations, particularly in the past several years, has been mainly the result of new construction. Oakland County is a part of the wealthiest, most populated and most industrialized part of the state, and it is predicted that the equalized valuation should exceed one billion dollars within a relatively short period of time.

Data relating to the total labor force and its breakdown into special categories are not yet available for 1950. However, the total labor force in Oakland County as indicated by the census of 1940 was 86,482, of which 46 per cent was engaged in manufacturing; 1.6 per cent in business and personal services; 15 per cent in retail and wholesale trade establishments; 10 per cent in transportation, communications, utilities, construction, and mining; 4.6 per cent in agriculture; and 8 per cent in unclassified occupations.

Manufacturing Industries

Heavy industry principally centered in the Pontiac region, consists mainly of plants manufacturing automobiles, coaches, automotive parts, rubber and steel products. The larger manufacturing firms established in the area are the General Motors Corporation, Wilson Steel Foundry, and the Baldwin Rubber Company. Elsewhere in the county, and particularly in the southeastern part, the industrial plants are classified as light manufacturing, such as machinery, machine tools, fabricated metals and gears, and stone, clay, wood, chemical, and allied products. The types of industrial establishments are shown in Table 4 of this report. During the war years 1940 through 1945, the major war supply contracts reached nearly 2.5 billion dollars.

The industrial growth of the county for the past decade is indicated by the increase in the number of manufacturing establishments from 183 to 873. Further growth is expected because of the trend toward decentralization of industry away from the highly populated localities of the metropolitan area. The principal factor in movement of industry beyond the perimeters of the densely populated areas is the availability of low cost land. Although initially the factor of lower tax rates may be appealing, it is not the major stimulus toward decentralization, since tax rates increase with time and eventually become comparable to taxes of the more populated areas. Decentralization also leads to a dispersal of industries over a wider area, a desirable condition from the military point of view.

In 1940 the total number of manufacturing plants in Oakland County was 183 of which 79 were classified as heavy and 104 as light. By 1950 the heavy industry plants increased to 263 and the light industry to 610 plants. In the same period total employment for industries of all classifications more than doubled—increasing from 22,145 to 50,874 wage earners. The primary industrial areas of Oakland County today are located in the Pontiac region and in the southeastern part of the county. In the Pontiac industrial development area, the total number of plants increased from 68 to 166 with an employment gain of 14,775 wage earners; the present employment figure is 33,823. Both heavy and light industries more than doubled during the decade, heavy industry having a slightly greater gain. The industrial growth in this older manufacturing area was based on the already established motor vehicle industry. Transportation equipment, rubber, lumber and wood products, primary metals and chemicals are manufactured in this area. The southeastern industrial development area increased its employment from 1,947 to 12,886 wage earners, and its manufacturing plants by nearly ten times. Heavy industry increased from 23 to 132 plants and light industry from 35 to 396 plants. Industrial growth in this area was characterized by the development of fairly small plants of a diversified nature, many of which are suppliers for heavy manufacturing. Manufactured products are mainly instruments, machinery, fabricated metals and paper items.

Water-using industries, principally chemical, steel processing, machine tool and food products, increased from 107 to 465 in the same period. The increase in use of groundwater supplies is of paramount importance in both the Pontiac region and in southeastern Oakland County for continued industrial expansion. According to the Regional Planning Commission (Reid, 1950), manufacturing employment is estimated to reach 89,750 wage earners by 1970. It is predicted that employment in the Pontiac area will nearly double and more than double in the southeastern Oakland County area. The 1970 projections for employment gains are based on past growth trends and on the general pattern of industrial development in the region. Since the present industrial production pattern has already been established by such factors as market, proximity of raw and semi-finished materials, it is not expected that in the next 20 years any significant development will take place in the form of plants of a new industrial classification. However, the St. Lawrence Seaway may introduce new industrial classifications and thus change the manufacturing pattern of southeastern Michigan. The seaway will provide cheap transportation and access to foreign markets and raw materials.

[1]A "metropolitan area" is based on a concept that includes entire counties. However, a county is included in a metropolitan area only when 50 per cent or more of its inhabitants fall within the limits of a metropolitan district, as defined in 1940 for the Census of Population. A "metropolitan district" consists of a central city or cities having a population of 50,000 or more and certain adjacent minor civil divisions or incorporated places. Ordinarily, the adjacent places include those having a population of 150 or more per square mile. Thus, a "metropolitan county" is applied to any county that is included within a metropolitan area. Source: County Data Book, U. S. Department of Commerce, Bureau of the Census.

[2]Office of the State Board of Equalization, State of Michigan, Lansing, Michigan, June 2, 1952

Mineral Resources

The extractive industries have not been included in Table 4, and some mention should be made of the county's natural sand and gravel resources which have importance as building materials. The principal source of these materials is the outwash plains of the county. The largest commercial pits are located near Oxford where the most prolific sand and gravel deposits within the state are found. Small pits are numerous and scattered throughout the county. In 1939, the extractive industries employed 200 wage earners and the products were valued at $648,000. On the basis of 1951-52 large-scale operations of the large commercial pits, the value and tonnage of the products today must certainly exceed the 1939 figures by several times.

Trade

In 1948 three and one-half times as many persons were employed in manufacturing as in retail trade in Oakland County. This relationship is usually typical of highly industrialized areas. Net sales in 1948 exceeded 313 million dollars in comparison to the 1939 sales of 83 million dollars. In the same period employment in retail trades nearly doubled and the number of establishments increased from 2,832 to 8,419.

Agriculture

Early farming in Oakland County was devoted principally to wheat as a cash or barter crop and to corn and potatoes as staples. With the gradual increase of industrial activity, the type of farming changed from production of essential crops to specialized production to meet the demands of urban markets in Pontiac and Detroit. It also resulted in an increase in livestock population and the production of dairy products. Today the primary farm income is from livestock farming, especially production of dairy products. Income from fruit cultivation is secondary.

Approximately 60 per cent of the county is devoted to agriculture. In 1945, the county had 4,054 farms, averaging 88 acres per farm. Of these farms 2,606 were classified as commercial and 1,448 as non-commercial. According to the 1950 census, approximately 3,200 farms are now considered as commercial. The following table shows the number and size of farms in 1940 (Alchin, 1940):

Size of Farm	Number of Farms
3-20 acres	1,255
20-70 acres	821

100-180 acres	869
180-260 acres	276
260-500 acres	151
500-700 acres	20
700- acres	17

Table 5. Size and number of farms in Oakland County, Michigan

Since 1940, the trend in agriculture has been toward less tenant farming and to an increase in the number of small farms between 3 and 20 acres. The purchase of smaller plots (usually less than 20 acres) has been commonplace in order to provide elbow room or land to supplement family income by gardening. The increase in small farms has taken place in Royal Oak, Southfield and Waterford townships which are rather heavily populated since these areas have taken the overflow from Pontiac, Royal Oak and Detroit. It may be well to note that this trend toward smaller farms, small residential plots and estates has placed an added demand upon the ground-water resources of the county. Watering of vegetable and flower gardens of such small-acre plots has not been an uncommon observation made by the writer in the course of the field investigation. The larger farms today are mostly in the northern townships where population increases have not been as great in the past decade.

Soils of the county are varied and the types widely scattered because of drainage characteristics and development on morainic, glacial outwash and lacustrine deposits. Muck acreage is small, and the soils developed thereon are devoted to canary grass, barley and truck crops. Loams and silt loams constitute 45 per cent of the total soil acreage and where well drained they are especially adapted to apple trees, small grain and hay. Where drainage is needed beets, beans, corn, alfalfa and small grain are grown. Fruit, such as peaches, apples and pears, is most suitably grown on sandy loams, which make up twenty per cent of the soils of the county. Loamy sands and sands make up twenty-five per cent of the soil cover, and special crops, as melons, cucumbers and potatoes, are grown on them. The value of farm products in 1945 was more than 4.5 million dollars, of which 56 per cent was derived from livestock and livestock products and 30 per cent from crops. Nearly 44 per cent of the total number of farms produced farm goods valued at less than $400. Intensive fruit areas are in Novi, Farmington, Bloomfield, West Bloomfield and Lyon townships. Production of small fruit is not popular on a large commercial scale because of the high labor requirements and hence such fruits are grown on the small farms for home use or sale on highway fruit and vegetable stands. Troy and Avon townships have the greatest concentration of vegetable growers, and milk production is carried on mainly in Novi, Brandon, Springfield, and Groveland townships. Livestock in the county consists of approximately 18,000 dairy cattle, 1,200 beef cattle, and 10,000 sheep.[1] Poultry farming is restricted primarily to chickens and turkeys—the major production divided among ten townships.

[1]Personal communication, County Agricultural Agent.

Recreation

The 425 inland lakes within the county have led to the development of some of the finest estates, palatial residences, public resorts and state parks. The public resorts and state parks are considered summer playgrounds and hence income is derived from nearby motels, tourist cabins, lake cottages and retail stores. This picture is changing somewhat since much of the land is now being purchased for the construction of permanent year-round residences.

Transportation and Public Utilities

Oakland County is served by three railroads—the Grand Trunk Western, Pere Marquette, and New York Central. In addition to the railroads, the industries and populace of the area are also served by several inter-and intra-state truck freight forwarding companies and passenger busses. Air transport on a limited scale is available at the Municipal Airport located several miles northwest of the city of Pontiac near Williams Lake. Major air service, however, is provided from the air terminals at Willow Run and Detroit.

The principal Federal highways are U.S. 10 and U.S. 16. U.S. 10 traverses the county diagonally from southeast to northwest passing through the cities of Royal Oak, Birmingham, and Pontiac. U.S. 16 located in the southern part of the county trends west-northwest and east-southeast, passing through the city of Farming-ton and the villages of Novi, West Novi, and New Hudson. The county has 188 miles of state trunk line highways of the rigid concrete, bituminous or flexible bituminous type, 635 miles of primary roads (concrete, bituminous, gravel) and 1,697 miles of secondary roads (bituminous, gravel, earth). The total road mileage of all types is approximately 2,520 miles.

Electric power is furnished by the Detroit Edison Company for the entire county with the exception of Holly Township, for which service is supplied by the Consumers Power Company. Gas transmission lines are operated by the Consumers Power Company, which serves the principal towns of the county. Telephone service is provided by the Michigan Bell Telephone system.

Summation

The decade 1940-1950 has been a period of active residential and industrial construction, particularly in the southeastern part of the area under study. The county population of 393,467 has shown a gain of nearly 55 per cent since 1940 and is predicted to reach between 709,000 and 846,000 inhabitants by 1970. Industrial establishments have increased in number from 183 to 873 plants in the same decade; 465 of these plants have been classified as water-using industries.

The growth in population and the attendant construction of new residential dwellings together with the increase in number of industrial and commercial establishments have placed an added demand upon the groundwater supply.

On the basis of a conservative estimate, a minimum of 30 million gallons is pumped daily, chiefly by communities and industries situated in the southeastern part of Oakland County. The continued growth of this county appears assured, and a knowledge of the geology and hydrology becomes an important factor in the future development of the region.

Chapter II: GEOLOGY OF THE AREA

The indurated sediments beneath the unconsolidated mantle of Oakland County are all of Paleozoic age. The surficial deposits are of Quaternary age, consisting of tills, outwash sands and gravels and lacustrine deposits of Pleistocene time and some recent alluvial deposits along the major streams. Knowledge of the indurated strata of the region is restricted in scope owing to the total absence of rock exposures and the limited number of deep borings in the county. The few but widely scattered deep wells that penetrate the bedrock formations are for the most part exploratory tests or wildcat wells in the search for petroleum or natural gas. Although the water wells greatly exceed the number of deep borings, the majority of them end in the surficial deposits of glacial origin and only a few reach or penetrate the rock for any appreciable depth. Many records lack adequate descriptions of the rock penetrated. Hence, the following discussion pertaining to the stratigraphy, structure and nature of the rock surface is based on limited data obtained from wells within the county and from available rock quarries found in areas adjacent to the region under consideration. Most of the formations exposed in neighboring areas have been more thoroughly studied. In order to avoid placing emphasis only on the lithologic characteristics of the rock strata as they occur in Oakland County, the following text includes only those parts of such studies that seemed most applicable.

The geologic map of Oakland County included herein (fig. 7) is adapted from the Centennial Geological Map of the Michigan Geological Survey with the contacts between formations or groups modified on the basis of additional data made available since 1936. Only 168 records indicate that consolidated sediments beneath the drift have been reached or penetrated. Fifteen records were detailed logs related to deep oil and gas borings, and the remaining records were logs of water wells and test holes, many of which did not describe adequately the nature of the rocks penetrated. The inferred outcrop areas of the Bedford and Sunbury formations were extended or added only wherever the data permitted a reasonable inference. Immediately beneath the surficial deposits, the county is underlain primarily by shales, sandy shales and sandstones of lower Mississippian age. Below these formations as indicated by deep borings are older Paleozoic sediments of Devonian and Silurian age consisting of limestones, dolomites, shales, sandstones, and beds of rock salt. These older strata in turn may be underlain by still older Paleozoics which finally rest upon the crystalline rocks of the pre-Cambrian floor.

STRATIGRAPHY

Silurian

SALINA GROUP (CAYUGAN SERIES)

Deepest of the consolidated sediments penetrated by exploratory oil or gas wells in the Oakland County area are those of the Salina formation. In general, the Salina consists of beds of rock salt of varying thicknesses and separated by dense to finely crystalline gray or brown dolomite much of which is gypsiferous, micaceous or shaly, and by some shaly sediments or beds of hard, gray to blue limestones. Since the underlying beds of the Niagaran series were not reached, on the basis of records available the total thickness of the Salina in Oakland County remains undetermined. Its base may not be too difficult to determine since the immediately underlying beds of the Lockport (Niagaran series) are hard, generally fine-grained, light-colored dolomites devoid of anhydrite, salt beds or appreciable thicknesses of shales. It is reported that the beds are easily recognized by drillers elsewhere because the "cuttings and wash on bailing have the color, thickness and viscosity of buttermilk." The upper limit of the Salina is more difficult to establish because of its lithologic similarity with the basal beds of the overlying Bass Island group, but the contact appears to be arbitrarily placed above the uppermost well defined layer of salt or anhydrite.

The formation is economically important for brines and has been penetrated by many wells mainly along the Detroit River. From the available records, the Salina beds thicken northward. At Wyandotte, Michigan, the Salina between the limits defined is 780 feet and the aggregate thickness of the salt beds is 160 feet (Sherzer, 1916, p. 44). At the salt shaft in southwestern Detroit, the Salina is 929 feet with 600 feet of rock salt. Northward, in section 21, Royal Oak Township, the formation was reached at a depth of 1,543 feet (RO-68)[1] and penetrated for 950 feet of which 609 feet were rock salt. Approximately 23 miles to the west in section 21, Lyon Township, the Salina beds are at a depth of 2,025 feet below the ground surface. At this location the well (LY-5)[2] penetrated 1,585 feet of the indurated sediments of which 690 feet were salt. Individual beds of salt varied in thickness from 5 to 205 feet. In the Lyon Township well salt water was reported between the depths of 3,250 and 3,270 feet.

BASS ISLAND GROUP (CAYUGAN SERIES)

The Salina beds are succeeded by the Bass Island group which has an approximate thickness of 435 feet. The Bass Island is reached at depths of about 1,600 feet in the southern part of the county (Lyon and Royal Oak townships) and at 2,667 feet in the northern part (Brandon Township). Well records in Oakland County reveal the Bass Island to be dominantly composed of dense to finely crystalline dolomite, light gray, buff to brown in color with some chert and traces of anhydrite. Sandy, shaly or gypsiferous zones appear in the sequence. The basal contact of the Bass Island formation is difficult to recognize on the basis of well cuttings because of lithologic similarity with the underlying Salina and the rarity of fossils. However the contact with the overlying Sylvania sandstone is easily distinguished on the basis of lithology.

As shown on the geologic map of Michigan, the Bass Island group consists, in ascending order, of the Greenfield dolomite, Tymochtee shale, Put-in-Bay dolomite and the Raisin River dolomite. Exposures of the upper two formations are in quarries in Monroe County, south of Detroit. The dolomite formations are generally light to drab gray or brownish in color, thin bedded with some zones bearing ripple marks and mud cracks. Locally they may be cherty or siliceous or have some thin shales. Pyrite scattered throughout the beds, upon weathering produces brownish stains or spots. Crystal masses of calcite, celestite and fluorite are found in many cavities and seams. Some thin shales and oolitic beds may be observed. The lower two formations of the group have been noted in wells only. According to Sherzer (1916, p. 47), fossils are most abundant in the upper formations and are relatively lacking in the lower beds. The most characteristic fossil is a small brachiopod *Whitfieldella prosseri*. Stromatopora reefs are known to be in the Greenfield formation. It is possible that such fossils if recognized in cuttings may be significant in the recognition of the zones. Ehlers and others (1951, p. 10) classify the Greenfield and Tymochtee in the Salina group in contrast to the classification proposed by Lane and others in 1909.

Only two logs of deep borings in Oakland County indicate penetration of the total thickness of the Bass Island. The deep boring in Lyon Township (LY-5) reveals that the beds are dominantly dolomitic with no appreciable shale that might be equivalent to the Tymochtee shale, which the geologic map of the state records as 90 feet in thickness. The deep boring in Royal Oak Township (RO-68) shows 68 feet of "rotten lime or shale" at the bottom of the Bass Island. Whether this in part represents some of the basal shales in the Greenfield member of the group is not ascertained since the contact between the Salina and Bass Island is difficult to place on lithology alone. In logs from other areas both fresh and mineralized waters have been recorded.

[1]Royal Oak Well No. 68.

[2]Lyons Well No. 5.

Middle Devonian

DETROIT RIVER GROUP (ULSTERIAN SERIES)

On the basis of a classification proposed by Ehlers and others (1951, p. 10) the Detroit River group is of Middle Devonian age and consists, in ascending order, of the Sylvania sandstone, Amherstburg dolomite, Lucas dolomite and the Anderdon limestone formations.

The Sylvania sandstone formation rests disconformably on the Raisin River dolomite except where it may be underlain by Bois Blanc beds. Its contact with the Raisin River formation is well exposed in the Holland quarry, approximately 7.5 miles south of Silica, Ohio. At this locality the basal beds of the Sylvania contain pebbles of the Raisin River dolomite, and some fractures in the dolomite were noted to be filled with sandstone. The contact of the Sylvania with the Amherstburg is not clearly defined as many of the lower beds of the Amherstburg are dolomitic sandstones. The Sylvania is a white or light gray, fine to medium sandstone in which the individual grains are frosted, subangular to round in shape and poorly cemented. The sandstone is extremely friable upon exposure to weathering and when washed is compared to granulated sugar. Beds of light gray to brown dolomite, some of which are crystalline and contain some gray chert, may interrupt the sandstone. An exposure of the Sylvania in a quarry at Rockwood, Wayne County, Michigan, displays poorly defined and irregular bedding. Individual beds range in thickness from several inches to a few feet. The beds are nearly level or slightly tilted and in places show a lamination that is inclined to the bedding planes. This lamination and the frosted appearance of the sand grains suggest wind-transported sediments which at a later time were reworked by a transgressive Devonian sea. Cavities and seams lined with calcite and celestite are quite numerous and some rare native sulphur may be found. The formation is quite barren of fossils but the existence of former plants and/or animals is indicated by carbonaceous partings. Some suggestion of plant remains can be found in the higher beds exposed at the quarry. Ehlers and others (1951, p. 10) report a meager fauna consisting of crinoid columnals, *Favosites* sp., dendroid graptolite fragments and other indeterminable fossils. These forms were reported from the upper 33 feet of the sandstone exposed in the quarry. Beneath the floor of the quarry, the formation, formerly exposed along the walls of the crusher pit, consists of 12 feet of similar sandstone underlain by 15 feet of highly arenaceous dolomite which in turn is underlain by 30-35 feet of sandstone. The known total thickness of the formation at this quarry is 90-95 feet. In the arenaceous dolomite Ehlers and others (1951, p. 7) report bands of chert nodules and a fauna consisting of gastropod and pelecypod fragments, *Mesoconularia* sp., *Tentaculites* sp., and worn pieces of arthrodiran bone. Water seeps at the quarry have a strong odor of hydrogen sulfide. The thickness of the Sylvania in Oakland County indicated by the well records ranges from 250-325 feet in the southern part to 147 feet in the north. The latter figure may be incorrect since unstudied lithologic changes may disguise the true thickness of the formation. The occurrence of salt water in the formation was reported at a depth of 836 feet during drilling operations in Royal Oak Township.

The remaining three formations of the Detroit River group that succeed the Sylvania are difficult to differentiate in well records on the basis of lithology alone. The combined thickness increases from 325-350 feet in the southern part to 430 feet in the northern part of the county. The Amherstburg and Lucas beds are dominantly dense to finely crystalline dolomites, buff or light brown to brown in color, interspersed with some dark gray to black micaceous shale and with some limestone. Dolomite beds containing some anhydrite and gypsum (selenite or earthy gypsum) are found throughout the section. The lower beds contain an increased amount of angular to subangular quartz grains. The lower limit of the Amherstburg is easily recognized on the basis of lithology, but the upper limit of the Anderdon limestone (member of the Detroit River group) is more difficult since the beds of the overlying Dundee are also limestones. Differentiation of the individual beds in well cuttings no doubt can be made possible by thorough studies of insoluble residues, microfauna or spectrochemical analyses of trace elements. The spectrochemical method should be useful in distinguishing disconformities, since oxidizing conditions accompanying weathering should result in the concentration of such elements as iron, manganese and aluminum.

The formations of the Detroit River group are exposed in quarries in southeastern Michigan and northwestern Ohio. Though difficult to distinguish from the older Bass Island on the basis of lithology, the dolomites of the Detroit River group contain fewer oolitic limestone beds, but the presence of celestite, calcite, and sulphur is more noticeable. The deep oil and gas well borings in the Oakland County area show the occurrence of porous zones in the sequence which, when penetrated, yielded water some of which was black in color. At Sibley quarry near Wyandotte, Michigan, beds of the Detroit River are exposed along the quarry floor. Near the approximate center of the quarry are several artesian springs which have a combined flow of approximately 600 gallons per minute. The water has a strong sulphur odor and taste.

The formations comprising the Detroit River group are best recognized by the fossil assemblages contained in each rather than by lithologic characteristics alone. Many of the fossils are small forms occurring as external and internal molds, and hence coarse cuttings from wells, if carefully examined, may yield enough fossils to permit recognition of the horizons. The following fossil list is taken directly from the work of Ehlers and others (1951, p. 23).

a. Amherstburg fm. in Livingston Channel, Amherstburg, Ontario. Molds of *Zaphrentis carinata* (Sherzer and Grabau), *Heterophrentis alternata* Sherzer and Grabau, *Prosserella modestoides* Sherzer and Grabau, *Schuchertella amherst-burgense* Grabau, *Stropheodonta homalostriata* Sherzer and Grabau, *S. vasculosa* Sherzer and Grabau, *Spirifer submersus* Sherzer and Grabau.

b. Lucas fm. in southeastern Michigan and northwestern Ohio. Excellent guide fossils for correlation of Lucas strata in the two regions are *Prosserella lucasi* Sherzer and Grabau, *P. planisinosa* Sherzer and Grabau, *Acanthonema holopiforme* Sherzer and Grabau, *Murchisonia subcarinata* (Grabau).

c. Anderdon fm. near Amherstburg, Ontario; Sibley, Michigan, and Silica, Ohio, recognized by occurrence of *Conocardium sibleyense* La Rocque, and several small pieces of gastropods that remain undescribed.

CAZENOVIA GROUP (ULSTERIAN SERIES)

The Cazenovia group consists of the Rogers City and Dundee formations in the northern part of the Southern Peninsula of Michigan. If the Rogers City extends to southeastern Michigan the two formations have not been differentiated as well records refer only to the Dundee. The Dundee formation consists largely of gray, buff to light brown limestone beds that are finely to coarsely crystalline in texture and contain varying amounts of chert and a little gray to black shale. The upper limit is marked by the gray shales and limestones of the Traverse group. Where it is in contact with the shale, the top of the Dundee is easily defined, but when overlain by a limestone layer, the separation between the Dundee and Traverse is more difficult and unsatisfactory. The lower contact, as previously stated, is difficult to place since it rests disconformably on the Anderdon limestone. The formation exposed along the upper part of the wall at Sibley quarry is a gray, buff to bluish, thinly bedded to massive limestone, in several places displaying fine straticulation. Chert and secondary calcite are common, and in places the limestone becomes somewhat siliceous. Many carbonaceous partings may be noticed and some cavities have a slight show or suggest evidence of petroleum. Frosted quartz grains are abundant in the basal bed of the Dundee limestone. The formation is fossiliferous and contains the forms *Atrypa elegans* Grabau and *Brevispirifer lucasensis* (Stauffer) which are restricted to the Dundee according to Ehlers and others (1951, p. 23). The same species are present in northwestern Ohio, southwestern Ontario and near Rogers City in northern Michigan, and this is suggestive of the widespread nature of the Dundee sea.

The thickness of the Dundee in Oakland County, indicated by well records, ranges from 150 to 260 feet. Natural gas, sulfate and salt water which is generally artesian, have been reported in many records from various areas. In Royal Oak Township salt water was found in the Dundee.

TRAVERSE GROUP (ERIAN SERIES)

The Traverse group is undifferentiated in the well records of southeastern Michigan. It consists of a series of limestones and shales which occupy a stratigraphic position between the underlying gray to light brown Dundee limestones and the predominantly black to brown Antrim shales above. Available well records report that the limestones are dense to coarsely crystalline with a gray or buff to brown color. Most of the interbedded shales are blue-gray but some are brown in color. Some strata of magnesian limestone or dolomite appear in the sequence. In places the limestone strata are so fossiliferous that the term "shell limestone" is frequently used by well drillers to describe them. Chert and pyrite are present in both the limestone and dolomite strata. The Traverse-Dundee contact may be difficult to recognize in areas where a limestone bed of the Traverse rests directly upon Dundee limestone. In the Mackinac Straits region the Traverse beds lie disconformably on the Rogers City limestone (Ehlers, 1949, p. 114). In general, however, the limestones of the Traverse contain a large percentage of argillaceous matter, and this characteristic may be used to distinguish them when samples are collected (Sherzer, 1916, p. 58).

The Traverse in Oakland County increases in thickness northward from 215 to 363 feet as indicated by records of deep borings. Stratigraphic sections (fig. 8) in Oakland County suggest that the upper part of the Traverse consists largely of limestones, and that the lower strata are more shaly and interbedded with limestone or dolomite. Oil and gas shows have been indicated on several of the well records, and the occurrence of salt water in the Traverse has been reported in Pontiac Township.

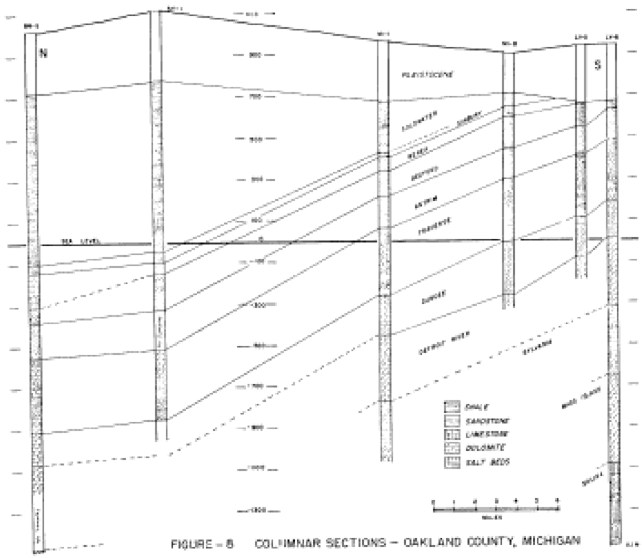

Figure 8. Columnar sections of consolidated sediments in Oakland County, Michigan

Mississippian

KINDERHOOK GROUP (IOWAN SERIES)

<u>Antrim Shale</u>

The Antrim shale is the oldest formation that occurs immediately beneath the surficial deposits of Oakland County. Its outcrop area beneath the drift is relatively small and is restricted to the southeastern half of Royal Oak Township and to the southwestern part of Lyon Township. On the geologic map (fig. 7) the relationship of the outcrop area of the Antrim with the next succeeding younger formation is suggestive of buried rock valleys. The formation, composed largely of black to brown with some dark gray to greenish-gray shales, is between the uppermost bluish-gray shales and limestones of the Traverse and the Bedford-Berea formations. Its thickness ranges from 124 to 168 feet. Calcareous phases are in the sequence and occasionally a reference to limestone or brown dolomite is made in well records. Descriptions of the Antrim, in other areas of the state where actual exposures are available, report the presence in the shale of large calcareous concretions of considerable range in diameter and thickness whose centers may contain crystals of calcite and siderite, and/or fossils. These concretions, when penetrated during drilling, may erroneously be called limestone beds. The well cuttings reveal that pyrite and marcasite are in the shale. On decomposition they stain the shale with iron oxides and affect the quality of percolating waters. Samples collected from a well recently drilled in Royal Oak Township (RO-52) show that the shale is black, highly carbonaceous, finely laminated, fissile and hard; the hardness often impels the driller to record it as "slate rock." Natural gas was encountered during drilling immediately upon penetration of the shale beneath the drift, and the water subsequently pumped showed traces of petroleum. The carbonaceous matter of the shales has been attributed to the presence of large numbers of sporangites (*Protosalvinia huronensis*), disc-like objects with thick walls which are believed to be the fossil spores of floating plants.

<u>Bedford Formation</u>

The Bedford formation occupies a position between the dark brown to black Antrim shales and the overlying Berea sandstone. In the absence of actual exposures the problems of thickness determination and areal distribution of the Bedford formation within the county are difficult to ascertain on the basis of a few well records, especially when the overlying and underlying beds have a similar lithology or when the available logs contain inadequate descriptions. From the information available, the Bedford is dominantly a gray to dark gray shale with scattered beds that are blue-gray in color and slightly micaceous. Some sandy, gray dolomite or micaceous sandstone may be present in the sequence. The lower limit of the Bedford formation is generally placed above the last beds of black or dark brown shales of the Antrim. The upper limit is more difficult to place since the overlying Berea, though dominantly sandstone, contains beds of gray shale of different thicknesses between the sandstone layers. Because of this difficulty in recognizing the upper limit, the Berea and Bedford formations are usually grouped as a single unit in the well records. However, from the best records available, the thickness of the Bedford in the county ranges from 65 to 155 feet. A deep well (LY-5) in section 21, Lyon Township, indicates the presence of the Bedford immediately beneath the drift deposits. The areal distribution of the Bedford in that area is tentatively indicated on the geologic map.

<u>Berea Sandstone</u>

Included in the Berea formation are fine grained, gray to light drab or brown, micaceous sandstone layers of different thicknesses which are nearly everywhere separated by beds of light gray to blue-gray shales that in places contain calcareous or dolomitic zones. The sandstone layers are generally well cemented, but friable zones, which are water-bearing, appear in the section. The reported thickness within the limits of the county is from 55 to 236 feet. The upper boundary of the Berea is placed just below the lowest brown to black shales of the Sunbury formation. Its areal distribution beneath the drift in Oakland County is an arc, two to five miles in width, extending from Troy Township southwestward to Farmington Township and thence swinging northwestward into Lyon Township. Salt water is present in the formation, and its occurrence was reported at depths of

1,017, 1,040, and 1,112 feet in a well (IN-15) drilled in Independence Township. At the first depth of 1,017 feet, the brine overflowed the top of the casing (approximately 1,005 feet above sea level), and then dropped to 40 feet and to 312 feet below ground level as the well penetrated the second and third depths.

Sunbury Shale

Succeeding the Berea sandstone is the Sunbury shale, whose thickness in the county, as reported on well records, ranges from 20 to 50 feet. Although the data available are meager, they indicate that the formation thickens northward. Position of the Sunbury in the section is easily recognized on the basis of lithology and change in color. Lithologically, the Sunbury formation is a hard, dark brown or dark gray to black shale with traces of dolomite. Some gray sandstone or light gray micaceous sandy shale is within its defined limits. The comment "looks like Antrim" is occasionally used by the drillers to describe the formation.

Coldwater Formation

Twenty-two of the twenty-five townships of the county are immediately underlain by the Coldwater formation. Its outcrop area, beneath the drift, is a broad belt as much as twenty-five miles wide trending northeast-southwest across the county. Only small areas exist in the northwestern and southern parts of the county that are underlain by younger and older formations respectively. Stratigraphically, the Coldwater lies below the Marshall formation and above the Sunbury shale. Its lower contact is easily recognized by the definite appearance of the dark brown or black shales of the Sunbury formation. The upper contact, according to Newcombe (1933, p. 54), is more difficult to recognize since it grades upward without sharp demarcation into the basal beds of the Lower Marshall formation. The change from Coldwater to the Marshall is indicated by the occurrence of several varieties of mica. Total thickness of the Coldwater in southeastern Michigan is approximately 850 feet. The formation is dominantly a blue to gray, micaceous shale or sandy shale becoming more arenaceous upward, and interspersed with limestone or dolomite beds, ten or less feet in thickness, which are not continuous over large areas. Interbedded shales and sandstones are in some parts of the section, but such zones are not persistent, or were missed by some of the drillers and hence not indicated on all logs. Reddish, greenish-gray or purplish shales may be near the base of the section, as revealed by two logs. The paucity of data does not permit this criterion to be established as a horizon marker.

A notable feature of the formation, where exposed elsewhere in the state, is the zones of clay-ironstone nodules. These are small to fairly large concretional masses characterized by shale centers surrounded by concentric limonitic shells. From the type area of the Coldwater in Branch County, Wooten (1951, p. 33) describes the presence of "ball" and "pillow" shaped clay-ironstones, the former averaging six inches in diameter, usually spherical, with a limonitic shell about a nucleus of dark, dense, micaceous shale. Many of the shale nuclei contained ammonoids (undescribed). The latter type of clay-ironstone is pillow-shaped and the largest found is 42 inches in diameter. Many contain a nucleus with septarian-like structure with secondary mineralization—usually of pyrite, sphalerite and barite (some barite has been reported as calcite). Fossils are rare, but Wooten (1951, p. 35) reports a fossiliferous zone from the same area which contained a variety of brachiopods, bryozoa, ostracodes and gastropods. Correlation of the Coldwater formation is difficult inasmuch as most of its lithologic characteristics or features are local in extent. It appears that deposition of these sediments was complicated by the transgressive and regressive nature of the Coldwater sea, which resulted in rapid changes in lithology. Salt water* and some gas are known to occur in this formation as reported in the records of wells (HO-5 and IN-15) drilled in Holly and Independence townships.

Marshall Formation

A single well record (HO-5) indicates the presence of the Lower Marshall beds in the northwestern part of the county. The outcrop area of the formation and its contact with the underlying Coldwater as shown on the geologic map can be made problems of debate. The well at Holly penetrates 125 feet of supposedly Lower Marshall beds which are described as "light drab shales with shells of sandstone." This description can easily be applied to the upper beds of the Coldwater formation. Data pertaining to the occurrence of this formation in Oakland County are lacking, and hence it is not possible to describe its occurrence in the area more adequately.

*Fresh water is in the so-called Coldwater Limestone in the western part of the state. See Part I of this report. *Editor*.

STRUCTURE

The Southern Peninsula of Michigan is a structural basin which extends into parts of northwestern Ohio and northern Indiana and beneath lakes Michigan and Huron. The center, and hence structurally the deepest part, of the basin is in the approximate center of the Southern Peninsula, toward which the Paleozoic strata dip from all sides. According to Sherzer (1916, p. 91), deposition of the Paleozoic sediments was nearly horizontal but with a slight central dip conforming with the basin-like structure. Subsequently the area underwent gentle tilting and warping, the effects of which accentuated the central dip and also produced local structures. In the southeastern part of Michigan, which includes Oakland County, the regional strike of the rock strata is northeast-southwest with the beds dipping gently in a northwesterly direction. The regional dip of the formations in Oakland County is somewhat modified by the extension of the Howell anticline (Livingston County) into the southwestern extremity (Lyon Township) of the county, as shown on the geologic map (fig. 7). Thus within the limits of the county, dip and strike determinations on top of the Antrim formation show that the rock strata have a more northerly dip and therefore an approximate east-west strike. In the southern part of the area the rate of dip is approximately 40 feet per mile, increasing to 45 or 50 feet at Pontiac and thence decreasing to 25 feet per mile in Independence

Township near the village of Clarkston. Dip of the beds on the northeastern limb of the local anticlinal structure trending northwest in Lyon Township (Howell anticline) is approximately 87 feet per mile. The trend of the structure itself is nearly at right angles to the northeast-southwest regional strike of the strata in southeastern Michigan. The occurrence of other local structures cannot be determined with the data available.

BEDROCK TOPOGRAPHY

The configuration of the bedrock surface (fig. 7) over most of Oakland County remains incomplete inasmuch as only 168 well logs, of the 1,138 collected, indicated that consolidated sediments were reached or penetrated. The greater number of these wells are within the limits of the glacial lake plain section of the county.

Bedrock elevations were obtained from the available records by subtracting the depth to rock from the ground elevation of the well. Elevations thus obtained were plotted on a base map of the region and contours were then drawn on the basis of these elevations and the bedrock-surface map of Michigan, which was used to establish the major trends of the divides with the adjacent areas. After initial contouring, the deep wells ending in drift were used to modify or to adjust the contours as much as the data would permit. This was accomplished by selecting the deep wells ending in drift and determining the bottom-hole elevation with respect to sea level. With these elevations plotted on the base, the positions of the contours were altered wherever necessary. All rock elevations used in the preparation of this map have been filed with the State Geological Survey so that they may be verified or eliminated as new data become available. In time new data will give a more detailed picture of the rock surface. From data available, the total relief of the area is approximately 550 feet. The known highest bedrock elevation of 967 feet was reported from section 24, Oxford Township, and the lowest elevation of 395 feet from section 6, Royal Oak Township. The principal bedrock divide trends northeast-southwest. It is in the northwestern third of the county, approximating the topographic divide, and declines in elevation toward the southwest as it passes from Oxford Township through Highland Township. From the position of this bedrock divide most of the rock surface slopes to the southeast excepting a small area in the extreme north and northwest parts of the county.

The physiographic subdivisions of the bedrock surfaces are twofold and consist of (1) the rock lowland of the Erie-Huron plain and (2) a part of the southeastern slope of the Thumb Upland rock surface. Geographically the rock lowland is in the southeastern extremity of Oakland County. It is developed partly on the Berea sandstone and older formations. Its elevation is generally 500-550 feet above sea level, except where the surface is incised by valleys. The major part of the county occupies a position along the southeastern slope of the rock upland (underlain by formations younger than the Berea), the elevation of which increases northwestward from 550 feet to 967 feet above sea level, the highest known point of the bedrock divide. Perhaps separating the two units is a low but somewhat steeper and dissected slope formed by the more resistant sandstone beds of the Berea formation. Excepting a small area northwest of the principal bedrock divide, pre-glacial drainage of the county was predominantly to the southeast. Since the greater number of rock wells and test holes were drilled in the southeastern part of the county, only the bedrock-surface configuration of the Erie-Huron lowland and the immediately adjacent upland slope can be shown on the bedrock-contour map (fig. 7). The most prominent pre-glacial valley extends from the city of Pontiac southeastward through the towns of Birmingham and Royal Oak and thence into Wayne County. Precise delineation of this valley between Birmingham and Pontiac was not possible because of lack of additional controls. Smaller valleys trending northwest-southeast which dissect the lowland and breach the lower part of the adjacent upland slope are likewise present. Whether these valleys extend in a northwesterly direction, beyond the upper limits of the Berea sandstone, is unknown, but very likely they become less significant as the regional bedrock divide is approached to the northwest. As shown on Figure 7, such small valleys are present in Farmington, Franklin Village, west of Birmingham, the Troy-Big Beaver area, Auburn Heights and Rochester Village—all in the southeastern part of the county. The delineation of major valleys and their tributaries in the upland area must await additional data from borings or geophysical surveys. Their presence is suggested by the few scattered known bedrock elevations on both sides of the divide. A buried valley of some prominence is suggested in the vicinity of the village of Ortonville in the northwest part of the county.

GEOLOGIC HISTORY

Pre-Pleistocene

The geologic history of the region may be briefly summarized as one of sedimentation, subareal denudation and glaciation. The earliest physical event is of Paleozoic sedimentation within a basin whose structural feature was apparently developed by late Silurian time, but whose development prior to such time was not of the same pattern. According to Kay (1951, p. 21), sediments of Cambrian and Lower Ordovician times, in the Southern Peninsula of Michigan, were deposited in a southwest plunging pre-Middle Ordovician trough that was not restricted by the Kankakee axis on the southwest as the present basin is. The thickness of such sediments increases southwestwardly but diminishes appreciably on the flanks of the trough. Middle and Upper Ordovician deposits are thickest just to the southeast of the center of the Southern Peninsula, which suggests that deformation began and initiated the present structure. Through continued sedimentation the warping became more prominent so that by late Silurian time, according to Kay (1951, p. 21), the present autogeosynclinal structure was well developed. The term autogeosynclinal is restricted to a basin structure developed within a hedreocraton (stable shield) but without adjacent highlands. Devonian and Mississippian sediments increase in thickness toward the center of the structural basin and, although principally of terrigenous debris, the sediments came from adjacent low lying lands or else from distant highland areas, inasmuch as nearby adjacent highlands are not associated with autogeosynclines. The youngest preserved sediments of Pennsylvanian age likewise are thickest in the center of the Southern Peninsula of Michigan. Owing to the fluctuating seas and the constantly changing environments, the sediments deposited, particularly in late Paleozoic time, were unlike lithologically in areal distribution and in geologic range. Since deposition was not uniform, a variety of rock formations now fills the structural basin. Paleozoic sedimentation was terminated by the Appalachian revolution, which probably started in Mississippian time and continued with increased intensity through the Permian period. This orogeny resulted in the general elevation of eastern North America and involved the closing of the Appalachian geosyncline through the folding, faulting, and jointing of the rock strata contained therein. In the Michigan basin the Paleozoic deposits were not greatly deformed, the general effect upon the region being wholly one of simple uplift.

With the exception of the Pleistocene, post-Paleozoic sediments are absent in Michigan. Because of this absence the number of erosion cycles that have been initiated and subsequently completed (peneplanation), or else interrupted is not known. This is a difficult problem to solve, considering the long interval involved and the fact that data to complete a detailed map of the rock surface are still unavailable. However, it is not unreasonable to assume that erosion cycles were initiated after each of the uplifts resulting from the orogenies that closed the Paleozoic and Mesozoic eras and from the disturbances at the close of the Miocene and Pliocene periods. Thus, following the Appalachian orogeny which terminated Paleozoic sedimentation, the Mesozoic history of Michigan was primarily one of prolonged subareal erosion of an uplifted basin. The number of erosional cycles initiated or completed during this long interval remains undetermined, but peneplanation of the area, whereby the gently dipping formations were beveled, probably occurred by the close of the Mesozoic era.

The Laramide revolution marking the close of the Mesozoic era probably resulted in simple uplift of the Michigan area, thereby initiating a new erosion (second) cycle of early Tertiary. It is conceivable that early Tertiary time may have been of sufficient length to result in peneplanation, thereby leaving no record, as far as is known, of the earlier peneplain. Since the basin structure of the Southern Peninsula remained unchanged, except for elevation, the resulting landscape changes throughout the early Tertiary cycle must have been similar to changes of the Mesozoic. The major drainage courses probably had similar positions and the escarpments, resulting from differential erosion of the more resistant formations, continued to shift in the direction of dip. The early Tertiary beveled surface was uplifted as the result of the Miocene disturbance that initiated but did not complete the third cycle of erosion. The less resistant rocks, stratigraphically below the Berea sandstone, are along the outer rim of the basin structure and hence were first to be reduced to the new base level which is now indicated by the bedrock surface of the Erie-Huron lowland. Its northwesterly limit is differentiated by the more resistant sandstone beds of the Berea formation. To the northwest the uplifted surface (Thumb Upland area) of the second cycle, being underlain by more resistant beds, was gradually incised by many new valleys. Fenneman (1938, p. 468) suggests that the uplands of Michigan represent the Highland Rim (Lexington) peneplain that has been extended with some certainty from Tennessee to western Ohio and into the Great Lakes section.

Inasmuch as the present rock surface (500-550 feet a.s.l.)[1] of the Erie-Huron lowland is incised by several valleys which also breach the Berea beds, it is suggested that the third cycle was interrupted by renewed uplift in Pliocene time or later. The present valleys in the rock lowland in Oakland County are not more than 75 to 150 feet deep and appear to be in the youthful stage (fig. 7), despite the fact that their original depth and characteristics were modified, no doubt, by subsequent and repeated glaciation. This fourth cycle, initiated by the Pliocene disturbance, was interrupted by repeated glaciation of Pleistocene time which modified the pre-glacial surface. The events as discussed concur with the work of Rhodehamel on the pre-Pleistocene geomorphology of the Saginaw lowland, where the configuration of the bedrock surface is much better known. Rhodehamel (1951, p. 152) states that the last cycle may have been initiated as late as Pleistocene but prior to Illinoian glaciation. In this respect it is conceivable that several small uplifts in late Pliocene and Pleistocene times may have occurred, but if base level by streams was attained each time, then their straths, or evidences of entrenchment, have not been recognized or more probably destroyed through abrasion by subsequent and repeated glaciation. The possibility that small uplifts occurred during the interglacial stages of the Pleistocene epoch is not precluded. This could result in the entrenchment of streams into the strath beveled by the previous cycle, provided the factors of time and thickness of drift mantle were favorable. Inasmuch as the glacial deposits form the most important hydrologic unit for groundwater recovery, the Pleistocene history and nature of its deposits are treated separately.

[1]Above sea level.

Pleistocene

The published results of earlier workers suggest several probable invasions of glacial ice in southeastern Michigan, the areas of accumulation of the ice sheets being either the Keewatin or Patrician centers (Sherzer, 1916, p. 104). That some of the earlier ice invasions fell short of later advances is strongly suggested in southeastern Michigan, but the problem of recognizing and dating the various invasions remains inconclusive since the evidence thus far gathered is insufficient. Drift deposits of earlier glaciation have either been destroyed or covered by deposits laid down by younger ice. Thus, the recognition of different tills in Oakland County must be made primarily from well records. Earlier glaciers in their retreating phase of the cycle must have deposited a system of moraines and glaciofluvial features which have yet to be recognized. A facet of the current investigation was an attempt to extend the mapping of the glacial deposits as exposed at the surface so as to include the full thickness of the glacial drift with a view of locating favorable areas for present and future groundwater projects. Recognition of buried deposits of the different glacial stages or substages necessitates a study of till fabrics. Except for small areas of recent alluvial deposits along streams, practically all of the surficial cover of Oakland County is related to the Wisconsin, or latest, glacial stage. Thus earlier drifts are covered, and their recognition on the basis of well data alone is exceedingly difficult. The fabric of the materials penetrated by wells is more often inadequately indicated on the logs, or if indicated, cannot be extended areally for any particular horizon owing to the absence of records, or to inconsistencies on the part of the drillers in their use of terminology, particularly the term "hardpan." The criterion of color and the nature of the clay in the majority of drill holes were completely disregarded, thereby adding difficulty to the interpretation of the available data.

ILLINOIAN DEPOSITS

The first ice movement over southeastern Michigan for which we have some direct evidence is the Illinoian glaciation. Sherzer (1916, p. 105) cites the presence of Illinoian till resting on the Detroit River formation which was temporarily exposed in the bed of the Detroit River during the excavation of the Livingston Channel near Stony Island. This till is more stony than the till of Wisconsin age exposed at Sibley quarry. The Wisconsin till is somewhat more laminated horizontally and is nearly free from pebbles. Some additional evidences of the Illinoian zone are indicated in several test borings that were drilled to bedrock along the Detroit River waterfront. The boring records indicated for the most part a blue clay, containing some sand, gravel, or sand and gravel zones, resting upon several feet of compact, stony, gravelly or sandy brown clay, poorly to well cemented which generally yielded sulphur water. This zone in turn is underlain by bedrock usually described as limestone which could represent strata of either the Dundee or Detroit River formations.

Stanley (1936, p. 22) calls attention to what seems to be Illinoian till exposed along the bed and lower slopes of the Grand Trunk Railroad cut through the Inner Defiance Moraine just east of Bloomfield Center. The Illinoian till is described as gray in color and more indurated than the overlying Wisconsin till. The two tills are separated by a bed of sand and gravel which in places is well cemented by lime. Data secured by the writer's examination of the cut, show that it can be argued that the sequence and nature of the materials exposed in the cut may be related to the fluctuation of the ice front during a substage of Wisconsin glaciation. It is apparent that the evidence is much too inconclusive to say definitely that the lower till is of Illinoian age. Other indirect evidences cited by Stanley (1936, p. 22) on the pre-Wisconsin are descriptions of two areas where vegetal matter was encountered during the drilling of water wells. Pieces of black wood were found at depths of 50 feet (710-760 feet a.s.l.) during the drilling of several wells for the Oakland Hills golf course in section 33, Bloomfield Township. A two-foot log (guessed to be tamarack) was found at a depth of 150 feet (750-800 feet a.s.l.) in a well drilled in section 17 of the same township to a depth of 363 feet without encountering bedrock. The writer was informed by a driller that fragments of wood were taken out from a well (TR-2) at a depth of 224 feet (525 feet a.s.l.) which was drilled in the southwest quarter of section 3, Troy Township (Profile A, fig. 12). At this location rock was reached at 242 feet or at an elevation of 508 feet above sea level. From none of the drillings were samples reported saved for botanical examination or age determination by the carbon 14 method. Whether the plant matter represents the same time interval or different intervals in the glacial history remains uncertain. The occurrence of wood in drift so near the bedrock surface might well represent Illinoian till since it so nearly corresponds in position to the occurrence of brown till just above bedrock in the Detroit area. The other occurrences perhaps may represent a substage of the Wisconsin. The widely scattered nature of this evidence does not permit more than conjecture on the part of the writer.

Other evidences of earlier glacial stages, or substages of the Wisconsin, may be indicated by the presence of brown, red, or purplish clays and scattered sands that have been reported below the surface. If the change in color of the clays from the usual blue or gray represents oxidation, then the oxidized zones perhaps can be used to determine the sequence of glacial events if sufficient and properly distributed data are made available that show color changes with depth of materials penetrated. A well in section 12, Bloomfield Township (BL-18) showed 14 feet of purple clay resting on the gray shale at a depth of 208 feet (662 feet a.s.l.). In the northeast quarter of section 20, Pontiac Township, red clay or red stony clay was encountered in three wells (PO-37, PO-39, and PO-40) at depths of 233, 175, and 169 feet respectively or between horizons of 742 and 775 feet above sea level (fig. 9). Other records in which oxidized horizons are indicated are shown plotted on the three profiles drawn across the glacial lake plain of southeastern Oakland County (Profiles A, B, C, fig. 12). The purple "gumbo" clay just above the bedrock may be interpreted as Illinoian till, and the red clays in section 20, Pontiac Township, which are at a considerable distance above the bedrock in that area, represent a stage of Wisconsin glaciation (Gary?). The brown clays of the lake plain may be interpreted as substages, or fluctuations within the latest substage, of Wisconsin glaciation. This, again, is only conjecture based on rather fragmentary data, and other interpretations are quite apparent. However, the area under investigation is underlain by tills of several ice advances.

The problem of time designation for each of the horizons indicated can only be conjectured until more data become available. Although the results presented in this study are discouraging, the sequence of glacial events can be interpreted if a satisfactory procurement of data can be arranged. What is needed most is a series of detailed profiles, if not for the entire county, then at least for the southeastern part. Cooperation of the drillers is also needed to the extent of providing the State Survey with samples of plant matter found in drilling, and with detailed well records. Only then can much be added to the present knowledge of Pleistocene history in Oakland County. A more complete picture of the bedrock surface would help materially since the older tills are more apt to be preserved in the rock valleys than on the ridges. The botanical examination and age determination of wood fragments would permit some delineation of the tills, and the oxidized zones could be used to extend the correlations into areas where more positive evidence is lacking. Such samples and related data will require the cooperation of the drillers who in turn must be shown the mutual benefits that may be derived from such a program. Because the old land surface slopes to the southeast it is reasonable to believe that earlier Wisconsin or pre-Wisconsin glacial lakes existed and built beaches, the recognition of which would prove useful to the drillers and certainly to the intelligent selection of future well-drilling sites.

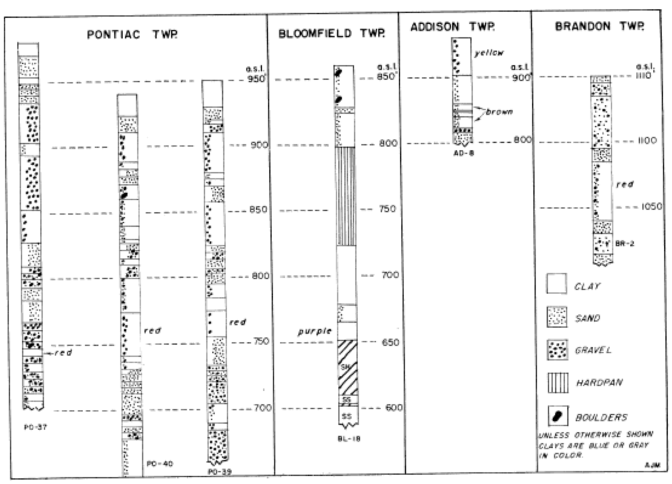

Figure 9. Logs of wells showing probable oxidized zones in drift

Wisconsin Glaciation

The entire area of Oakland County was covered by two lobes of the Wisconsin glacier: The Saginaw lobe which advanced from the north and the Erie-Huron lobe from the southeast. Both lobes joined approximately along the northeast-southwest line of hills that stands above the present outwash plains as shown on the glacial maps of Oakland County (fig. 2). The withdrawal of the ice from the county began with the development of a re-entrant between the, two lobes that first uncovered the area in the vicinity of Milford Village, and then gradually extended and widened in a northeasterly direction. As the two lobes separated, the meltwaters discharged by the ice front from all sides of the re-entrant deposited outwash sands and gravels in the form of plains that increase in elevation northeastward. The southernmost, and hence earliest formed, is the Commerce Plain which is centered about the village of Commerce. The highest part of this plain is adjacent to the Fort Wayne Moraine immediately to the southeast and has an elevation of 950 feet above sea level. From this line the plain slopes northwestward indicating the direction of meltwater flow when the Erie-Huron ice front stood along the position marked by the Fort Wayne Moraine. The Drayton Plain, named after the village of Drayton Plains, lies to the northeast of Commerce Plain and was the second to form. It attains an elevation of 1,000 feet and has a general slope to the southeast, suggesting deposition primarily by meltwaters coming from the Saginaw lobe ice front. The Clinton River roughly parallels the southeastern edge of this plain and thereby drained the meltwaters during its formation. The north-easternmost plain, and the last to be developed in the county, is known as the Oxford Plain in the vicinity of Oxford Village. Its elevation ranges from 1,060 to 1,085 feet and slopes generally to the southwest, and may have been formed by the meltwaters derived from both lobes but more probably from the Saginaw lobe. It is interesting to note the position of the line of kames and morainic hills with respect to the outwash sand and gravel area shown on the glacial map (fig. 2). The line of hills appears to divide the area into almost equal parts. Leverett (1915, p. 187) postulates the origin of the kames to have taken place in sags of the ice while the Saginaw and Erie-Huron lobes were still in contact. With this assumption then these kames are older than the moraines and gravel plains of the area.

During the development of the outwash area, the Erie-Huron lobe occupied a position along the Fort Wayne Moraine, and the Saginaw lobe a position coincident with the northerly range of morainic hills and till plains in the northwest part of the county. The elevation of this northerly range decreases northwestward from 1,100 feet to 850 feet and marks the direction of recession of the Saginaw lobe from the county. From the Fort Wayne Moraine, the next known position taken by the Erie-Huron lobe is marked by the Outer Defiance Moraine. Its northwestern boundary is not clearly defined in the county since it lies against and hence is confused with the Fort Wayne Moraine. However, southwest of the county and in the vicinity of Ann Arbor, an outwash area separates the two moraines. The next position of the Erie-Huron ice front is marked by the Inner Defiance Moraine, a narrow hilly belt not exceeding three miles in width, which enters the county in southeastern Novi Township and extends northeastward through Franklin Village and. Bloomfield Hills, finally becoming confused with the Outer Defiance and Birmingham moraines southwest of Rochester Village. The moraine is generally lower in elevation and less rugged than either of the previously formed moraines. To the northwest it is separated from the Outer Defiance by a sand- and gravel-filled channel which represents the marginal drainage from the ice front while it remained at its new position. To the southeast the Inner Defiance is separated in part by the Birmingham Moraine and the highest beach of the glacial lake plain. Eskers are associated along the southeastern slope of this moraine, but all of them are poorly developed and of short length.

The Fort Wayne and the Outer and Inner Defiance moraines comprise the southerly range of hills, mentioned earlier in the report, which has a trend across the county similar to the trend of the northerly range of hills.

Succeeding the Inner Defiance is the Birmingham Moraine, the southwestern part of which was deposited in the waters of glacial Lake Maumee and the northeastern part on land. The land moraine extends from East Long Lake Road northeastward to Rochester Village, and the waterlaid part of the moraine southwestward toward the city of Birmingham. Its characteristics are comparable to the previously formed moraines but the relief is not as conspicuous. Taylor (1915) describes the Birmingham Moraine as being formed by the readvance of the ice after it had previously withdrawn from the Inner Defiance to a position several miles to the southeast. The Detroit Interlobate Moraine was deposited contemporaneously with and at right angles to the Birmingham Moraine. It trends southeastwardly through Southfield and Royal Oak townships and thence into Wayne County. It is a broad, low, smooth ridge apparently deposited under the ice along the contact of the Huron and Erie lobes and below the level of Lake Maumee to the west. Topographically it is neither conspicuous nor easily recognized, but it influenced the drainage at the time, and its position is now indicated by the sharp change in trend of the glacial lake beaches and by the contours on the topographic map. The position of this interlobate moraine is of interest with respect to the trend of the major rock valley in southeastern Oakland County. It appears that the shallow rock valley was influential in the sub-glacial deposition of the moraine along the line of contact of the two lobes. Both waterlaid moraines have been reworked in part by the waters of glacial Lake Maumee and are covered now by lacustrine clays, sands and gravels.

Since the natural slope of the topography was to the southeast, a series of glacial lakes was formed between the moraines to the north and the ice front to the south as the glacier receded. The sequence of these glacial lakes has been determined by Leverett and Taylor (1915). Several beaches of the earlier formed glacial lakes are well represented in Oakland County. The individual glacial lake beaches are at progressively lower elevations southeastward and represent the gradual withdrawal, and temporary readvances, of the ice as it receded from the area. Drainage of the earlier formed lakes was to the west; at first through the Fort Wayne Outlet by way of the Maumee River (which flowed in a reverse direction to the present day Maumee River) and later by the Grand River channel. Eventually drainage of the glacial lakes to the Atlantic was made possible after an outlet was uncovered by the retreat of Wisconsin ice near Syracuse, New York. This outlet established the level of glacial Lake Wayne in southeastern Michigan. Thus the southeastern extremity of Oakland County consists of a glacial lake plain which is in part developed over the waterlaid Detroit Interlobate and Birmingham moraines. The surface of the plain is characterized by clayey and sandy sediments and coarser elastics associated with such surface features as beaches, eskers, deltas and river terrace gravels.

NATURE AND STRUCTURE OF THE DRIFT

Unconsolidated materials which are predominantly of glacial origin and which have been deposited on a surface directly by the ice, or indirectly by meltwaters derived from the glacier, are termed "drift." Deposition accomplished by the glacier directly results in a mantle of rock waste which consists largely of unassorted particles of various sizes and composition. Such deposits are frequently called "tills" or "unstratified drift." Where the action of melt-waters has been the dominant agent of deposition, the materials deposited though heterogeneous in size and composition, are for the most part sorted into layers, lenses or beds in accordance with the laws of running water. In contrast to the unstratified tills, these glacial deposits fall under the heading of "stratified drift," and are associated with such glaciofluvial features as outwash plains, kames and eskers.

Moraines and Till Plain Deposits

The moraines forming the northerly and southerly belts of hills in Oakland County are composed largely of unassorted till deposits. The particles comprising the till range in dimension from fine clays to large boulders. Nearly everywhere the finer materials form the matrix in which the coarser fragments are imbedded. Porosity of such deposits may be high and hence capable of storing large quantities of water, but permeability on the other hand can vary greatly, depending upon whether the matrix is predominantly clay or a matrix that is sandy or gravelly. Within the morainic and associated till plain areas, layers of sand and gravel may be the result of deposition by meltwaters which are always associated with large ice masses. These sands or gravels may be at or below the surface, their intercalation throughout the morainic and till plain areas being "chaotic." These pockets of more permeable materials are not always extensive in areal distribution, nor are they present at any established depth or thickness beneath the surface. This condition has, on occasions, resulted in misunderstanding between driller and client since neighboring wells may have great differences in depth within relatively short distances. Because of the complex nature of glacial deposition, the correlation of the materials from well to well is not possible, and test holes or wells reveal only the nature of the sediments for the point drilled. Many buried layers of sand and gravel when penetrated yield adequate water supplies for most domestic and farm purposes, and in some places a larger stratum is found which is capable of development for an industrial or municipal supply. The city of Pontiac has its water supply drawn from sand and gravel deposits which are traceable for a distance of several miles. These deposits, in all probability, represent outwash material deposited earlier in the glacial history of the area and subsequently buried by younger deposits of till that now constitute the present morainic hills and till plains.

The absence of sufficient bedrock-surface elevations in the county made it difficult to evaluate the thickness of the surficial cover. In the area covered by the moraines and assorted till plains, the thickness of the drift, as indicated by well records, has been as much as 390 feet, and an average thickness of 250 feet is not unreasonable to assume for the entire area. Inasmuch as the greater part of the morainic deposits is on the dissected rock surface of the Thumb Upland, thicknesses in excess of 390 feet may be more frequently reported. From the drift-thickness map (fig. 2) the greatest thickness, from 300 to 390 feet, is seen to be over an area marked approximately by the junction of the outwash plains with the Fort Wayne Moraine and trending roughly northeast-southwest. The meager data available suggest that the thickness increases in a northeasterly direction, which harmonizes with the retreat of the re-entrant that developed between the Saginaw and Erie-Huron ice lobes as the ice masses wasted away. It is also noted that the greatest thickness of drift reported has been deposited southeast of the bedrock-surface divide. In section 28, Oakland Township, near the unincorporated settlement of Goodison, a well penetrated 550 feet of morainic deposits before bedrock was reached. Unassorted till 300 to 345 feet thick is reported in the till plain and the moraines that were primarily deposited by the Saginaw lobe. These areas appear slightly northwest of the bedrock-surface divide. More precise delineation than is shown on the drift-thickness map could not be made for lack of additional bedrock data.

The possibilities of securing adequate water supplies in the morainic belts for most domestic, farm, and commercial purposes are reasonably good considering the number of sands and gravels that may be encountered during drilling. Where larger water supplies are desired, it may be advisable that each of the sand and gravel strata below the level of groundwater saturation be developed and screened. The proximity of the morainic belts to the more highly porous and permeable outwash deposits, which are of considerable areal extent, favors adequate indirect recharge since movement of groundwater through the unassorted till and into the "pockets" is accomplished regardless of the varying and changing permeabilities of the sediments. Direct recharge of the buried sands and gravels by precipitation is also favored since the moraines are characterized by morainic lakes and depressions which act as reservoirs for surface run-off.

Outwash Deposits

The largest area of stratified drift is in the outwash plains separating the two morainic hill belts of the county. Smaller areas of stratified deposits occur between the Inner and Outer Defiance moraines, and in the morainic tract deposited by the Saginaw lobe in the northwestern part of the county. In the interlobate area, 300 feet of surficial mantle, principally of sand and gravel, has been reported. Clays are generally subordinate except in the scattered areas of morainic hills that rise above the level of the plain. Clays were almost or wholly absent in several wells 200 feet deep. It is probable that parts of the outwash plain may extend beneath the morainic belts since it is conceivable that the fronts of the ice lobe fluctuated during the glacial period. The stratified and sorted character of the sands and gravels is evidence of abundant melt-waters that were derived from all sides of the re-entrant developed between the Saginaw and Huron lobes. The degree of coarseness of the sediments from layer to layer varies considerably, but generally the materials of the outwash are of greater permeability than deposits in the moraine, till plain and lake plain sections of the county. The absorbent character of the outwash materials is indicated by the nearly complete absence of erosion, principally gullying along the steep slopes. In addition, the pitted nature of the outwash plain surface, and its numerous lakes, make this the most favorable catchment area for the precipitation that falls upon it. Therefore from the outwash storage reservoir gradual indirect recharge of the more permeable zones in the moraines and glacial lake plain sections of the region is possible.

Several of the natural lakes, as well as the lakes formed in abandoned gravel pits, are without inlets or outlets. Thus the water surfaces of such lakes represent the surface extension of the water table. In many places the static water-level elevations as measured in wells coincide with the water-surface elevations of the lakes in the vicinity. Some of the scattered clusters of hills that rise conspicuously above the level of the outwash plains are kames that formed along the junction of the two lobes, or are cross-moraines consisting of unassorted till which were probably deposited by ice bridges connecting the two lobes, or else may represent static conditions of the re-entrant as the ice retreated northeastward. Excepting the wells drilled in the kames, the static water levels of many wells in the cross-moraines are not in harmony with the water-surface elevations of the lakes. Most wells drilled in this section of the county are reported successful and have very favorable yields. Driven wells are most abundant around the beaches of the many inland lakes that have been developed in the past decade for recreational activities, domestic residences and estates.

Glacial Lake Plain

The surficial mantle of the lake plain that overlies the rock surface of the Erie-Huron lowland area ranges in thickness from 75 to 345 feet. In general the mantle has a thickness of 100-150 feet in the southeasternmost part of the lake plain and increases to 150-200 feet northward as the southern morainic belt of hills is approached. The greater thicknesses, as far as well records show, are in the bedrock valleys that were carved by pre-glacial streams. One well penetrated 345 feet. In comparison to the other drift areas, the mantle of the lake plain region consists of unassorted till, sandy and clayey sediments of lacustrine origin, and sorted sands and gravels of the beaches, spits, bars, deltas and river terraces. The unassorted till deposited directly by the ice is in part waterlaid and thus partially reworked by water, at least in its upper part. Although well records report abundant clay in the glacial lake plain, most of it is clay having various admixtures of sand, gravel, pebbles, or even boulders. The surface of the lake plain is veneered for the most part with lacustrine materials such as sandy clay or clay and in addition characterized by fine to coarse sediments that have been sorted by wave action or running water. The glacial lake beaches and sand bars composed of sediments ranging from fine sands to coarse gravels are the result of wave action of glacial meltwaters that were ponded between the morainic belt and the ice front. The Lake Whittlesey spit in Southfield Township was developed by shore currents that prevailed at the time of deposition. The deltas and river terraces, composed of coarser elastics mainly well sorted, stratified and crossbedded, are features deposited by streams flowing southeastward from the outwash and morainic areas and discharging into the glacial lakes. As lower outlets were uncovered by the receding ice, the lake levels declined, thereby establishing new base levels for the streams of the area. This led to the dissection of the deltas and also to the development of river terraces. The origin of these features and their sequence of development have been adequately described by Bay (1938, p. 13).

The nature of the sediments and the surface features just discussed is attributed to the last withdrawal of the ice. Bearing in mind the southeastward slope of the rock surface and considering the available evidence of earlier periods of glaciation, or substages of the Wisconsin glaciation, it appears valid to assume that similar events may have occurred more than once in the area. Thus similar depositional features that are geologically older may be beneath the surface but have yet to be recognized. No doubt some of the earlier formed beaches or other sorted deposits of sand and gravel were completely obliterated, altered, covered, or partially destroyed by later ice advances. And to all of this may be added the changes resulting from the fluctuation of an ice front of any particular glacial stage. Thus the lake plain area, because of its complex history, is composed predominantly of a heterogeneous assortment of sediments characterized by a wide range in porosity and permeability. Associated with the till and lacustrine deposits are sand, gravel, or sand and gravel deposits which are frequently called "veins, pockets or lenses" by the drillers. This distribution within the lake plain mantle has often been described as "chaotic," which in a sense is not truly descriptive. Rather, the distribution of the permeable zones should be described as "complex" since the details of glacial erosion and deposition cannot be interpreted to a final degree. The "pockets or veins" range in thickness from a few inches to tens of feet. They vary greatly in porosity and permeability, and rapidly lense out or grade into finer sediments or they interfinger with the waterlaid till or the material of lacustrine origin. Despite the complex distribution of the coarser and sorted zones, it appears that they are by simple and devious ways interconnected or closely interrelated with each other, thereby permitting the percolation of groundwater from the intake areas to the north.

The buried sand and gravel zones represent depositional features that are difficult to recognize or correlate on the basis of well records alone. Correlation of well records is made difficult by the complex nature of sedimentation by both ice and water, also the lack of uniformity among drillers in recording the nature of materials penetrated does not reveal the "till fabric." In addition, wells are constructed where they are needed, hence their records, if obtained, are not evenly distributed over the area but are bunched together. These factors make the problem of recognizing buried features extremely difficult, and the development of large water supplies is dependent upon the discovery of large sand and gravel bodies.

Chapter III: GROUNDWATER HYDROLOGY

OCCURRENCE OF GROUNDWATER

Water beneath the earth's surface which occupies the pore spaces or other interstices of both primary and secondary origin is generally termed subsurface water. This water lies in that part of the earth characterized by the presence of pores, fractures, voids and other openings, and is differentiated from magmatic or internal water that exists deep within the earth where no voids exist and hence where the water is in molecular association with other earth materials. The water in the upper zone is of prime importance to man since it is a natural resource in part recoverable for his use.

Subsurface water reservoirs may be subdivided into two zones, namely, the zone of saturation and the zone of aeration. The plane of separation between the two zones is known as the water table. In the zone below the water table, all the interstices of whatever origin are occupied by water, and thus the zone is properly called the groundwater zone. It is primarily from this zone that water is recovered by means of wells and springs for water-supply purposes. Above the water table in the zone of aeration the interstices are not filled with water excepting for periods of short duration during rainfall. In contrast to the underlying zone, the water that is present in the zone of aeration is not under a hydraulic pressure but is held within the zone either by molecular attraction or by capillarity. According to its occurrence within the zone of aeration, the water in this zone is classified as soil water, intermediate water and also as capillary fringe water which rises above the water table in capillary interstices.

MOVEMENT OF GROUNDWATER

The movement of water in permeable water-bearing formations within the saturated zone is accomplished by the differences in hydraulic head in different parts of the formation. The relationship between the various factors that control the quantity of water flow in permeable beds has been expressed by Darcy's law:

$Q = TIW$ where,

Q = flow in gallons per day through a strip of water-bearing material one foot wide and a depth equal to the saturated thickness of the material.

T = coefficient of transmissibility in gallons per day per foot of width of saturated material under a gradient of 100 per cent.

I = Hydraulic gradient in feet per unit distance in the direction of flow.

W = Width of water-bearing material at right angles to the direction of flow.

The difference in head between the place of water intake and the place of discharge provides the energy that keeps water in motion in the zone of saturation against the internal friction which is inherent in any permeable formation. The cross sectional area can be determined approximately from well logs and the factor of transmissibility from the thickness and physical properties of the water-bearing material. In the latter instance, the size, shape, arrangement and uniformity of grains that make up the formation, together with the degree of cementation, determine the amount of frictional resistance of the material to the movement of groundwater.

CONFINED AND UNCONFINED GROUNDWATER CONDITIONS

Groundwater beneath the level of saturation may be confined or unconfined. Unconfined groundwater conditions generally exist in areas covered by a mantle consisting of materials of uniform or nearly uniform characteristics. The top of the zone of saturation becomes the water table and the groundwater is thus stated to be under "unconfined or water-table conditions." In such a deposit of structureless material, the principal movement of the water is laterally in the direction of the hydraulic gradient. When permeable formations below the level of saturation are between beds of lesser permeability, then artesian or confined groundwater conditions are established. In artesian structures, the water is under a pressure which is determined by the position of the water table in the highest part of the formation or at its intake area. From the intake area the water moves down the dip of the confined aquifer, but in its later course it may move up or down depending upon the deformation or structure of the water-bearing bed. The height to which confined water will rise in wells penetrating the aquifer is designated the piezometric or pressure-indicating surface. If the loss in head due to seepage and the frictional resistance of the aquifer is less than the total physical descent of the water-bearing material, then the water will rise in wells to some level above the top of the confined bed. On the other hand, if the loss in head is less than the slope of the land surface, the artesian pressure may be sufficiently high to result in flowing wells. Therefore, depending upon the loss in head due to frictional resistance, the water in wells penetrating a confined aquifer may rise (1) just above the confined bed, (2) above the water table but not to the land surface or (3) above the land surface.

The effects of pumping on groundwater levels are indicated in Figure 10. The pumping or dynamic water level is lower than the static water level, and the difference between the two is called the "drawdown," which results as water is withdrawn from a well. Under water-table conditions it is an actual lowering of the water-table surface; whereas under confined conditions it is a decrease in the artesian pressure or piezometric surface. In the water-table conditions, a cone of depression develops about a pumped well and, in the confined conditions, a cone of pressure relief. The amount of lowering and the size of the cone developed in either case depend upon the period and amount of withdrawal versus the rate of recharge. The greatest drawdown takes place near the well and becomes less as the distance from the pumped well increases.

It may be pertinent at this point to mention that under water-table conditions, the water pumped initially comes from storage in that part of the aquifer immediately surrounding the well. The cone of depression thus created gradually increases in depth and in area with continued pumpage until the cone diverts into the well an amount of water equal to the withdrawal. The rate of growth and shape of the cone depend upon the storage capacity and the permeability coefficient of the aquifer, and therefore the greater the capacity the slower the development of the cone. The cone of pressure relief of an artesian aquifer (confined conditions) develops more rapidly than the cone of depression of a water-table aquifer simply because its storage capacity may be many times smaller.

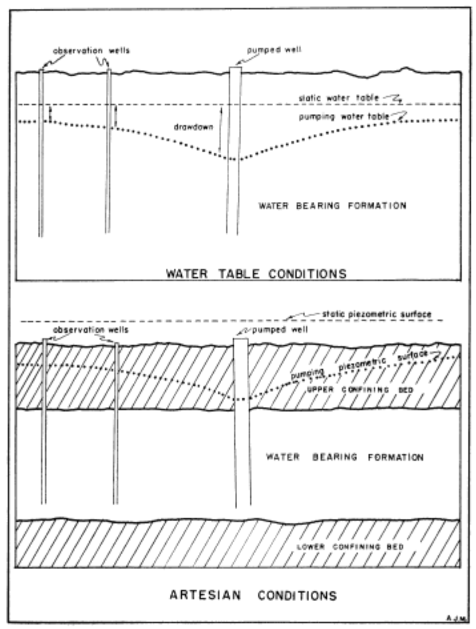

Figure 10. Pumping effects – water-table and artesian conditions

WATER-BEARING PROPERTIES OF CONSOLIDATED AND UNCONSOLIDATED SEDIMENTS

The quantity of water that may be contained in consolidated or unconsolidated sediments is determined by its porosity, but the amount that may be recovered from such storage is measured by its coefficient of storage. Under unconfined conditions the coefficient of storage may be considered to be the same as the specific yield of the water-bearing material which is the difference between 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.

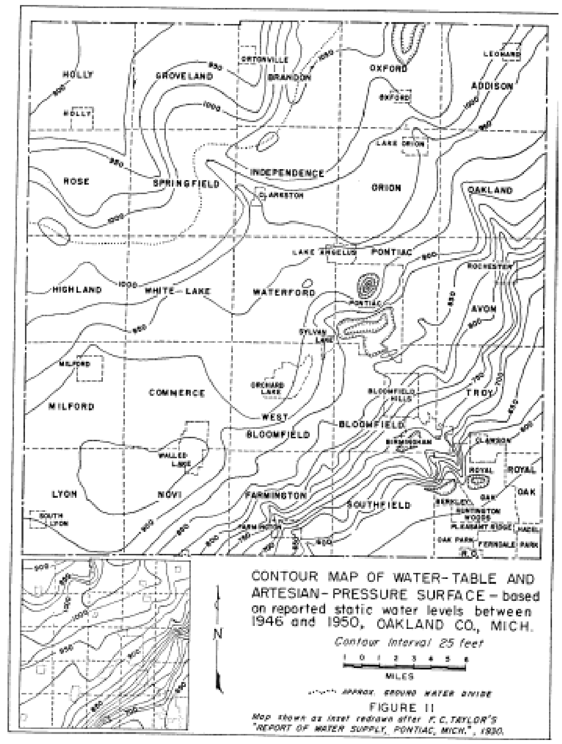

Figure 11. Contour map of water-table and artesian-pressure surface, Oakland County, Michigan

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 ground-water 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 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 ground-water levels in rural and suburban areas rose from several tenths of a foot to two feet, and in industrial areas depending on ground-water 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 out-wash 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 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 elastics.

[1]Gallons per minute.

[2]Personal communication.

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 recovery, 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.

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

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.

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.

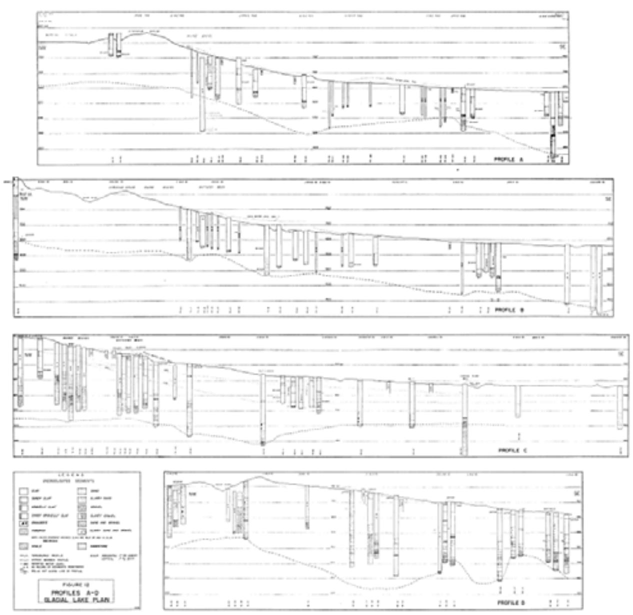

Figure 12. Profiles A through D – Glacial Lake Plain

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.

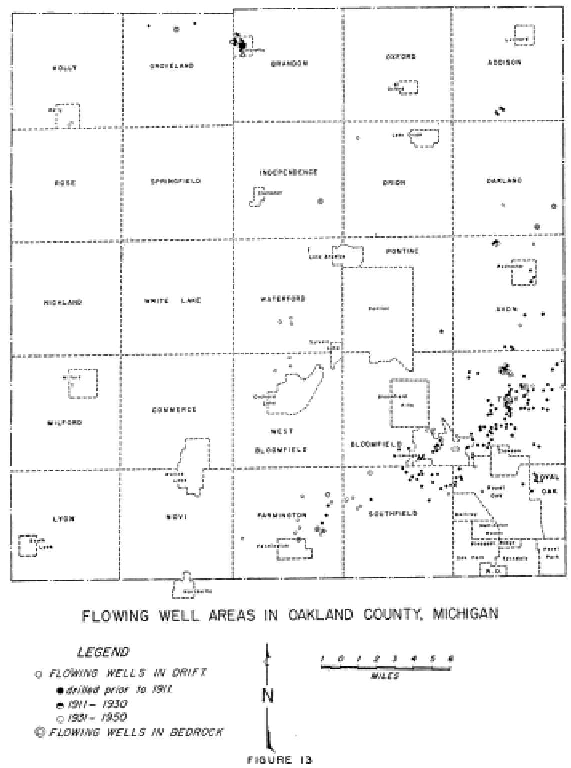

Figure 13. Flowing well areas in Oakland County, Michigan

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 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.

[1]Personal communication, September 13, 1949.

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.

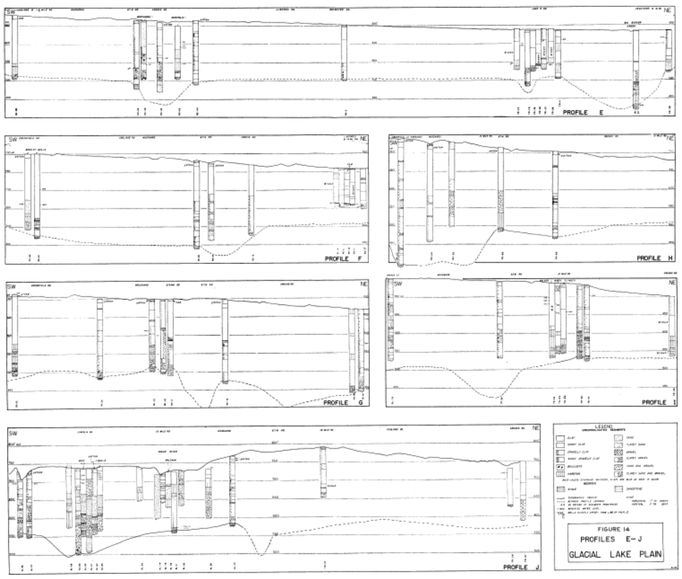

Figure 14. Profiles E through J – Glacial Lake Plain

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, South-field, 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 dimensions 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 elastics 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 elastics 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 elastics 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 ⅜-inch casing perforated with %-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 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 loss-age. 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.

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

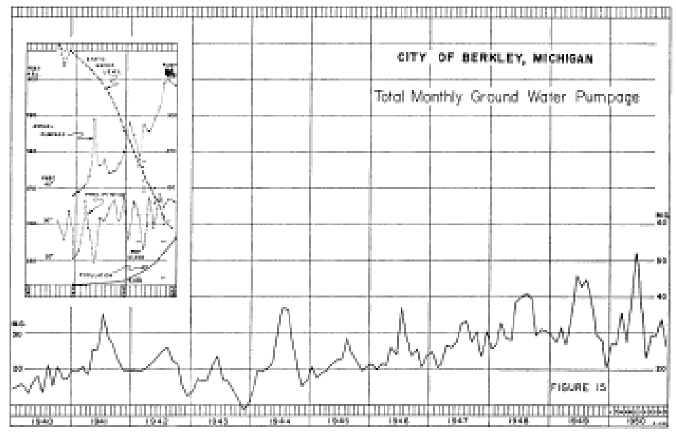

Figure 15. Monthly and annual groundwater pumpage, City of Berkeley, Michigan

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 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 elastics 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 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 ground-water 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 loss-age, assuming that the meters installed on well pumps and in consumers' dwellings were recording properly. In a survey 1 by the 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 loss-age 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 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 ground-water 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[3] 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 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.

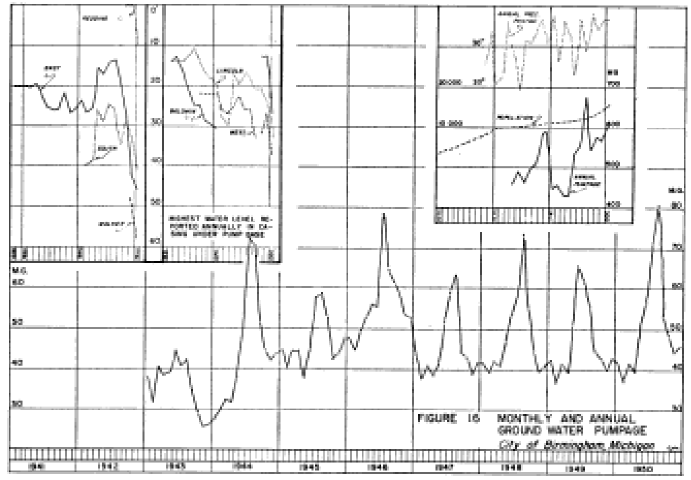

Figure 16. Monthly and annual groundwater pumpage, City of Birmingham, Michigan

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.

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

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

[3]Personal communication, September 13, 1948.

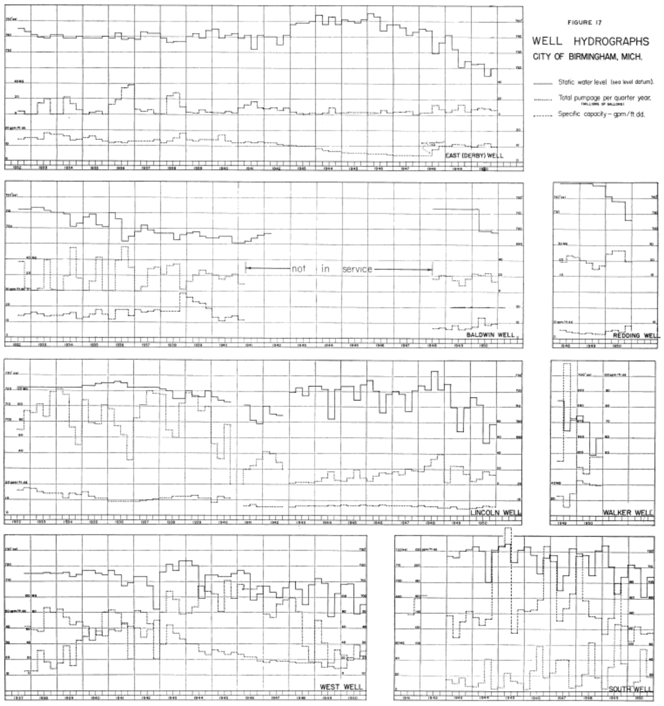

Figure 17. Well hydrographs – City of Birmingham, Michigan

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 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.

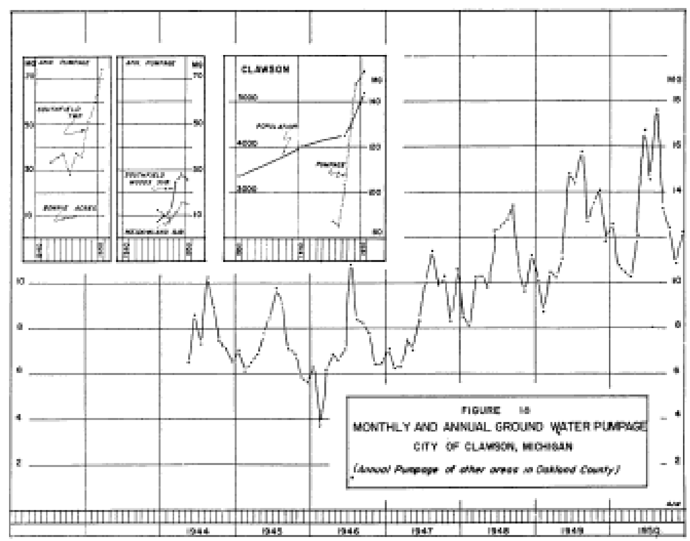

Figure 18. Monthly groundwater pumpage, City of Clawson and other areas in Oakland County, Michigan

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 out-wash 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.

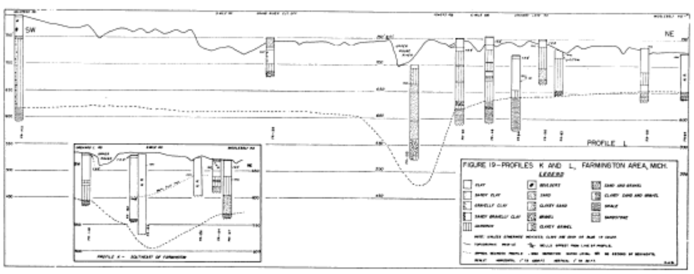

Figure 19. Profiles K and L, Farmington area, Michigan

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 between 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.[2] The profiles also show that 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 elastics 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 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.

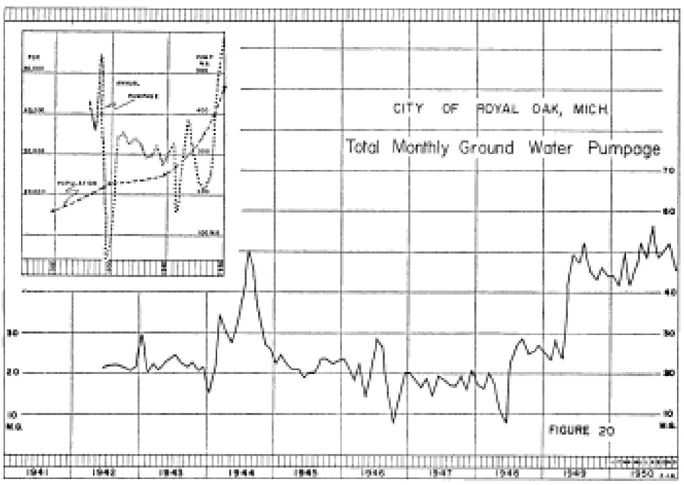

Figure 20. Monthly and annual groundwater pumpage, City of Royal Oak, Michigan.

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.

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

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

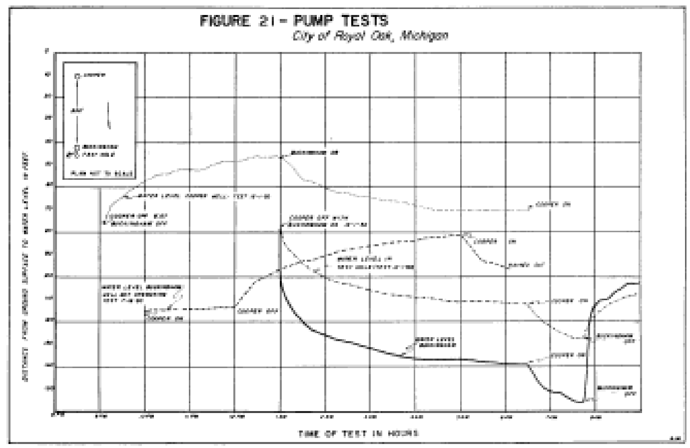

Figure 21. Pump tests, City of Royal Oak, Michigan

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, South-field 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 ground-water 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.

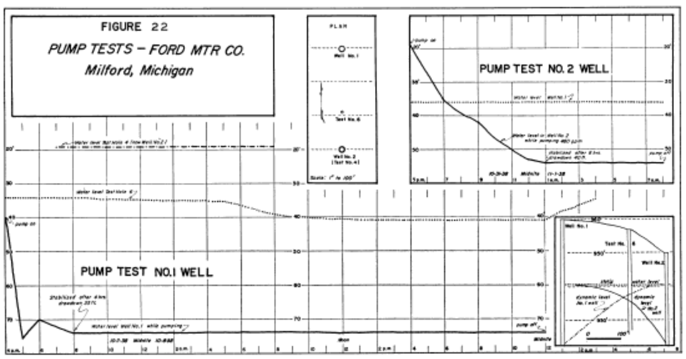

Figure 22. Pump tests, For Motor Company, Milford, Michigan

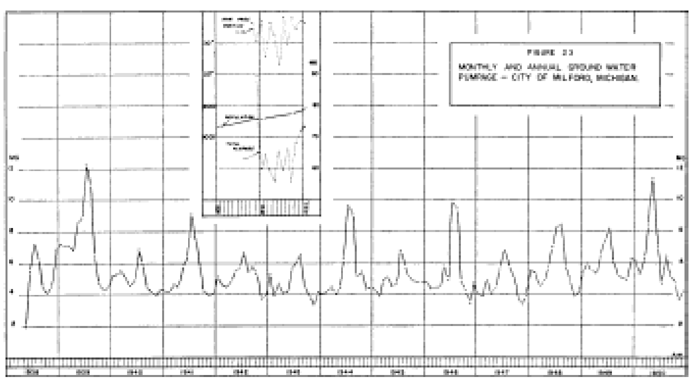

Figure 23. Monthly and annual groundwater pumpage, Milford, Michigan

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 out-wash 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.

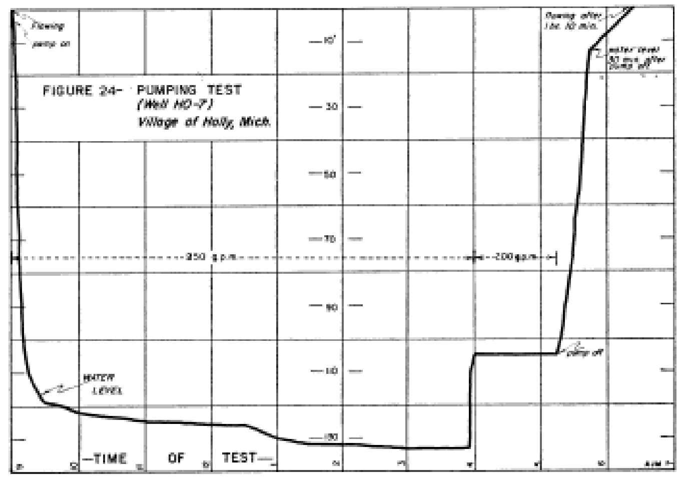

Figure 24. Pumping test, Village of Holly, Michigan

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.

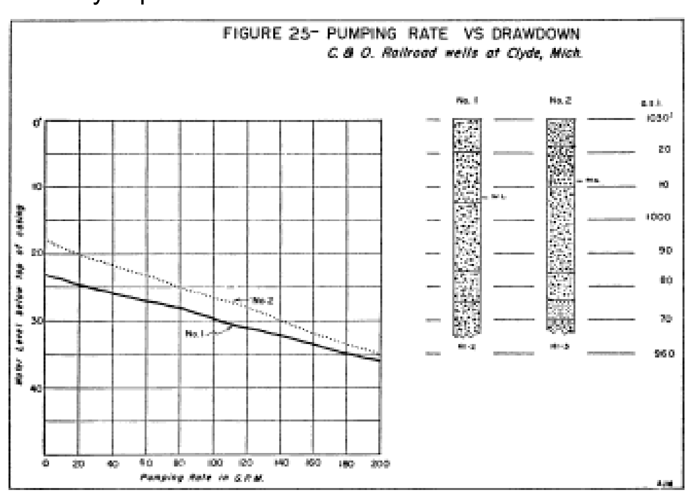

Figure 25. Pumping test, C & O RR wells at Clyde, Michigan

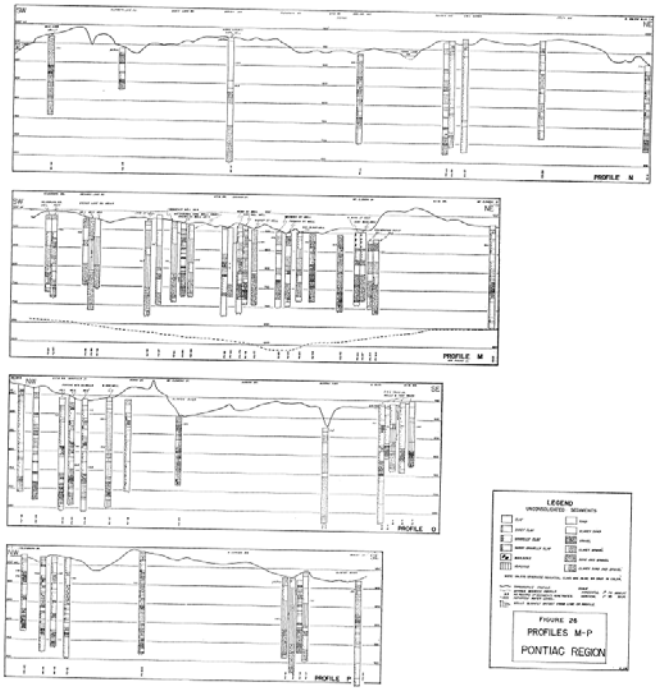

Figure 26. Profiles M through P – Pontiac region

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.

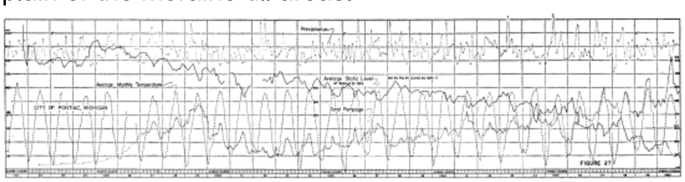

Figure 27. Monthly precipitation, temperature, groundwater pumpage, and average static water level, City of Pontiac, Michigan

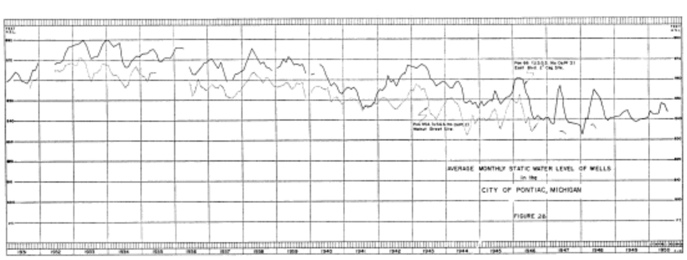

Figure 28. Average monthly static water level of wells, City of Pontiac, Michigan

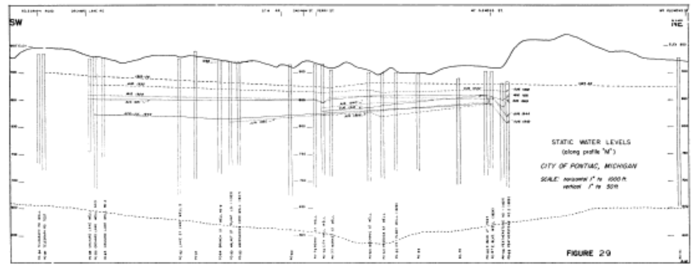

Figure 29. Static water levels (along profile M), City of Pontiac, Michigan

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 elastics, 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 ground-water 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 elastics 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 elastics within the more abundant till. The profiles constructed along a northwest-southeast trend likewise do not reveal any continuous body of coarse elastics except where the individual profiles intersect Profile M. It appears that the narrow belt of coarse elastics, 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 elastics 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 (NWi/4 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 out-wash 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 elastics. 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 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 Us rather than Vs. 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 temperatures 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 ground-water 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 inter-lobate 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 ground-water 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 south-easternmost 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 out-wash 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 $P=R+E_W+E_1+T+U$, where

E_W = Evaporation from water surfaces

E_1 = 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 $U=P—(R+E_W+E_1+T)$. 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_1	+ 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.

[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.

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 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 Michigan, fragments of such materials are in the drift deposits and may be leached by subsurface water. Sulfates may also be formed by the oxidation of iron sulfides and are in the minerals marcasite or pyrite of bedrock. These minerals are present in varying amounts in many shale formations and to some extent in limestones and dolomites. Sulfates in waters that also contain relatively high proportions of calcium and magnesium cause a hardness which is more difficult to remove and which is known as "non-carbonate" hardness. The precipitate or scale produced by sulfates of calcium and magnesium is more damaging to boilers and similar equipment than scale which is produced by carbonates of calcium and magnesium.

Within Oakland County, the groundwater averaged 23 ppm in sulfates with a range between 0 and 183 ppm. Of 50 determinations, only 5 analyses indicated sulfates in excess of 50 ppm. In analyses of groundwater samples collected from the glacial lake plain, the sulfates were generally less than 10 ppm, and between 10 and 30 ppm in water from the moraine-till and outwash areas.

Chlorides (Cl)

Chlorides are dissolved in small quantities from many rocks. According to the standards accepted by the American Water Works Association, water having a concentration of more than 250 ppm of chlorides is unsuitable for drinking purposes. However, chlorides in amounts less than 400 ppm cannot be tasted by most people, but in increasing amounts salt becomes progressively more noticeable to the taste. The chloride content of water may be several thousand parts per million before it is unsuitable for livestock. Because chloride salts are highly corrosive, most industries require water that is relatively free from such salts.

The average chloride content of groundwater in the county is 53 ppm with a range from 4 to 320 ppm as determined by 54 analyses. Groundwater in the glacial lake plain ranges from 4 to 320 ppm and averages 83 ppm. For the moraine-till plain and outwash areas, the chlorides range from 5 to 47 and 5 to 25 ppm, and average 27 and 15 ppm respectively. The higher chloride content of groundwater from the glacial lake plain makes it distinctive from the groundwater present elsewhere in the county. The occurrence of salt water in the glacial lake plain will be discussed more fully in a subsequent section of this report.

Fluorides (F)

Extremely small amounts of fluorides are in most natural waters. Water containing fluorine in amounts exceeding 1.5 ppm is said to cause the dental defect known as mottled enamel if the water is used for drinking by young children during the period of tooth formation. On the other hand, it is reported that water containing less than 1.5 ppm of fluorine has caused a lower incidence of dental cavities. From 21 analyses, it is shown that groundwater from the county averaged 0.6 ppm of fluorides with a range between 0.2 and 1.5 ppm. For the outwash areas the average is 0.3 ppm; for the moraine-till plain areas 0.5 ppm; and for the glacial lake plain 0.7 ppm. The higher average and greater range of fluorides in groundwater from the glacial lake plain may be due in part to the infiltration of water from the underlying bedrock into the drift.

Dissolved Solids

Dissolved solids are the residue left upon evaporation of a measured quantity of water and are mainly the dissolved mineral constituents in the water. The desirable maximum of dissolved solids for most commercial and industrial uses is about 500 ppm, but water having a greater content of dissolved solids may be suitable if the hardness, iron, and chlorides remain low. From the unconsolidated deposits of the county, the dissolved solids from groundwater samples averaged 398 ppm and ranged from 276 to 834 ppm. The greatest range and highest average of the dissolved solids were found in groundwater of the lake plain section. The range is 276 to 834 ppm and the average 430 ppm. For the outwash the average is 354 ppm with a range from 300 to 496 ppm, and for the moraine-till plain area 384 ppm with a range of 322 to 604 ppm.

Hardness

Hardness is a characteristic of water that receives the most attention in the development of domestic, commercial and industrial supplies. This characteristic is determined by the increase in the quantity of soap that is necessary to produce a lather, or by the minerals that are deposited as scale in boilers and kettles when hard water is heated or evaporated. The total hardness of water includes both the carbonate and non-carbonate hardness. Carbonate hardness is due to the bicarbonates of calcium and magnesium in water, and the non-carbonate hardness is due to the sulfates, nitrates and chlorides of calcium and magnesium. The amount of soap needed is determined by both types of hardness, but the carbonate hardness is more easily removed, whereas the non-carbonate hardness produces a harder scale that is considerably more troublesome in its removal.

Generally water under 60 ppm in hardness is considered soft. Softening it further is not profitable excepting for special uses, as for steam boilers if it approaches the upper limits and is used in very large quantities. Hardness between 60 and 120 ppm does not seriously hamper domestic uses and most industrial needs. Commercial laundry enterprises may find softening economical as by softening the water the consumption of soap would be decreased. If water has between 121 and 200 ppm the hardness is noticeable by anyone, and such hard water generally needs to be softened by any industry using water for the processing of its products. Softening of such water may likewise be profitable for domestic and municipal supplies. Hardness in excess of 300 ppm makes water objectionable for nearly all uses.

Of 57 water samples analyzed in Oakland County, the total hardness ranged from 34 to 480 ppm and averaged 273 ppm. Groundwater from the outwash averaged 298 and moraine-till plain averaged 314 ppm in hardness. Water from the glacial lake plain averaged 238 ppm. Groundwater from the lake plain section is thus distinctive from that of other areas since it is from 60 to 76 ppm softer. Considering the slope of the hydraulic gradient from the interlobate outwash southeastward toward the glacial lake plain, it may appear somewhat unusual that the hardness of groundwater should decrease. On the other hand, analyses of groundwater samples from the lake plain indicate the chlorides in greater concentrations. Sodium and potassium combined are considerably higher here than indicated by water samples from the outwash and moraine-till plain sections. Thus, it is possible that a natural softening of water takes place in the glacial lake plain by the process of base exchange--the exchange of sodium in the sediments of the lake plain for the hardness-producing calcium and magnesium contained in the groundwater. Inflow of bedrock waters high in sodium and potassium salts into the unconsolidated sediments of the lake plain may vary in quantity from time to time, depending upon the piezometric pressure of the various drift aquifers. Thus, it is conceivable that in a period of years when rainfall is below the annual average, the lowering of the piezometric surface may be more rapid owing also to the increase of groundwater pumpage. At such a stage infiltration of rock water into the drift may furnish an excess of sodium ions to the sediments, which may later be used in the base exchange process. It is obvious that the mechanics involved in such a base exchange process are difficult to determine, considering the complexity of sediments and of the percolation of bedrock and drift waters. It is likewise conceivable that the low total hardness of subsurface waters in the glacial lake plain may be indicative that recharge by precipitation that falls directly upon the area is more significant than supposed. Since much of the glacial lake plain consists of waterlaid till and lacustrine deposits, it is likely that a greater quantity of soluble salts had been leached. Thus, the infiltration of meteoric waters falling directly upon the area would eventually cause groundwater to have a lower concentration of hardness-producing compounds in solution.

The hardness of groundwater in the county is primarily carbonate rather than non-carbonate. Of the total determinations, the carbonate hardness averaged 262 ppm and the non-carbonate hardness 16 ppm. Excepting four samples, the non-carbonate hardness was less than 50 ppm. In 29 of the 49 complete analyses, the total hardness was less than or equal to the total alkalinity, in which case the non-carbonate hardness of the water was zero. For the outwash and moraine-till plain areas, the non-carbonate hardness averaged 25 and 26 ppm respectively, and for the glacial lake plain 6 ppm. The majority of analyses of samples from the glacial lake plain showed absence of non-carbonate hardness. From the analyses of water samples taken from the glacial lake plain it was noted that the total initial hardness of water from newly completed wells was owing to the presence of calcium and magnesium bicarbonates. However, after prolonged use and/or heavy seasonal groundwater withdrawal, subsequent monthly or annual analyses revealed either an appearance or an increase in the amount of non-carbonate hardness. Many subsequent analyses indicated the total hardness to exceed alkalinity, and the excess thus represents hardness due to the presence of non-carbonates. Variation in the quality of water will be more adequately discussed later in the report.

QUALITY OF WATER FROM THE CONSOLIDATED SEDIMENTS

In contrast to the water of the glacial mantle, the water recovered from the consolidated sediments is nearly everywhere more highly mineralized. Bedrock wells are not numerous in the county. Most of them were drilled in the glacial lake plain section where thin drift cover, or deposits predominantly clay, made it necessary to drill into the rock formations to secure palatable water. The rock wells in use today are primarily for domestic or stock purposes but a few are for industrial use. No bedrock wells have been developed for municipal systems. In the morainic, till plain and outwash areas, where population density is low in comparison to the lake plain, the demand for water is not as great and the available supply in the unconsolidated sediments is more than ample. In addition, these areas have a thicker drift cover, shallower water levels and a greater abundance of more permeable water-bearing materials. Thus, it is usually not necessary to drill beyond the depth of the surficial mantle in areas other than the glacial lake plain.

Only a few analyses of bedrock water were obtained and are shown in Table 10. Of the analyses included, three represent samples taken from shallow rock wells, and the remaining four are water samples drawn from deep oil and gas exploratory holes. In a comparison of the results of the analyses with respect to reported depths and geologic horizons, several generalizations become apparent and are given in the succeeding paragraphs:

1. The most obvious feature of bedrock water is its high mineralization in contrast to the water contained in the drift. In nearly all wells, the dissolved mineral constituents, excepting iron, silica and some alkalies, show a significant increase, an extremely wide range or both. A comparison of the individual factors of these analyses with the water-classification table (Table 11) reveals that much of the bedrock water is highly objectionable in nearly all respects.

2. Of particular note is the total hardness of the water recovered from bedrock, which ranges from 270 to 45,945 ppm. It is general practice to assume that hardness of water is owing to the carbonates present if the total hardness of the water sample is equal to or less than the alkalinity. If the reverse is shown by the analyses, then the excess of the total hardness is owing to the non-carbonates present in the form of sulfates, nitrates and chlorides. From the tabulated results of bedrock-water analyses, it may be noted that non-carbonate, or permanent, hardness is more dominant. In water associated with drift deposits, the reverse holds true. Of the bedrock-water samples analyzed, the non-carbonate hardness ranged from 42 to 45,907 ppm and the carbonate hardness from 2 to 230 ppm.

3. In general, the quantity of dissolved mineral matter in water increases with increased depth into rock. The total dissolved solids increase from 688 to 175,800 ppm, and the individual constituents increase as follows: Chlorides from 360 to 102,500 ppm, sodium and potassium 517 to 45,908 ppm, calcium 56 to 12,450 ppm, magnesium 26 to 3,600 ppm and sulfates from 0 to 1,881 ppm. As the amount of dissolved mineral matter increases, obviously, the density of the water increases. Specific gravity of water samples increased with depth, the indicated range being from 1.008 to 1.120.

4. A pronounced change in the chemical quality of bedrock water is very apparent in the rock formations older than the Antrim shale. Analyses of samples of water from the Traverse, Dundee, and Detroit River formations strongly suggest the impossibility of recovering palatable water even for livestock purposes from these formations in the area of Oakland County. Hence deep rock wells should not be considered as a possible source for a groundwater supply.

Water from the Antrim shale and younger formations underlying the county is considerably less mineralized but not to the extent that it compares in quality to the water in the drift. The analyses indicate that it may be satisfactory for stock and domestic purposes if necessary. To a large degree the recovery of palatable water from any particular formation will be restricted to its outcrop area beneath the surficial deposits. For example, a few rock wells that penetrate the Berea in its outcrop area (beneath the drift) in the vicinity of Franklin Village (Southfield Township) yield water suitable for domestic use. This is not surprising since it is very probable that the more mineralized water in the Berea sandstone may be subjected, within its outcrop limits, to dilution locally by the infiltration of less mineralized water from the overlying drift. On the other hand, wells ending in the Berea sandstone where it underlies younger rock formations, as in the northern half of the county, may yield water so highly contaminated by mineral matter that it is unsuitable even for stock use. Such mineralization may be anticipated, and is verified by comparison of the water analyses for wells AV-57 and IND-15. The analysis for well AV-57 is of a sample of water recovered from the Berea sandstone where it is overlain directly by drift, and the analysis for well IND-15 is of water from the Berea where it underlies the Sunbury and Coldwater formations. The difference between the tabulated results of the two analyses for dissolved solids, sodium and potassium, chlorides, sulfates and total hardness is marked.

Although the analyses of water samples taken from bedrock appear mainly unfavorable, it is not impossible to develop a greater supply of palatable water from the underlying formations if necessary. Whether or not water recovered from a rock well will be satisfactory depends upon a number of controlling factors, some of which are difficult to foresee in advance, whereas others may be drawn from inference. The most obvious factor is the depth of penetration of the well into the rock formation. It is clearly indicated by the tabulated analyses of bedrock waters that mineral contamination increases with depth. Thus, recovery of water from rock sources must be limited to wells of shallow depth into bedrock. Since the county is underlain principally by shales, mainly of low permeability, the yield from wells penetrating them is small. Where a larger yield is desired it must be produced at greater depth or by an increase in the diameter of the well, or in places both. A greater depth into the rock results in a greater area of seepage, also the well may cut across additional bedding planes, fractures and perhaps lenses of more permeable materials, like the sandstones and scattered limestones in the Coldwater formation. Enlarging the diameter of the well increases the area of seepage without the necessity for added depth. For the known conditions in Oakland County, any desired increase in yield should preferably be obtained by increasing the diameter of the well rather than by added depth.

Another factor that may determine the quality of water recovered from a shallow rock well is its position with respect to the regional topography of the bedrock surface. Rock wells completed in formations that outcrop in the bedrock lowland are likely to be more mineralized than wells which have been drilled into the rock surface of the Thumb Upland. Two facts favor the upland rock wells with regard to quality of water--namely, the position of the groundwater divide and the nature and structure of the formations. As was shown earlier in this report, the groundwater divide is located within the interlobate deposits of outwash materials and scattered morainic hills. The groundwater divide approximates the position of both the bedrock and topographic divides. It is logical to expect the rocks of the upland surface to be subjected to more infiltration of water from the drift because of their location with respect to the major intake basin of the county. The rock surface of the lowland area is less favorable to this form of recharge because the drift deposits are less permeable and, furthermore, because the regional rock topography and structure lend themselves to an tip-dip movement of bedrock water. Thus, the rock wells of this region will yield water that is likely to be higher in the quantity of dissolved mineral contaminants.

To some degree, local bedrock topography may influence the quality of water recovered from a rock well. It is conceivable that a shallow bedrock well located on a divide between rock valleys may yield water of less mineral contamination than one completed within a bedrock valley, since mineralized water, originally present in the area of the divide, may have been flushed out owing to local percolation of drift water into the rock and thence toward the depressions of the bedrock surface. This factor of local topography is of little assistance in searching for a water supply since the detailed configuration of the rock surface is not known. Knowledge of its character will remain unknown until additional bedrock elevations are obtained either by geophysical methods or by the gradual accumulation of well and test-hole records that give bedrock data.

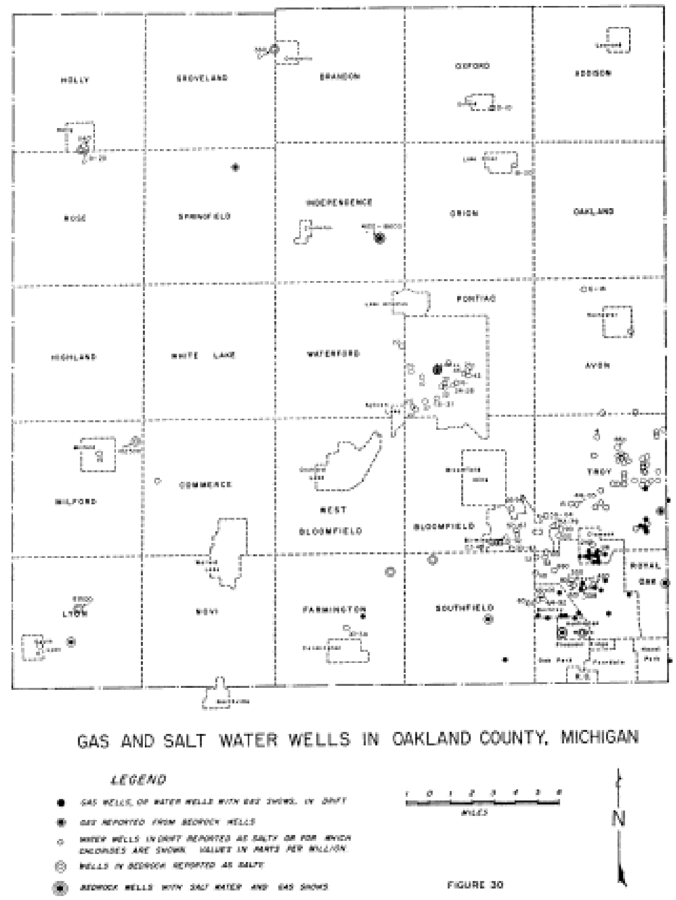

Figure 30. Gas and salt water wells in Oakland County, Michigan

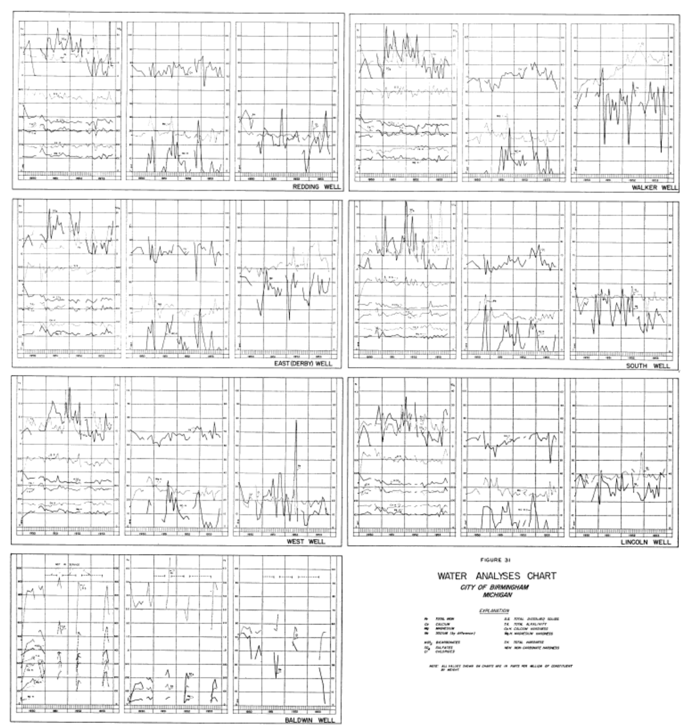

Figure 31. Water analyses chart – City of Birmingham, Michigan.

OCCURRENCE OF SALT WATER IN DRIFT OF THE GLACIAL LAKE PLAIN

The presence of water of saline taste, or high in chlorides, in the glacial sediments of Oakland County has been previously reported by Leverett. A number of well logs tabulated in Leverett's report (1905-06) show that salt water was reported in many wells in the eastern part of the drift deposits that in part comprise the Troy flowing-well district. Several of the wells, reported as yielding salt water, were drilled before 1910 when the county as a whole was sparsely populated. It is suggested, therefore, that the chloride water in the drift is not all of recent origin: That is, its occurrence is not a direct result of the rapid development of groundwater-supply systems within the county. The general areas of salt-water occurrence in the county were determined by plotting on a base map all wells for which chlorides were indicated either by notation on the record or by analyses. From this map several facts become apparent which may be worthy of note:

1. Wells for which a salt-water taste was reported on the logs were all located within the limits of the glacial lake plain, particularly in the southeastern half of Troy Township and the northern half of Royal Oak Township. Well records were not available for the southern half of Royal Oak Township as the area is served by the Detroit water-supply system. It is probable that groundwater in this area may be high in chlorides.

2. Nearly all the chemical analyses of water samples that indicated chlorides in excess of 50 ppm or more, were of water from wells within the glacial lake plain section. The only exceptions were two analyses of composite water samples taken from the village of Holly water-supply system. The wells in service at the time were completed in sand and gravel deposits probably in association with a bedrock valley. In the glacial lake plain section the water samples from the various wells showed a range in chlorides from 4 to 420 ppm.

3. From the preceding paragraphs it may be generally concluded that waters of saline taste are most likely to be encountered in the sediments of the lake plain which have been deposited over the bedrock lowland and in part along the lower limits of the rock slope which rises northward toward the rock upland. By reference to the geologic and surficial maps, it is seen that the sediments of the lake plain have been deposited over the Berea sandstone and older formations. From the distribution of the wells for which salt water or high chlorides are indicated (fig. 30), it appears that the upper boundary of the Berea formation marks the northwesterly limit of salt-water occurrence in the drift cover of the glacial lake plain. Surficially, this northwesterly limit is approximately indicated by the general northeast-southwest trend of the Maumee beaches which, in this county, pass through the southeast corner of Avon Township and thence southwestward through Troy, Bloomfield, Southfield and Farmington townships.

4. Analyses showing the highest concentration of chlorides (up to 420 ppm) were of samples taken from municipal wells in Berkley, Clawson and Royal Oak. With respect to the rock surface these wells and test holes are drilled into sediments associated with or deposited over bedrock valleys (fig. 7). Two explanations may account for the fact that drift deposits that fill and cover rock valleys are likely to contain saline water. First, since saline water is of higher density, its infiltration from bedrock into drift would tend to percolate toward unconsolidated sediments that occupy depressions in the bedrock surface. This would be especially true of bedrock-water seepage from the slope of the bedrock upland. Second, the valleys carved into bedrock provide a greater seepage area for percolation of saline water into the drift especially since the bedrock water is under artesian conditions.

5. The chloride values of individual well samples when plotted on the base map increase in amount from Pontiac (10-45 ppm) southeastward through Birmingham (15-150 ppm) and Royal Oak (44-420 ppm). The increase follows the trend of the major rock valley of the area.

The salt water in the lake plain sediments may be attributed to infiltration from the underlying rock formations. Infiltration may be natural or induced. Induced infiltration results from local overdevelopment of aquifers in the drift, which induces movement of confined water from the bedrock. Additional infiltration may have resulted from the improper grouting of test holes or wells drilled into rock.

From shallow and from deep borings into the underlying rock strata, brines were reported in nearly all formations from the Detroit River group upward through the Lower Marshall beds. The source of chlorides in the groundwater of the drift is therefore the bedrock. Natural infiltration of salt water into the overlying sediments is due to geologic conditions of rock structure, rock topography, surface topography, and the nature of the surficial deposits. When the glacial and bedrock-surface maps are viewed together, it is clearly seen that the mantle of the lake plain is deposited over the rock lowland surface and along the lower part of the adjacent rock upland slope. Test borings show that the Berea formation constitutes a part of the slope which separates the rock upland from the lowland. The principal source of the salt water in the drift is probably the Berea sandstone, although there is no strong reason (other than degree of permeability) to exclude the formations immediately above and below the sandstone as additional source beds. Excepting variations caused by local structures, the gentle regional dip of the rock formations is to the north. As the groundwater divide is located to the northwest, the movement of confined water in the rock formations would be in an up-dip direction until it entered the unconsolidated sediments of the glacial lake plain. The conditions as described would result in the natural infiltration of mineralized water into the unconsolidated drift overlying the bedrock lowland. The degree of salinity of water in the drift may vary considerably from place to place and from time to time, variation being dependent on a number of factors such as (1) the salinity of the water from the rock formation, (2) the ease of percolation through the rock formation as well as the drift, (3) the amount of dilution caused by the less mineralized water of the drift, (4) the rise and fall of the piezometric surface and (5) the position of the sand and gravel aquifers in the drift with respect to the rock surface. With reference to the last factor, sands and gravels resting directly on the bedrock surface and overlain by clays would generally contain salt water since dilution would be retarded by the confining clays. This is clearly shown by a test hole (RO-37) drilled for the city of Royal Oak. The log of the well reveals 12 feet of sand overlying the Antrim shale and succeeded by unassorted till and lacustrine clay. A sample of water taken from the test hole contained 350 ppm of chlorides. Other bodies of sand and gravel that are more or less confined by clays both above and below, but which extend laterally so as to abut against the wall of a bedrock valley, or perhaps overlap .a part of the slope ascending to the rock upland may likewise contain saline water. This may be the character of an aquifer associated with a bedrock valley which has been penetrated by a test hole (RO-25) in the city of Royal Oak. The water-bearing zone consists of sand, sand and gravel, and gravel layers 33 feet thick and confined by less permeable materials above and below. A sample of water taken from the test hole showed 890 ppm of chlorides. It is conceivable and very likely that older buried beaches or marginal outwash materials of pre-Wisconsin or Wisconsin age may have been deposited against the bedrock slope of the rock upland and thus be in a position to receive mineralized waters by infiltration.

The natural infiltration of bedrock waters into the drift appears to be proved by the initially high chloride content of water samples taken from several test holes. An analysis of a sample taken from the original Magnolia well (RO-45), city of Royal Oak, shortly after its completion in 1923, showed chlorides in the amount of 322 ppm. Since this area was not previously developed for a public water supply, the original high chlorides of the sample must suggest a natural rather than induced flow from bedrock sources. And since the Magnolia well is completed in drift which buries a rock valley, it is not surprising to find saline water in the filled depressions of the rock surface.

Additional saline water in the drift may be the direct result of induced infiltration from the bedrock as overlying sand and gravel bodies within the mantle are overdeveloped. The groundwater in the bedrock and in the water-bearing aquifers of the glacial lake plain, is under complete or partial artesian conditions of varying pressures. When, through development, the water pressure of a confined aquifer in the drift is lowered below the pressure of water in the bedrock, induced flow from the rock results. This manner of flow will continue until the reverse conditions of pressure are again re-established between the consolidated and unconsolidated aquifers. This seems to be indicated by analyses of water samples taken at a later time from the Magnolia (RO-45) and Northwood (RO-46) wells in the city of Royal Oak. Both wells are within influence of each other to the extent that the Northwood well has been known to surge, thereby requiring the operation of both wells under partially closed valves. The operation of both wells simultaneously results in overdevelopment, which in turn reduces the pressure in the sand and gravel aquifer sufficiently to induce flow of water from the bedrock. The quality of water from the Magnolia well has been so unsatisfactory that it has been generally kept out of service except when peak demands occur during the summer months. The original Magnolia well, destroyed by a gas explosion in 1925, was replaced by a new well near the original site. Although periodic analyses were not made, Table 12 illustrates the variation in chlorides from samples collected since the new well was completed. The chlorides varied from 140 to 465 ppm, and the variation is undoubtedly related to the pumping schedule of the Magnolia and Northwood wells.

Two of the monthly analyses of water samples taken from each of the wells owned by the city of Birmingham, strongly suggest induced infiltration of water from bedrock sources. The dissolved constituents have been plotted and are shown on Figure 31. Of specific interest to the immediate discussion are the graphs for the Walker and Baldwin wells. The Walker well penetrates the same water-bearing zone as the city of Clawson well (TR-69) and the Bundy Tubing Company well (TR-65) penetrate. From data on hand, all three wells, with respect to the underlying rock surface, are completed in sediments that are along the easterly slope of the principal bedrock valley of the glacial lake plain. Earlier data indicate that the wells are within influence of each other, which again causes local overdevelopment. Monthly water analyses of the Walker well are continuous from May 1950 through October 1953 with but few omissions. From the graphic representation of these analyses it may be noted that chlorides have been increasing gradually. This increase in chlorides for the period covered by the analyses indicates infiltration of bedrock water as a natural consequence of local overdevelopment of drift water.

Induced infiltration from bedrock is again suggested by water analyses collected from the Baldwin well. Records of this well are not continuous since it is occasionally out of service primarily for reasons of quality rather than because of mechanical difficulties. The Baldwin, located in the valley of the River Rouge, is the shallowest of the Birmingham wells, being only 73 feet deep. With reference to the rock surface, the well is drilled in glacial sediments that rest on a bedrock ridge between the major rock valley and a principal tributary that joins it from the northwest. The slope of the rock ridge is to the southeast and is probably formed by the Berea or possibly younger formations--that is, the Sunbury shale and basal Coldwater beds. Of all Birmingham wells, the water analyses collected from the Baldwin show the greatest content of dissolved mineral contaminants. As shown on Figure 31, the dissolved solids, total hardness and non-carbonate hardness have values which greatly exceed those of samples collected from the other six municipal wells. Of particular significance is the behavior of the curves from May 1950 through October 1952 for the total and non-carbonate hardnesses, sulfates and dissolved solids. Two periods are indicated when the well was not in service--the first from January through June 1951 and the other from October 1951 through April 1952. The analyses immediately following the April 1952 period are of prime interest. After a seven-month rest period, the sulfates increased in one month (May to June 1952) from 18 to 236 ppm, dissolved solids from 519 to 902 ppm, total hardness from 244 to 538 ppm and non-carbonate hardness from 0 to 230 ppm. Such a pronounced change in the quality of water again indicates induced infiltration of water from bedrock while the Baldwin well is in frequent service. The more favorable analysis of May 1952 suggests that when not in service the sediments in the vicinity of the Baldwin are recharged by effluent seepage of surface waters from the River Rouge, or possibly from nearby Quarton Lake. The extreme variation in quality is not indicated by the analyses for July and August 1951 immediately following the first period when the Baldwin was out of order. After a six-month interval, it is logical to assume that the water from the Baldwin well should be more favorable in quality but the curves, however, fail to prove such an assumption. Since it is highly improbable that the May and July 1952 analyses are in error, the pronounced change in quality failed to appear for some other reason. The reason may be in the time interval between the date that the Baldwin was again restored to service and the date of sampling, that is, the July 1951 sample was collected several days, or possibly weeks, after the well was back in service, and the May 1952 sample was collected very shortly after the well was in use. If this assumption is correct, it is likely that infiltration of bedrock water into the drift takes place rapidly, and that recharge by effluent seepage from nearby surface bodies of water is ineffective while the well is in daily service. It would seem practical to rest the Baldwin well more frequently in order to maintain a better quality. Chlorides are not especially conspicuous in the water samples taken from the Baldwin well--they range from 48 to 67 ppm. No explanation is immediately apparent. It is possible that the high sulfates reflect the possibility that the mineralized quality of water from the Baldwin well is due to infiltration from the Sunbury and/or Coldwater shales. The Sunbury is a black to brown shale resembling the Antrim shale in color and perhaps contains a higher percentage of iron sulfides, and the Coldwater formation in this area possibly contains more gypsum. It is postulated that the aquifer tapped by the Baldwin well probably extends laterally until it is in more direct contact with the rock formation comprising the ridge. A more positive conclusion regarding induced infiltration of bedrock water into the drift must await additional monthly analyses so that a longer interval of time is represented and so that variations may also be plotted against monthly precipitation data. Other factors to be considered include the length of time the well was in operation before sampling, the influence of precipitation falling upon the area, recharge in the immediate vicinity, and the influence of nearby wells having a high daily production. Another cause for infiltration of bedrock water into the drift may be owing to improper grouting of unsatisfactory wells and test holes that have penetrated the underlying rock formations. This opinion was expressed on several occasions to the writer by a number of drillers familiar with the region, and although it is undoubtedly true as a contributory cause, it does not account for all the salt water in the drift. Although some abandoned rock wells and test holes were reported, no pertinent data regarding them were obtained.

OCCURRENCE OF GAS IN DRIFT

Gas has been reported in a number of wells and test holes from the sediments of glacial origin. In some localities the gas in the drift is of sufficient quantity and under sufficient pressure to be usable locally for space heating and other purposes. In most of the area the gas is reported as "slight shows" or as very small pockets which initially may be under several pounds pressure. The presence of gas in the drift is detrimental to any groundwater supply unless proper measures are taken for its removal. Well explosions on several occasions have resulted in personal injury and damage to equipment and property.[1] The original Magnolia well (RO-45), city of Royal Oak, and a school well in Southfield Township are two of the several explosions that came to the attention of the writer during the course of the investigation. The city of Ferndale,[2] which now obtains water from the Detroit system, abandoned groundwater use after a series of minor domestic explosions. In certain areas of Macomb County it is a general practice to install gas-escape valves for hot water tanks. In Detroit a serious gas explosion[3] occurred in a huge raw-water main, approximately 95 feet below surface, which is being constructed by subsurface construction methods. Gas seepage from a two-inch seam of sand took place despite the fact that the underground tunnel is being constructed under pressure, which from time to time is adjusted up to twenty pounds. Groundwater containing a small amount of gas by volume is generally unsuitable for use in steam boiler equipment since it results in frothing of water. Two explanations are offered for its presence. It may be a marsh gas derived from buried deposits of plant matter in the process of peat formation, or it may be natural gas that has seeped into the drift from the underlying bedrock formations.

Deep and shallow wells and test borings in bedrock have reported gas flows in formations ranging from the Detroit River group of Devonian age to the Coldwater shale of Mississippian age. From evidence available, it is the writer's conclusion that the gas in the drift is derived by seepage from bedrock sources. The Disposal Plant well (RO-55), now abandoned by the city of Royal Oak, was originally drilled to 132 feet at which depth the Antrim shale was reached. The water-bearing formation consisted of a gravel stratum 6 feet thick which is immediately above the shale. At some later date, the well was deepened another 138 feet into bedrock to provide storage. This opened so appreciable a flow of gas that an attempt was made to utilize it as fuel for the disposal plant. Improper dynamiting damaged the casing and rendered the well useless. A shallow private well (RO-52) reached the Antrim at 110 feet and blew gas at 111 feet. In this well the flow of gas from the shale was of short duration. Apparently the gas was a local pocket that was confined by overlying clay hardpan. No peat was indicated in any of the records of wells or test holes in which gas was found. Hence the occurrence of gas in the drift is presumed to be seepage into the overlying sediments from bedrock sources.

The thirty wells and test holes for which gas was reported are all located within the limits of the glacial lake plain (fig. 30). Logs of the individual borings or wells revealed that gas was most generally in the coarser elastics. In some wells gas was found in zones described as clay or sand and gravel hardpans. Some gas was reported from soft, soupy or putty-like clays. The gas-bearing zones ranged in depth from 38 to 131 feet below the surface and had pressures up to thirty pounds. Gas was even in water recovered from shallow dug wells that were in the city of Pleasant Ridge.[4] Gas concentration per unit volume was sufficient to discourage use of the water for steam locomotives. It appears that the concentration of natural gas in the buried "pockets or veins" of coarser elastics within the glacial lake plain sediments is made possible by the lacustrine clays and silts or reworked waterlaid tills that are near the surface and serve as confining layers or caps. No gas shows were noted on any records collected for the morainic, till plain and outwash areas, but it is not impossible for gas to seep into the mantle rock of these areas from the underlying rock formations. The apparent absence of gas pockets in these areas of the county is probably owing to the more permeable nature of the mantle which permits its escape.

Wells and test holes for which gas was reported or indicated were plotted on a base map in order to determine the areal distribution and areas of concentration within the limits of the glacial lake plain. The majority of the wells were found to be in sediments which overlie the outcrop area of the Antrim shale formation. Only three wells had positions in the glacial lake plain north of the inferred Bedford-Antrim contact as shown on the geologic map. From the distribution pattern of these wells it is indicated that the primary seepage of the drift gas is from the Antrim shale. The wells beyond the Antrim outcrop area suggest that the gas in that part of the lake plain may be derived directly from the Sunbury or from the Berea-Bedford formations, or may be owing to indirect seepage of Antrim gas into that area by devious courses established by more permeable materials.

The largest concentration of gas wells is in and around the city of Clawson, in sections 3 and 4, Royal Oak Township. Many of the wells in this area were drilled expressly for gas for space heating and other domestic purposes. Pressures between five and eight pounds were generally reported, but as the number of wells increased within this small area the gas pressures declined, and the infiltration of water began. A majority of gas wells have since been abandoned. On the geologic and bedrock-contour map (fig. 7) it is shown that the gas of this area is concentrated in sediments that bury a tributary rock valley carved into the Antrim shale formation. This valley in the Antrim provides a greater seepage area for the shale gas which eventually finds its way into the confined sand and gravel pockets. Another area of gas wells is located in the southeast corner of Troy Township in sections 24, 25, 26, and 36. The nature of the rock surface and the precise contacts of the underlying formations in this area cannot be too clearly defined on the basis of the available information. However, the gas wells are in drift associated with rock valleys, or in drift along the contact of the Bedford-Antrim beds. Gas pressures up to 30 pounds were recently reported in this area. Gas wells in sections 8, 9, 10 and 14, Royal Oak Township, are located in drift related to the major rock valley.

From the consideration of all known data it is concluded that gas may be anywhere in the glacial lake plain section, but particularly where sediments bury rock valleys. Gas has also been reported from a great number of borings and water wells drilled in the glacial lake plain sediments of Wayne and Macomb counties. Several opportunities were afforded the writer to study logs of test holes drilled along the frontage of the Detroit River for foundation studies. Gas was nearly always encountered in a hardpan presumed as Illinoian till, which is immediately above the bedrock, and below blue or gray clay up to 100 feet thick. Since the Detroit area is underlain by rocks of Dundee through Antrim age, it is concluded that the gas in the sediments of the lake plain may be derived from several rock formations rather than from the Antrim alone as might be inferred from the discussion relating to Oakland County. Although the nature of the rock surface underlying the entire lake plain is not known in detail, it is very probable that gas in larger concentrations will be found in sediments deposited over existing rock valleys. Its presence adds another unfavorable factor to the quality of groundwater found in the lake plain section. However, the data acquired as the result of this investigation should not preclude development of groundwater if the quality is not impaired by other dissolved minerals. If gas is indicated in otherwise suitable water, then measures should be taken to provide for its escape so as to minimize the danger of explosion.

[1] *Detroit News*, September 10, 1950.

[2] Personal communication, August 9, 1949.

[3] *Detroit Times*, November 22, 1950.

[4] Oral communication, City Engineer.

CHANGES IN QUALITY OF GROUNDWATER IN AN AREA OF HEAVY WITHDRAWAL

In an effort to determine the effect of heavy withdrawal on the quality of groundwater, arrangements were made to secure monthly analyses from several municipal wells that are in service daily. The Birmingham wells were selected, primarily because the city has maintained more complete records relating to groundwater than has any other community within the limits of the glacial lake plain in Oakland County. The city maintains seven wells which are operated daily in accordance with a pumping schedule. Monthly water analyses of each well were made available to the writer, the analyses extending over a period of 32 months excepting occasional omissions. Data from current records do not permit positive conclusions, but some features in the quality of groundwater are suggested, as shown by the plotted analyses on Figure 31. For proper evaluation of the data, it is necessary to call attention to the fact that the analyses shown for the period May 1950 through December 1952[1] were made by the city of Birmingham, and those prior to May 1950 were obtained from the Michigan Department of Health or private sources.

Dissolved Solids

The curves representing the dissolved solids show a pronounced increase whenever a comparison is made between the first available analysis and the analysis of May 1950. The significance of such an increase may be questionable, considering the fact that analyses made by different agencies are being used in the comparison. Despite any possible variations, or inherent errors in the method or technique employed by the analysts, the curves for the dissolved solids show increases for each well. Granted also that a "part per million" represents a fine unit of measure, some of the curves should show a trend in the opposite direction if serious differences were made among the analysts. From May 1950 on, the dissolved solids appear to be somewhat constant, despite the minor monthly variations which may be caused by any of a number of factors. Thus from the data as shown, it appears that high-producing wells in this area are likely to show an increase in dissolved solids initially, but with time the dissolved solids may become more or less stabilized if no other new factors are introduced. This change in the quantity of dissolved solids may represent the withdrawal of water from deeper parts of the drift, or else the start of induced infiltration from the underlying rock formations.

The Redding is the only well which suggests a downward trend since May 1950 in the quantity of dissolved solids. It will be recalled that the well is 80 feet in depth and located in the River Rouge valley between Endicott and Quarton lakes in the northern part of the Birmingham area. It is not certain if this decrease can be attributed to induced surface-water seepage by virtue of a reduction in the static level about the pumped well. The dissolved-solid curves for the West, Lincoln, and South wells are remarkably similar. Other quality curves, excepting the chlorides and sodium and potassium curves are also similar. This similarity in the quality of water from the South well (249 feet deep) and from the Lincoln and West wells (173 and 172 feet deep) suggests that all three penetrate the same water-bearing zone, or possibly separate zones that are intimately related. The northwest-southeast alignment of the wells coincides with the trend of the buried rock valley in that area. In any event, the similarity in quality of water tends to support an earlier statement that many of the buried "pockets" of coarser elastics are interconnected in devious ways. Also, the similarity in quality of water tends to support the fact that the three wells are within influence of each other, as suggested by the specific-capacity curve for the South well.

Iron

No general, annual or seasonal trends in the iron content are noted in the groundwater of the Birmingham area; rather, the curves are extremely erratic in trend. From a comparison of values, the iron content for each of the wells is generally considerably above the accepted maximum. Water recovered from the Baldwin well has the greatest iron content, and monthly variations are frequently quite pronounced.

Chlorides

For the Lincoln, West, South and East wells the chloride curves show no appreciable change for the period covered by the monthly analyses. The Walker well shows a gradual but definite increase in chlorides for the past two years. Its nearness to the Clawson and Bundy Tubing Company wells has resulted in local overdevelopment of the drift aquifer, which in turn has led to the infiltration of rock water in that vicinity. For the Redding well, the chlorides show a slight but definite downward trend, which agrees with the decline of the curve for dissolved solids. This decline may be the effect of infiltration or seepage from the River Rouge, but additional data are needed to determine this positively.

Calcium and Magnesium

Excepting the erratic character of the Baldwin well analyses, the calcium and magnesium curves fail to indicate any significant trends. The slight increases or decreases noted are of doubtful significance at the present time. One notable characteristic is the convergent nature of both curves in the latter part of 1950 (August-December), after which they appear to diverge. This characteristic is more noticeable in the calcium and magnesium-hardness curves. No explanation is offered for this behavior.

Sulfates

The sulfates, despite their erratic monthly variations, seem to be increasing. Generally, the sulfates when reported are under 50 ppm and compare favorably with the amount present in surface bodies of water in this region. The Baldwin well is most exceptional as may be noted in the May-June 1952 part of the curve. The increase in concentration of sulfates from 18 to 236 ppm strongly suggests bedrock infiltration of water into the drift mantle.

Sodium and Potassium

Monthly changes in the quantity of sodium and potassium are very conspicuous, but no general trends of either annual or seasonal nature are noticeable.

Bicarbonates and Total Alkalinity

Bicarbonates and total alkalinity curves show a slight downward trend since 1950. The high of each curve occurred during the latter half of 1950 and corresponded in time to the convergence of the calcium and magnesium curves.

Total Hardness

From the plotted curves, the total hardness of water in the Birmingham area appears remarkably constant, showing only a few slightly increased trends. Only the Baldwin well is exceptional, as may be expected from the nature of the other curves. The total hardness curve eventually intersects the total alkalinity curve as shown on Figure 31. The intersection of the curves marks the point where the total hardness of the water is in part due to the appearance of non-carbonates. From the analyses, it seems evident that wells of high production will initially yield water whose total hardness is owing primarily to carbonates, but with time the non-carbonate hardness factor is introduced. This assumption appears to be supported by the fact that sulfates were absent or less than 10 ppm in nearly all of the groundwater samples collected in the glacial lake plain section.

[1]Since the completion of the manuscript, monthly analyses through November 1953 have been added to the charts shown on Figure 31.

Chapter VIII: SUMMARY AND CONCLUSIONS

It is estimated that a minimum of thirty million gallons of water is recovered daily from wells in Oakland County. The principal recovery is from the unconsolidated sediments of glacial origin. The underlying bedrock formations contribute but a negligible amount to the total daily withdrawal. Approximately 25 million gallons, or 85 per cent of the total daily recovery, is from within the limits of the nine townships of southeastern Oakland County where 84 per cent of the total county population is settled. The prospects of this area for continued growth in population, industry and business are very promising because of its proximity to Detroit. Its rate of growth, however, will be dependent in part upon the amount of water that becomes available, particularly in that area known as the glacial lake plain section.

Future recovery of groundwater will continue to be from the unconsolidated deposits rather than from bedrock sources because quality and yield are better from the glacial drift. Many more data are needed to evaluate the rate of safe withdrawal in some of the rapidly developing areas within the southeastern part of the county. Inability to locate buried water-bearing sands and gravels before drilling has retarded, to some degree, the development of the groundwater resources of this county. The full development of the groundwater resources will require complete integration of glacial studies with studies of the underlying bedrock surface, primarily with reference to the quality and yield. To secure such data, the cooperation of drillers is desired to the extent that they provide the proper agencies with well records and samples. Geophysical methods can be used to provide the details of the rock surface where they are needed.

THE CONSOLIDATED SEDIMENTS

Oakland County occupies a position along the southeastern margin of the structural basin of southern Michigan, the basin containing consolidated sediments of Paleozoic age. According to Kay (1951, p. 21), Cambrian and Ordovician sediments were deposited in a southwestward plunging pre-Middle Ordovician trough which at the time was not restricted by the Kankakee Arch on the southwest. By upper Silurian time the Southern Peninsula area developed into an autogeosyncline, described by Kay as a structural basin unassociated with rising nearby highlands. The source for the sediments deposited in the basin during Paleozoic time came from the adjacent low lying areas or from quite distant highland areas or from both.

Within the limits of the county, deep exploratory oil and gas wells have penetrated Paleozoic formations which range from the basal beds of the Lower Marshall of Mississippian age through the Salina group of upper Silurian age. The Antrim and younger formations outcrop beneath the drift mantle within the limits of the county, but are nowhere exposed at the surface. They consist principally of shales, sandy shales, or shales with interbedded sandstones or scattered layers and lenses of limestone or dolomite. The Berea is the only prominent sandstone in this series of formations. Formations stratigraphically older than the Antrim are predominantly non-clastic and are represented by limestones, dolomites, anhydrite, gypsum, and salt beds. Clastic sediments such as shales and sandstones are subordinate.

The formations within the county strike east-northeast and west-southwest and have a gentle but undulating regional dip of 25 to 50 feet per mile. The regional dip of the strata is in places modified by local structures such as the extension of the Howell anticline into the southwestern extremity of Oakland County. The dip along the northern flank of this structure is approximately 87 feet per mile. Data relating to bedrock were too meager to permit detection of any additional fold or fault structures within the civil boundaries of the county.

The picture of the pre-glacial rock surface remains incomplete over most of the county since only 168 well logs, of 1,138 collected, recorded that consolidated sediments were reached or penetrated. From the data available, it appears that the physiographic subdivisions of the bedrock topography are twofold and consist of (1) the rock lowland of the Erie-Huron plain and (2) a part of the southeastern slope of the Thumb Upland rock surface. Geographically, the bedrock lowland is in the southeastern extremity of Oakland County, specifically in Royal Oak Township and in parts of Southfield, Farmington, Troy and Avon townships. The elevation of this lowland is generally 500 to 550 feet above sea level except where the surface is incised by valleys. The slope of the rock upland underlies the major part of the county and increases in elevation northwestward from 550 feet to 967 feet above sea level to the highest known point of the bedrock divide. The principal divide, trending northeast-southwest, is in the northwestern third of the county, and passes from Addison Township southwestward through Oxford, Independence, Springfield, White Lake and Highland townships. Available data indicate that the elevation of the divide decreases toward the southwest. From the position of the principal divide, approximately one-third of the area of the rock surface slopes to the northwest and the remaining two-thirds to the southeast. The outcrop of the Berea sandstone formation indicates that the rock upland slope becomes steeper as the lowland of the Erie-Huron plain is approached.

Because more rock wells and test holes have been drilled in the southeastern part of the county than in the other areas, only the configuration of the rock surface of the Erie-Huron lowland and the lower part of the adjacent upland slope could be shown on the bedrock-contour map. The most prominent of the pre-glacial valleys is traceable from the city of Pontiac southeastward through Birmingham, Royal Oak and thence into Wayne County. Between Birmingham and Pontiac the precise delineation of this valley was not possible, owing to the lack of additional bedrock elevations. A good many smaller valleys, which dissect the lowland as well as breach into the lower slope of the rock upland slope, are also present. Most of these valleys have northwest-southeast trends, but determination of their extension in a northwesterly direction, beyond the upper limits of the Berea sandstone and into the upland slope, is not possible to prove as control data are lacking. Very likely the magnitude of these valleys becomes less significant as the principal bedrock divide is approached to the northwest. The delineation of other valleys, and their tributaries, in the upland area must await additional data from borings or geophysical surveys. However, a few scattered bedrock elevations on both sides of the divide indicate such valleys but not clearly enough to be of value in this report. All elevations of the rock surface have been plotted on the map as a matter of record. In Oakland Township drift thickness of 550 feet was reported, which placed the rock surface at an elevation of 435 feet above sea level at this point. The reliability of this elevation could not be verified. If accurate, it suggests a deep valley, but how the valley may be related to the regional drainage pattern of the county is a question. Excepting the small area northwest of the principal divide, the pre-glacial drainage of Oakland County was predominantly to the southeast.

With the exception of Pleistocene and recent sedimentation, post-Paleozoic sediments are absent in Michigan. Therefore the number of erosion cycles that have been initiated, completed, or interrupted during the long time interval between the end of the Paleozoic and the Pleistocene is not known. This is a difficult problem about which to speculate, considering the immense time interval involved and the fact that a detailed knowledge of the rock surface is still unavailable. Erosional surfaces or straths such as those known in the Appalachian region have yet to be recognized if present in Michigan but probably they were destroyed by peneplanation or by repeated Pleistocene glaciation. However, it is reasonable to assume that erosion cycles were initiated after each of the uplifts resulting from the orogenies that closed the Paleozoic and Mesozoic eras and from the disturbance at the close of the Miocene period. From what is now known of the pre-glacial surface, it seems likely that the bedrock lowland is the product of the erosion cycle initiated by the Miocene disturbance. The development of this lowland and others, in their present geographic positions in Michigan, was dependent upon the basin structure and the amount of uplift. In the Oakland County area, the extension of this lowland surface may have been retarded to some degree by the more resistant Berea sandstone. Since the structural basin was developed during the Paleozoic era, it is probable that earlier erosion cycles may have resulted in physiographic units similar to those of the present rock surface although not necessarily of the same areal extent.

The cycle of erosion initiated by the Miocene disturbance was interrupted by a later uplift that caused the system of bedrock valleys of the lowland and adjacent upland slope. The uplift initiating the second cycle of late Tertiary may have occurred in Pliocene time or possibly in the Pleistocene. Since the presence of tills older than Illinoian is not even suggested in Oakland County, it is probable that if the uplift occurred during the glacial regime, it was pre-Illinoian. As far as known in the county, the valleys of the rock lowland are not more than 100 or 150 feet deep. Their original depth is not known, since subsequent repeated glaciation, which interrupted the second cycle, by its erosive action modified the valley depths and the general elevation of the rock lowland. The rock valleys today are buried by glacial drift. The principal valley is filled mainly by waterlaid till, in which are scattered sand and gravel zones. The tributary which joins the main valley at Berkley has sand and gravel deposits against a part of the south wall, and it is probable that the floor is covered by similar sediments. The valleys in Farmington and Birmingham are filled with sand and gravel as shown by the number of successful wells of high yields completed in them. Their trends suggest possible extension northwestward beneath the marginal outwash deposits and the Inner and Outer Defiance moraines. From the general conditions, the sediments in the rock valleys are favorably situated with respect to local natural recharge and in respect to the piezometric gradient. Future exploration should be directed toward (1) determining the extension of the known valleys and (2) the location of bedrock valleys not yet detected. Inasmuch as the general trend of the valleys is northwest-southeast, it seems appropriate that future test drilling or geophysical surveys be conducted along lines at right angles to the predominant trend. In recent years electrical resistivity methods have been successfully employed in the location of large aquifers within glacial till and for the location of drift-covered valleys (Spicer, 1952).

THE UNCONSOLIDATED SEDIMENTS

Excepting small deposits of recent alluvium along some of the principal streams of the county, the surficial mantle overlying the bedrock formations is of Pleistocene origin and consists of outwash sands and gravels, unassorted till deposits, and lacustrine clays and silts. The till deposits are mainly clays or clays with varying admixtures of sand, gravel and boulders. Within the till may be found interbedded and scattered deposits of sorted sands and gravels of different thicknesses and extent. Some are sufficiently large that they yield moderate to large supplies of water. The bulk of the till deposits forms two belts of morainic hills which trend across the county from northeast to southwest. The more northerly range contains some of the most elevated tracts in the county (1,000-1,100 feet) and is associated with the withdrawal of the Saginaw ice lobe. The major divide, separating the north- and south-flowing drainage systems, can be traced along a good portion of this range. The southerly range, associated with the movements of the Erie-Huron lobe, is somewhat lower in elevation (800-1,000 feet). The waterlaid Birmingham and Detroit Interlobate moraines which are within the glacial lake plain section are likewise composed of till deposits.

The two belts of morainic hills are separated by interlobate outwash deposits that form a sandy and gravelly plain, in which the clays and tills are subordinate. The elevation of the plain increases gradually northeastward, its surface pitted with numerous depressions, many of which contain lakes. The hills rising above the general level of the plain are either kames that formed at the junction of the Saginaw and Erie-Huron ice lobes, or are clusters of morainic hills. Marginal outwash sediments are between the Inner and Outer Defiance moraines. Additional sand-gravel out-wash deposits of local extent are irregular patches within the morainic belts.

The sediments of the lake plain section of the county are deposited almost entirely on the surface of the rock lowland and consist of waterlaid till that has been partly reworked by water and covered by a veneer of lacustrine clays and silts. As in the moraines, scattered zones of sorted coarse elastics are interbedded, but the data indicate that they are usually less numerous, of smaller magnitude and more difficult to locate in advance of drilling. The profiles constructed across the lake plain from northwest to southeast suggest that sands and gravels are more abundant to the northwest. A series of beaches, which are deposits of former glacial lakes impounded between the morainic hills and the ice front, interrupts the surface of the lake plain. Additional surface deposits of a sandy to gravelly character are associated with eskers, spits, bars, deltas and river terraces--all of which are associated with the last withdrawal of Wisconsin ice.

The surface features of Oakland County were formed during the last (Wisconsin) period of Pleistocene glaciation. Evidence of earlier ice visitations in the county is meager and very scattered. Leverett (1906-07) referred to Illinoian till in the flowing-well district centered about Ortonville. Stanley (1936, p. 12) referred to a probable Illinoian till exposed at the base of a railroad cut near Birmingham. At this exposure the probable Illinoian till is separated from the younger Wisconsin till by a conspicuous layer of gravel. But this gravel may be also interpreted as an outwash between tills deposited by an earlier substage of Wisconsin ice. Other evidence of possible pre-Wisconsin glacial deposition consists of buried fragments of plant remains reported in well records, cited in the geologic literature, and reported orally to the writer. Some well logs record the penetration of red, brown, yellow or purplish clays which might be interpreted as oxidized zones. Such oxidized zones and the remains of plant matter in drift immediately above the bedrock in Oakland County were twice noted as the well records were collected and evaluated. These facts may indicate Illinoian till since they correspond to the occurrence of Illinoian till in the Detroit region. Leverett reported that Illinoian till, resting directly on bedrock, was exposed during the excavation of the Livingston Channel in the Detroit River. Also, a number of records of test holes drilled along the Detroit River water front revealed poorly to well cemented, brown sediments immediately over the rock surface, and underlying 80 to 100 feet of blue clay. The oxidized zones at shallower depths are more likely representative of Wisconsin substages of glaciation, and possibly of fluctuations within a substage. Although the evidence is by no means conclusive it seems that the oldest till known thus far found in Oakland County is of Illinoian age, but owing to the erosion by later glaciation only fragmentary patches remain.

Considering the slope of the rock surface, the movement of Wisconsin ice over the area and the resultant features produced, especially over the glacial lake plain, a question has been raised as to whether pre-Wisconsin glaciation, or possibly Wisconsin substages, produced features similar to those seen at the surface today. Thus, if earlier glacial lakes were in existence, then their beaches and associated features were subsequently buried or else partially or completely obliterated by later glaciation. The buried sand and gravel deposits of the glacial lake plain may represent features of earlier glacial lakes or merely local deposits of sorted sediments deposited by glacial meltwaters. Large bodies of gravel in the moraine-till areas may be either outwash separating tills of different ages or substages or merely local outwash deposited by local glacial meltwaters. The correct interpretation of earlier glacial episodes requires more precise data. A series of profiles is needed. They should be constructed at right angles to the major trend of the glacial features and based on a series of favorably spaced borings whose logs bear more precise descriptions of the sediments penetrated. Such a program is not usually practical, unless independently financed, since wells and borings are drilled for other than purely academic purposes involving interpretation of glacial history. However, data for such studies can be obtained if local drillers can be induced to cooperate to the extent of providing the proper agencies with better logs and samples for each well or boring completed in the future. Information would be available for all drillers concerned, and for the integration with the present known facts by students of glacial geology.

OCCURRENCE OF GROUNDWATER IN THE COUNTY

From the description of the bedrock and glacial geology of the area, it is readily apparent that groundwater in the county is under confined and unconfined conditions. Unconfined groundwater is mainly in the interlobate outwash area as shown by the harmony of static levels in wells with the levels of the inland lakes. Exceptions are wells that were completed in the morainic hills that stand above the general level of the outwash. Confined groundwater conditions are found in the many sand and gravel bodies that are interbedded with the unassorted till deposits of the two morainic ranges and the waterlaid moraines of the lake plain. The static levels of wells that penetrate such buried aquifers are usually not in harmony with the level of the inland lakes in the immediate vicinity. The piezometric map constructed for Oakland County thus represents water-table conditions over the interlobate outwash and artesian conditions predominating over most of the remaining area. The map is based on static water levels measured or reported for wells completed during the period 1946-1950. Additional levels for the same period were obtained from private or municipal sources. The resultant map compares favorably with a similar map constructed by Taylor in 1930. The principal groundwater divide is approximately along the junction of the interlobate outwash and the morainic deposits left by the retreat of the Saginaw lobe. The position of the divide also approximates the topographic divide but is slightly offset to the southeast. On the map the divide can be traced from the northeast corner of Brandon Township southwestward through Independence, Springfield, White Lake, and Highland townships, and thence into the adjacent county to the west. The divide has an elevation between 1,000 and 1,050 feet above sea level and slopes to the southwest. Excepting in a small area northwest of the divide, the movement of groundwater in Oakland County is in a southeasterly direction. A secondary divide is near Walled Lake in southwestern Oakland County, in the townships of Milford, Commerce, Novi and Lyon. The position of this divide suggests that Walled Lake, as well as its immediate surrounding area, may be a local recharge basin that serves to maintain the somewhat higher water levels reported for the vicinity.

The contours shown on the piezometric map show an uneven water-table surface which changes its character with each period of significant precipitation. The gradient of the water-table surface is more gentle in the outwash area, in contrast to the steeper gradient associated with the moraine-till area and the glacial lake plain. The bunching of the contours along a northeast-southwest trending belt marked by the junction of the glacial lake plain with the southern morainic belt is of special interest. Southeastward from this belt the contours show a more gentle piezometric gradient over most of the lake plain area of the county. This behavior appears to be in harmony with the nature of sediments as suggested by the several profiles drawn across the lake plain section. It was previously noted that the volume of coarser sediments becomes greater as the junction of the lake plain with the moraine is approached. From this junction the pressure declines more rapidly since the decrease in size and in number of the buried aquifers (and hence volume) offers a greater frictional resistance to percolating water, thereby causing a more rapid loss of head. The present water-table map departs in only two respects from Taylor's map of 1930. The most significant departure is the 75-foot difference in elevation of the southeasternmost contour. This difference indicates the approximate magnitude of the decline in the piezometric surface that has taken place in the southeastern extremity of Oakland County since 1930. The amount of decline decreases in a northwesterly direction. The other departure is that local areas of heavy groundwater withdrawal are shown by the depression contours. Areas of concentrated groundwater withdrawal are in Pontiac, Birmingham, Berkley and the Royal Oak-Clawson areas and align themselves in a northwest-southeast direction: That is, at right angles to the trend of the contours. The regional decline of the piezometric surface in the lake plain area is in part due to the areas of heavy withdrawal, but no doubt other factors have contributed to the decline. These factors include (1) the decrease in the amount of natural recharge by direct precipitation upon the area through the construction of dwellings and roads, (2) the increase in run-off resulting directly from the construction of roads, sewer lines, and drainage ditches, and (3) the drainage of former marsh areas to provide additional land for farming or urbanization. The data collected during this investigation were not of a nature to permit quantitative evaluation of the factors involved.

THE HYDROLOGIC UNITS

From the summary given of the bedrock and surface geology, it appears that at least four distinct hydrologic units are within the limits of Oakland County. The mantle of glacial drift contains three of the hydrologic units, and the consolidated sediments comprise but one. This subdivision is justified on the basis of the following factors, namely (1) the presence of water in consolidated or unconsolidated sediments, (2) the presence of water in conditions of confinement or unconfinement, (3) the quality of the water, and (4) the ease of recovery.

The Bedrock Unit

The first and most widespread of the hydrologic units is the underlying bedrock formations. It is treated as a single entity because recovery of water from this unit is almost negligible and because the amount of usable data is too meager to permit further subdivision of the unit. From the structure of the underlying formations and the nature and distribution of the overlying mantle, it is apparent that water in this unit is under confined conditions, the movement of water contained therein being generally in an up-dip direction. Static levels in the rock wells examined always stood above the elevation of the bedrock surface or above the ground surface, depending upon the geographic and topographic positions of the individual wells. For only 38 of 113 borings and wells that reached or penetrated bedrock were logs kept that bear sufficient information to permit tabulation as to static levels and yields. Of the tabulated wells, eleven were flowing with heads up to 5 feet above ground surface. The remaining non-flowing artesian wells had reported levels as much as 95 feet below the top of the casing or ground surface. Reported yields (natural flow or pumped) of all wells varied from 1.5 to 100 gpm with an average of 20 gpm. The water-bearing characteristics of each of the underlying formations could not be determined from the data obtained, but the records show that the specific capacity of rock wells ranged from 0.06 to 10.0 gpm per foot of drawdown and averaged 2 gpm. The individual yields from most of the wells of this unit were small. 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.

This unit is distinctive from the other hydrologic units since the quality of water from practically all wells is considerably more mineralized than the water recovered from the unconsolidated glacial mantle. Excepting iron, silica and some alkalies, the dissolved mineral constituents show a significant increase and/or a wide range when compared to drift water. A comparison of bedrock-water samples factor by factor with the acceptable standards indicates that most water recovered from the bedrock is objectionable in nearly all respects. The available analyses show a hardness ranging from 270 to 45,945 ppm, with non-carbonate hardness varying from 42 to 45,907 ppm and carbonate hardness from 2 to 230 ppm. Thus, water from this hydrologic unit is characterized by a non-carbonate, or permanent, hardness that is largely owing to chlorides and sulfates. The degree of mineralization increases with the depth of penetration into the bedrock. Analyses tabulated with respect to depth show that the dissolved solids increased from 1,570 to 175,800 ppm, chlorides from 360 to 102,500 ppm, sulfates from 0 to 1,881 ppm, sodium and potassium 517 to 45,908 ppm, calcium 56 to 12,450 ppm and magnesium 26 to 3,600 ppm. A pronounced change in the degree of mineralization is most apparent in waters recovered from formations older than the Antrim shale. Analyses of water samples taken from deep borings strongly indicate the impossibility of recovering palatable water even for livestock purposes from the deeper rocks. Bedrock water recovered from within the outcrop limits of the individual formations immediately beneath the mantle is generally less mineralized but not enough to compare favorably with the quality of water taken from the drift. Actually, palatable water from any one particular formation is more likely to be recovered from within its outcrop limits beneath the drift than from areas where that formation is overlain by other rock layers. Although most of the chemical analyses appear unfavorable, it may be possible to obtain additional palatable waters from this unit. Recovery of palatable water from rock wells for domestic, farm and stock purposes will be controlled by such factors as (1) the depth of penetration into rock, (2) the position of the rock well with respect to the regional topography of the bedrock surface, (3) the position of the well with respect to local bedrock topography, and (4) the amount of dilution of bedrock water by infiltration from the overlying sediments.

The Interlobate Outwash Unit

The second hydrologic unit consists of the interlobate outwash deposits between the two ranges of morainic hills. This unit is the major intake area for recharge in the county. Water of the unit is primarily under unconfined, or water-table, conditions as demonstrated by the harmony of inland lake levels with the reported static levels in wells. Inasmuch as natural materials are seldom, if ever, entirely without structure, confined groundwater conditions are scattered within the interlobate outwash. Flowing wells or springs may be in depressions or near the base of relatively steep slopes that have fine sands overlying coarser materials. Wells within this unit average 92 feet in depth but range anywhere between 18 and 320 feet. Actually the depth of any well is more dependent upon the topographic situation than upon the configuration of the water-table surface. Adequate supplies for most domestic, farm and commercial purposes are generally obtained from wells between 20 and 60 feet in depth. Yields range from 1 to 925 gpm and average 70 gpm. From a tabulation of the records it was noted that two-inch driven wells furnished 10 gpm, three-inch wells between 10 and 30 gpm, and six-inch wells between 50 and 300 gpm. Yields from 100 to 925 gpm have been reported mainly from municipal or industrial wells 8 to 12 inches in diameter. Specific capacities ranged from 1.5 to 27 gpm per foot of drawdown and averaged 13 gpm per foot of drawdown. Most of the highly productive wells reported from this area were not developed by any special methods other than continuous pumping. The water level in wells ranged from 1 to 192 feet below ground surface and averaged 33 feet. As far as records show, no decline occurs in the regional water level other than the secular, annual or seasonal fluctuations that occur in response to the variation in the amount of precipitation falling upon the area. Even progressive declines of a local character are notably absent within the limits of this hydrologic unit.

Excepting iron, the quality of water recovered from the outwash can be rated satisfactory for most needs. Dissolved solids average 354 ppm, chlorides 15 ppm, and sulfates 29 ppm. The total hardness averages 298 ppm and approaches the upper limit of waters classified as satisfactory. In direct contrast to bedrock water, the total hardness of water from the outwash is dominantly carbonate rather than non-carbonate. The principal communities located within the boundaries of this unit having a groundwater-supply system are the villages of Milford, Lake Orion, Oxford, Holly and South Lyon. On the basis of metered and estimated water consumption, the total combined pumpage of these villages is approximately 1.6 million gallons daily. No water problems have arisen restricting the use of water for any purpose, and from the present data, this unit is capable of extensive groundwater development.

The Unassorted Till Unit

The third hydrologic unit consists of the unassorted till deposits associated with the northern and southern morainic belts of hills that stand above the general elevation of the intervening interlobate tract. The vast number of wells tap sand and gravel aquifers of various dimensions that are interbedded with materials characterized by a poorer permeability coefficient, thus the water contained within the aquifers is under confined conditions and most of the wells of this unit can be classed as artesian, although only a few of them are actually flowing. The few reported flows within the area may be attributed either to their lesser topographic elevation with respect to the altitude of the interlobate outwash intake area, or to local, but individually independent, artesian structures. Unconfined, and even perched, conditions of groundwater are restricted to the scattered surface deposits of coarse elastics. Recharge of the buried aquifers is accomplished partly by the percolation of water from the principal area of intake and partly by precipitation falling directly upon the area. The magnitude of each form of recharge has not been evaluated, but no doubt the depth, extent, and interdependency of each of the aquifers determine to a considerable degree which form of recharge is to be the most effective. The importance of recharge by direct precipitation within the limits of this hydrologic unit cannot be minimized since the topographic character of the surface lends itself favorably to this kind of recharge. The numerous depressions and lakes not only act as reservoirs to regulate stream flow but likewise act as reservoirs for groundwater recharge, especially under conditions of prolonged drought or of heavy withdrawal. The surface deposits of coarse elastics, depending upon their location in relation to higher terrain, likewise constitute storage reservoirs which under proper conditions may slowly release water to the buried aquifers. The profiles drawn in the Pontiac region suggest the probability of many complex direct and indirect connections of surface sands and gravels with sands and gravels buried at various depths.

The depth of wells in this unit is between 24 and 330 feet with the average depth being 129 feet. Approximately 50 per cent of the wells are less than 100 feet in depth and nearly all provide more than adequate yields for domestic purposes. Most wells of high yields, constructed for municipal or industrial purposes were found to penetrate large aquifers at depths of 150 or more feet. The depth to the water level ranged from 17 to 165 feet for the non-flowing wells and averaged 43 feet. Flowing wells are not common, nor are they concentrated in any particular district. The average yield of flowing wells in this unit is 99 gpm with a range from 2 to 1,225 gpm. Two- to four-inch wells furnished as much as 30 gpm, 6-inch wells up to 50 gpm, and 8- to 14-inch wells had yields from 600 to 1,000 gpm. Specific capacities, measured in gallons per minute per foot of drawdown, ranged from 0.1 to 100 and averaged 11.8. The water recovered from this unit is similar in quality to water obtained from the outwash unit. In the majority of wells, the various dissolved constituents were found to have only slightly higher averages; the chlorides show a more prominent, though not serious, change--averaging 27 ppm or 12 ppm more than in the second unit; total hardness averaged 314 ppm, which is slightly more than the upper limits of waters classified as satisfactory; carbonate hardness averaged 289 ppm, and the non-carbonate 26 ppm.

Pontiac and Rochester are the largest communities within the unit. Both towns have public groundwater-supply systems with pumpage that, in 1950, averaged 12.2 million gallons per day for Pontiac and 0.7 mgd for Rochester. The village of Rochester has an excellent system, the supply is more than ample, and so far as is known, no noticeable decline is detectable in the static level. Within the civil limits of Pontiac two areas of heavy groundwater withdrawal are shown on the water-table map. The decline in the smaller of the two areas is owing to three closely spaced industrial wells that have a combined daily capacity of at least 2.6 million gallons. The decline for the larger area has been caused by heavy withdrawal by a concentration of municipal wells that tap a buried marginal outwash deposit which trends across the city from west to east. The wells owned by the city roughly follow the course of the Clinton River. In 1888 the static water level of wells located in the western end of the city stood at ground level. By 1930 the static level declined to 50 feet below surface and by 1950 the average water level was 104 feet. This represents a decline of 1.68 feet yearly since 1888, and a decline of 2.7 feet per year since 1930. With minor exceptions, the groundwater pumpage has increased from an average of three million gallons daily in 1922 to 16 million gallons daily in 1950. In the decade 1940-1950 the population of Pontiac increased only 9 per cent, but since the termination of World War II, the pumpage chart shows a sharp upward trend which is attributed to the greater consumption of water by both the old and the new industries established in the city. As long as the demand for water increases yearly, the static head will continue to decline, and no stabilization of the water level can be expected until the annual consumption rate becomes stable. Thus, it cannot be stated definitely that the aquifer has been overdeveloped until further hydrologic studies involving pumping tests on the stratum are made. However, the decline in static level may mean that the withdrawal exceeds the rate of replenishment from immediate storage, and if so then a problem of transmissibility exists. The current rate of decline in the static level of the Pontiac wells can be decreased by artificial recharge. This can be accomplished by diverting a part of the Clinton River flow (with prior treatment) directly into the aquifer by means of recharge wells. This form of recharge could best take place during the winter and early spring seasons when (1) the rate of flow of the Clinton River is more than the summer average, (2) the temperature of the water is most favorable, (3) disagreeable tastes and odors are at a minimum, and (4) the recovery of water from the aquifer is at its lowest rate. In addition, the present situation may be partly remedied through the construction of additional wells in the more northerly parts of the city. A carefully planned test-drilling program based on the available knowledge of the region should be followed. The construction of wells in other areas would relieve to some degree the concentrated pumpage which is now taking place from a theoretically "single" aquifer. Reduction in the rate of withdrawal would be reflected either in a rise of the static level within the present area and perhaps lead to equilibrium conditions, or to a lower rate of decline. Considering all factors, the city of Pontiac is most favorably situated geographically for the development of an artificial recharge program, and the geologic conditions within its limits are such that obtaining additional water supplies is possible. Certainly the large number of inland lakes within Pontiac's immediate vicinity is sufficient evidence that an abundance of water is in storage both on and beneath the surface, and that the problem faced by the municipality is primarily one of groundwater transmissibility.

From a review of the well records and geologic conditions of this hydrologic unit, it is concluded that the potential groundwater supply has been only partially developed. Records show that moderate supplies for most purposes are easily obtained but that test drilling will be necessary to locate large buried aquifers for municipal or industrial water supplies.

The Glacial Lake Plain Unit

The sediments within the limits of the glacial lake plain constitute the fourth hydrologic unit in Oakland County. From the limits of the southern morainic belt of hills, the elevation of the lake plain declines gradually to the southeast so that the average elevation of this unit is below the moraines and interlobate outwash. As in the unassorted till unit, recovery of water is largely from buried deposits of sand and gravel in which water is under confined conditions. Some of the sand and gravel deposits are associated with bedrock valleys, as shown by profiles for the cities of Farmington and Birmingham. Other buried sands and gravels may represent either features deposited by meltwater or remnants of beaches and other features formed by earlier glacial activity but similar to those on the present surface of the lake plain. Regardless of origin, the presence and location of such favorable sediments for groundwater recovery are difficult to determine in advance of drilling. Furthermore, fewer beds of buried sands and/or gravels are within the waterlaid till deposits of this unit than in the moraines and tills found elsewhere in the county. This is partially attested by the larger number of dry holes or wells of very low yield that have been drilled in the area. The profiles drawn across the lake plain show that the volume and frequency of coarse clastic deposits decrease southward. The profiles likewise indicate that most of the individual zones of sand and gravel cannot be correlated between the test holes, even though the borings are closely spaced. This fact suggests that many of the aquifers are of small areal extent and of limited storage capacity. Therefore in all probability a well tapping such an aquifer not only obtains water from the bed in which it is completed but also drains other neighboring beds, above and/or below, despite any till barriers between them, since few natural sediments are totally impermeable. Whenever clay zones act as more effective barriers against the drainage of water from higher levels, infiltration from lower sources and even from bedrock will occur if the pumping rate has sufficiently lowered the pressure within the tapped aquifer. This may explain the erratic variation of the chloride content in water samples recovered from relatively closely spaced wells. Within the unit groundwater is also under water-table conditions, but is limited to the surface deposits of sand and gravel whose origin is associated with the glacial lakes of Wisconsin time or with contemporaneous stream deposition. In the time of early settlement shallow dug wells were commonly constructed in such deposits. Recharge of the buried aquifers is accomplished by percolation of water from the higher land that is to the northwest. To some extent recharge by direct precipitation is possible despite the low permeability coefficient of the sediments, but this form of recharge would be effective only for the replenishment of water in the surface deposits of sand and gravel. Recharge by precipitation is somewhat less effective now than in the past since urbanization normally leads to increased run-off and rapid drainage.

Wells of this unit ranged in depth from 10 to 258 feet and averaged 109 feet. The average depth of wells drilled since 1930, on the whole was not greater than the average depth of wells drilled before 1910. A distinctive feature of this unit is the abundance of flowing wells in contrast to other units. The lake plain area centering about Troy, Royal Oak and Southfield townships is the largest of the flowing-well districts in southeastern Michigan. From the known geologic conditions it can be concluded that flowing wells may be obtained anywhere within the lake plain provided the established head is sufficient to overcome the frictional resistance offered by the highly varied glacial deposits of the area. The number of flowing wells has declined considerably since the time of Leverett's study. In the tabulation of wells drilled before 1910 included in Leverett's report 97 per cent of the total were reported as flowing. Static levels at the time ranged from 9 feet below to 30 feet above ground surface. Of the 193 records collected for this unit of wells which were drilled in the period 1930 to 1950, only 30 wells (approximately 15%) were reported as flowing. Static levels ranged from 137 feet below the surface to 9 feet above. In the past a non-flowing well was the exception rather than the rule; today the flowing well is exceptional. The average static level of the non-flowing wells is 32 feet. The average level below ground surface is 81 feet in Royal Oak Township and 16 feet in Avon Township. The decline in head is clearly shown in the current water-table map by comparison with the map prepared by Taylor in 1930. The areal decline shown for the lake plain unit may be attributed in part to the several areas of concentrated groundwater withdrawal centered about Royal Oak, Birmingham, Berkley, and Clawson and partly to conditions that have resulted from the urbanization of the area.

Reported yields ranged from 0.2 to 1,500 gpm and averaged 102 gpm. The average yield is somewhat high in contrast to the figures cited for the other hydrologic units of the glacial drift, but an explanation is found in the increased diameters of wells and in well improvements, particularly of those wells owned by the several municipalities of the area. Actually, of all the yields reported, 72 per cent were less than 21 gpm. A breakdown of yields in relation to casing diameter revealed that most 2-inch wells furnished less than 10 gpm, and 3- to 6-inch wells not more than 30 gpm.

Scattered yields between 50 and 450 gpm were from 8-inch wells, and yields between 500 and 1,000 gpm were furnished normally by 12-inch wells. Exceptionally high yields up to 1,500 gpm required wells having diameters between 18 and 30 inches. The extremely large casings required to produce wells of good yields are an indication of the difficulty involved in developing large water supplies in the lake plain unit. It is not surprising that the specific capacities per foot of drawdown ranged from 0.03 to 166.4 gpm and averaged 22.4 gpm.

The quality of water within the limits of the lake plain has some notable differences which make this hydrologic unit even more distinctive from the others in the mantle. The dissolved solids average 430 ppm, which is greater than is normal elsewhere in the county. The total hardness, calcium, magnesium and sulfates, on the other hand, average generally less when compared with the other units of the drift mantle. The chlorides and the sodium and potassium combined are conspicuously higher, averaging 83 and 68 ppm respectively. Total hardness ranges from 34 to 446 ppm and averages 238 ppm or 60 to 76 ppm less than for the other two hydrologic units. As usual, the carbonate hardness predominates; the non-carbonate hardness averages but 6 ppm. Two possible explanations may account for the lower average value in the hardness of groundwater from this unit. First, the decrease in hardness itself might be an indication that the major recharge of the buried aquifers is not from the moraines and more distant inter-lobate outwash areas; that precipitation over the area may be significant in recharging the area to the extent of decreasing the hardness factor of the water since percolation in the direction of the hydraulic gradient should bring in water of greater hardness from the moraine and interlobate outwash areas. Recharge by precipitation through more local intake areas would result in diluting the hardness because a part of the calcium and magnesium of the waterlaid and lacustrine sediments was previously leached away by the waters of the pro-glacial lakes. The second, or alternative explanation for the lower average hardness of groundwater in this unit may be the result of a natural softening brought about by the process of base exchange. Excess sodium ions in the sediments, brought in by periodic infiltration of bedrock waters, may be exchanged for the hardness-producing calcium and magnesium ions more commonly present in the drift waters. Some mechanics of percolation between drift and rock waters must be involved since the mere intermingling of both would not likely result in a decreased hardness. The non-carbonate hardness of water recovered from wells of this unit is extremely low. It was noted in a majority of records that the initial analyses of water samples taken from newly constructed wells always indicated either a total absence of, or a very low value in the non-carbonate hardness content. After the wells had been in use for some time, subsequent analyses generally revealed the appearance of, or an increase in, the non-carbonate hardness. The sulfate content of the water samples averaged but 12 ppm, and in the tabulation of the analyses for the lake plain section the sulfate was parallel to the non-carbonate hardness.

The most conspicuous difference in the quality of water of this unit is in the amount of chloride, sodium and potassium. The chlorides ranged from 4 to 320 ppm and averaged 83 ppm; sodium and potassium combined were 20 to 239 ppm with an average of 68 ppm. It is not surprising that the chloride salts are in tastable quantity. Salt in the sediments of the lake plain may be accounted for by both natural and induced infiltration from the underlying rock formations. Since the sediments of the lake plain have been deposited over the rock lowland and against the lower part of the upland slope, they are in a favorable position to receive the more highly mineralized bedrock waters whose movement in the consolidated beds is in an up-dip direction. With but rare exceptions, wells reported to have water with a salty taste, or for which analyses revealed 50 ppm or more of chlorides, are within the limits of the lake plain. The chloride content of the water apparently increased southeastward, and its concentration was found greatest in sediments filling, or closely associated with, bedrock valleys. Additional bedrock infiltration of an induced nature was also caused locally through improper grouting of unsatisfactory rock wells and test holes, or by the heavy withdrawal of drift water in areas where highly productive wells are concentrated. Monthly analyses of water samples taken from two Birmingham wells indicate such induced infiltration from bedrock sources. The few analyses of samples taken from Royal Oak, Berkley and Clawson wells suggest induced infiltration, but cannot be demonstrated graphically.

The quality of water within this unit is further impaired by the gas in the drift. Gas wells and water wells having gas shows were found only within the limits of this lake plain unit. Most of the gas was from coarse sediments interbedded within the clays and tills, and in a few places was reported in clays described as soft, soupy or putty-like. The gas-bearing zones are at various depths beneath the surface and have pressures as high as 30 pounds. The wells when plotted on a base map were found to be mainly in that part of the lake plain mantle immediately overlying the Antrim shale, and particularly in sediments filling or covering the rock valleys carved in the Antrim shale. The largest of the known drift gas areas is centered around the city of Clawson whose inhabitants utilized this gas as a source of fuel for cooking and for space heating. In recent years many of the gas wells have been abandoned owing to declining pressures and the infiltration of water. The source of the gas in the drift is concluded to be principally seepage from the Antrim shale. It is not believed to be marsh gas of more recent origin since logs of holes drilled within the unit fail to show any evidence of peat deposits or other organic matter in sufficient quantity. Owing to the number of well explosions, gas in the drift is considered as another unfavorable factor in the quality of water in this area. However, the presence of gas should not preclude the development of groundwater in this unit if the quality is not impaired by other dissolved constituents since proper measures can be taken for its disposal to avoid explosions.

In addition to several unincorporated subdivisions, the principal communities within the lake plain unit depending totally or partially upon a groundwater supply are the cities of Royal Oak, Berkley, Clawson, Birmingham and Farmington. All but Farmington have been concerned with water problems during the past several years. Because of the perimeter spacing of wells and the operation of wells according to a pumping schedule, the decline of the static level, as shown by the hydrographs, in the Birmingham area has been slight in contrast to the other areas within the unit. Although Birmingham is concerned over future water demands, artificial recharge is possible by using surface waters from Endicott and/or Quarton lakes during the winter and spring seasons. It appears that the city can continue further development only to the point of limitations placed by the infiltration of rock waters, and to some degree it may be also limited by the laws of riparian rights. The declines centered about Royal Oak, Berkley and Clawson have been difficult to evaluate owing to the lack of hydrographs. However, it appears that withdrawal has been excessive as indicated by a few measurements of water levels, by declining yields and the increase in chlorides. It may perhaps be justifiable to state that the water supply has been overdeveloped at least to the point where induced infiltration of rock water has impaired the quality of drift water. This in itself is also an indication that transmissibility of water from the higher areas to the northwest does not keep up with the present rate of withdrawal. The water-table map shows that these municipalities are situated in an area where the decline of the piezometric surface has been greatest.

An examination on a strictly qualitative basis of the data collected seems to indicate that the lake plain aquifers are incapable, except at great cost and effort, of meeting a demand to be imposed by a future populace with a density comparable to that of the Detroit area. The area is capable of furnishing small supplies for most domestic needs; but a number of small areas already exist where building has not commenced, or else where it has been retarded in further development, owing to an inadequate water supply or to failure in locating and developing one. Without question some additional supplies can be developed to ease the shortages that occur today during the summer season, but it is doubtful if the large population predicted for 1970 for the lake plain area can be entirely supplied by groundwater resources. The basis for this conclusion has been made from the following considerations:

1. The thickness of the drift cover over the rock lowland is thin in comparison to the drift cover found elsewhere. Thicknesses in excess of 150 feet are found only over the buried rock valleys. This limits the number of possible aquifers before bedrock is reached.

2. The profiles constructed across the area suggest that the coarse sediments which may serve as satisfactory aquifers for moderate to large supplies are largely deposited in that part of the lake plain adjacent to the moraines. Southward, as may be noted, the volume and number of sand and gravel zones seem to decrease.

3. It is doubtful whether large bodies of sand and gravel are buried within the waterlaid and lacustrine deposits. At best, the profiles seem to indicate many small zones, and the heavy withdrawal of water by wells from any one of them no doubt leads to the drainage of water from others in the vicinity. Depending upon the permeability and position of the clay barriers, the transmissibility of water from the surrounding clays into the aquifers may be slow in contrast to the rate of withdrawal. Thus, overdevelopment of such localized aquifers is possible and eventually will lead to the further lowering and enlargement of the depressions already in the piezometric surface.

4. The water-table map shows a gradient to the southeast, and the crowding of the contours in a belt defined by the Maumee beaches suggests a change in the transmissibility coefficient of the sediments in the lake plain area. Thus, the small bodies of sand and gravel in the more southerly area are handicapped in relation to the rate of recharge that could take place by percolation of water from the northwest. Furthermore, because of the lower permeability coefficient of sediments in the area, the rate of recharge by direct precipitation on the area may be slow and ineffective. This form of recharge is further impeded by urbanization which has increased run-off and reduced the size of the area which can absorb rainfall.

5. The valleys incised into the rock lowland, as revealed by the well logs, are not for the most part of exceptional magnitude nor always filled with coarse elastics such as could constitute aquifers of large storage and/or good permeability. From what is known of the glacial history, it is likely that many of the valleys are filled primarily by waterlaid till in which are some lenses of sorted materials. Only two small valleys have been found which are sand- and gravel-filled and have been tapped by wells.

6. Recourse to artificial recharge is limited by the availability of surface-water supplies, and by cost if consideration is given to the utilization of flood waters arising from periods of excessive precipitation. If recharge by surface water is considered, only Birmingham is most favorably located. Other communities must depend on streams whose rate of discharge must be measured before utilization--or else the issue of riparian rights becomes involved. Utilization of flood waters will be costly since a single system of sewers now exists in the area for the disposal of flood waters and sewage.

7. Recourse to bedrock for additional supplies on a large scale is not possible for reasons of quality if not quantity. Furthermore, it has been demonstrated that the heavy withdrawal of groundwater locally from drift has already resulted in the induced infiltration of bedrock water that is highly mineralized. Thus, certain areas are already approaching overdevelopment since induced infiltration of rock waters has partially impaired the quality of drift water.

8. Development of large supplies of water from the drift of this area to meet future demands cannot be made on a community level, but must be accomplished on a regional

level. Development on a community level may result at some time in legal complications. The known good aquifers, as well as those yet to be discovered, are not controlled by civil boundaries. Adjacent communities may tap the same aquifers and legal questions of priority will arise if the water situation becomes more critical. Furthermore, development on a community level restricts exploration largely to its civil limits, and if no additional aquifers are found, then added cost is imposed in obtaining water from beyond its limits. Development on a regional level likewise has problems, involving the organization of an authority, the evaluation of the water problems of the individual units of government, and the procurement of funds for planning, exploration and development. From the preceding statements no attempt is made to argue that groundwater is lacking within the hydrologic unit defined by the limits of the lake plain. The quantity of water in storage is great because a layer of 100 feet of sediments spread over the entire lake plain (approximately 180 square miles) having an arbitrarily chosen porosity of 20 per cent, is capable of storing more than 700 billion gallons of water. However, it is argued that this unit contains major problems involving quality and transmissibility of water. Thus, to recover water from ground sources in sufficient quantity and of acceptable quality may result in the excessive expenditure of funds and effort for a great number of wells without the constant assurance of dependability. It appears that the most reasonable solution, from the standpoint of cost and the immediate availability of water, involves (1) the continuation of groundwater exploration and development within the unit, (2) the extension and development of the facilities of the Detroit water-supply system into the southern Oakland County area to augment the ground water supply, and (3) the creation of a regional water commission whose membership is represented by the communities and areas involved. This commission must be given authority to plan and act in the future interests of all. It is conceivable that even the future facilities of the Detroit water-supply system may be inadequate to deal with the demands imposed by surrounding fringe areas. A regional water commission may well justify its existence in planning a surface-water supply system from Lake Huron to serve Oakland and Macomb counties. The rapid development of the Detroit Metropolitan Area is certain when the St. Lawrence Seaway becomes a reality.

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DEPARTMENT OF CONSERVATION
Gerald G. Eddy, *Director*

GEOLOGICAL SURVEY DIVISION
W. L. Daoust, *State Geologist*