STATE OF MICHIGAN
DEPARTMENT OF CONSERVATION
GEOLOGICAL SURVEY DIVISION

Progress Report 16
GROUND-WATER RESOURCES OF SOUTHEASTERN OAKLAND COUNTY, MICHIGAN

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U. S. Geological Survey

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Contents

Illustrations

Plates

Figures

Tables

ABSTRACT

The area covered by this report comprises a square which measures three townships on a side and encloses 318 square miles in southeastern Oakland County. The investigation of the ground-water resources of this area was made by the U. S. Geological Survey in cooperation with the Detroit Metropolitan Area Regional Planning Commission, the Michigan Department of Conservation, and the Michigan Water Resources Commission.

In 1950 the population of this nine-township area exceeded 341,000, or more than 86 percent of the total population of Oakland County. This county ranks third in the state in number of industrial establishments and workers and is fifteenth in agricultural importance. Its numerous lakes and rolling uplands contribute to its top rank in the state in the number of recreational enterprises in rural or suburban areas.

The climate is moderately humid. The average annual precipitation is 30 inches and the mean air temperature is 47.2° F. Snowfall averages 38 inches in the November-April interval. The growing season averages 151 days.

The regional land surface slopes from northwest to southeast and has a total relief of 360 feet. Pitted outwash plains and morainal hills that are more than 19000 feet above sea level in the northwest corner of the area give way southeastward to a sequence of terminal moraines and intervening till plains in the middle part. These give way to the broad lake plains that cover the southeastern third of the area.

The area lies on the southeast edge of the Michigan Basin and the bedrock is composed of northwest dipping strata of the Devonian and Mississippian systems. The Antrim shale, of Late Devonian and early Mississippian age, is the oldest formation cropping out beneath the mantle of glacial drift in this areas it underlies the southeastern part. The Bedford shale, Berea sandstone, and Sunbury shale overlie the Antrim and are overlain by the Coldwater shale, their areas of outcrop beneath the drift lying successively farther northwest. These formations are of early Mississippian age.

Throughout the area the bedrock is covered by glacial drift which ranges in thickness from 25 to more than 350 feet. The drift increases in thickness from southeast to northwest, but considerable relief on the underlying bedrock surface greatly modifies this trend. Extensive moraines, till plains, lake plains, and gravel outwash plains cover the area. In the northwestern third of the

area an extensive upland of gravel plains is dotted with lakes ranging from a few feet to more than 100 feet in depth.

Precipitation is the perennial source of all water in this area, whether on the surface or underground. The average annual rainfall on the nine-townships is equivalent to a continuous supply of 450 m.g.d. or 9 times the combined annual withdrawal from all wells in the area.

About 53 percent of the area is drained by the Clinton River, 44 percent by the River Rouge, and the remaining 3 percent by the Huron River. Less than one-third of the annual precipitation reappears as surface discharge from the watersheds of this area.

About two-thirds of the annual precipitation on the area is lost by evaporation from water and land surfaces and by transpiration from vegetative cover. A substantial part of this large annual water loss is from the many lakes and other exposed water surfaces and from the contiguous lands where the depth to the water table is slight. Average annual water losses by evapotranspiration are equivalent to about 280 m.g.d. or nearly 6 times the combined withdrawal from all ground-water supplies in the area.

The principal aquifers are the alluvial deposits bordering streams and the buried outwash deposits which represent alluvial fills in preglacial or interglacial stream channels. Intensive well developments in the urban areas have greatly lowered ground-water levels in the buried outwash deposits, have brought localized problems of declining well yield, and have induced migration of mineralized waters from the underlying consolidated formations. During 1952, withdrawals of ground water in the nine township area averaged about 50 m.g.d., most of this quantity being pumped from municipal wells. This annual pumpage was distributed as follows: 60 percent in Pontiac and environs; 20 percent in Birmingham, Royal Oak and Troy Township; and the remaining 20 percent throughout the suburban and rural areas.

INTRODUCTION

Purpose and scope of investigation

Bordered by the Nation's greatest fresh-water lakes, Michigan is generally regarded as an area free of water problems. On a state wide basis this impression is correct as Michigan does possess a tremendous potential in both surface- and ground-water resources. However, the greatest part of Michigan's urban and industrial development and a large part of its agriculture and recreational development are concentrated within the southern third of the state. Consequently, numerous localized but highly important water problems have arisen through mutual interference of the developments of individual water users.

A principal factor in the unprecedented industrial growth of this state has been the widespread and ready availability of its water resources. However, the relative ease with which water needs of the past have been satisfied has created a false sense of security concerning the magnitude of the water resources. Indicative of our present and future water needs is the estimate (Wells and Williams, 1951)[/1] that since 1909, while the population of this country increased nearly two-fold our municipal water needs alone increased about six-fold.

From available records of municipal water use in Michigan during 1951, it is estimated that some 60 percent of the population is served from surface sources and the balance from ground-water sources. However, with the exclusion of Detroit this picture of source distribution is completely reversed and we find that about 70 percent of the remaining population is dependent entirely on ground-water sources. Of the nearly 600 municipal water supplies in operation in Michigan during 1951, about 450 were dependent on ground-water sources.

In Michigan, the earliest systematic investigation of ground-water resources was an inventory of flowing wells and municipal water supplies of the Southern Peninsula by Leverett (1906 and 1907) during the 1904 field season. In the following field season a similar reconnaissance (Leverett, 1906, pp. 29-53) was made of the eastern half of the Northern Peninsula. In 1932, the Geological Survey Division of the Michigan Department of Conservation entered into a cooperative agreement with the U.S. Geological Survey to set up on a small scale a continuing investigation of Michigan's ground-water resources. Until 1942 this program was limited, for .the most part, to the measurement of ground-water levels in a few urban areas in the southern part of the state and a group of observation wells in the north central part of the Southern Peninsula.

Accelerated water use by industries and municipalities in Michigan during World War II resulted in a rapid rise in the number of requests to the State Geologist for assistance in the location of additional ground-water supplies. Increasing reports of declining water levels and local water shortages prompted the expansion of the cooperative water-resources program. From 1942 through the balance of the war years and for several years thereafter the cooperative ground-water program was directed largely to assisting federal, state, or municipal agencies and defense industries in locating and developing adequate ground-water supplies. The many requests for assistance from other than direct defense agencies were fulfilled by the Michigan Geological Survey as a part of their general program of public service in the development of Michigan's water resources.

In 1947, a formal request was made to the State Geologist by the city of Birmingham, Michigan, that he inquire if the cooperative water-resources program might undertake an intensive study of the ground-water problems of central and southeastern Oakland County. Unfortunately, funds then available for cooperative water-resources investigations were fully committed and expansion of this work was not possible without prior legislative action. In 1950, through the Water Resources Steering Committee of the Detroit Metropolitan Area Regional Planning Commission, an official request was made to the State Geologist for the mutual assistance of the Federal and State Geological Surveys in a survey of existing ground-water problems in southeastern Oakland County. Again, because of prior commitments, it was found impractical to divert the limited facilities of this program to undertake this added assignment.

To avoid further delay, the following Oakland County cities and townships joined together to underwrite the water-resources program of the State Geological Survey to an extent that would permit a limited reconnaissance survey of the ground-water resources of central and southeastern Oakland County:

Cities	Townships
Birmingham	Bloomfield
Berkley	Southfield
Bloomfield Hills	Troy
Clawson	Waterford
Lake Angelus	West
Pontiac	Bloomfield
Royal Oak	
Sylvan Lake	

The objective of this reconnaissance survey was to collect information readily available within the files of state and municipal agencies which related to the ground-water resources of the area represented by the contributing civil entities. Insofar as the budget allotted would permit, evaluation was to be made of the extent and magnitude of existing ground-water developments; the nature of problems confronting water users in the area; and the deficiencies of existing data. Within the limitations of the data available, the order of magnitude of the ground-water resources of the surveyed area was to be indicated. The scope and extent of an investigation adequate to provide the hydrologic basis for sound future planning of ground-water developments by water users in the area was to be described.

/1 References are listed alphabetically at end of this report.

Location and extent of area

The area covered by this investigation is a square which measures three civil townships on a side and embraces 318 square miles in southeastern Oakland County. It is bordered on the east by Macomb County and on the south by Wayne County, and abuts the north boundary of Detroit. The northern tier of townships from west to east includes Waterford, Pontiac, and Avon; the central tier includes West Bloomfield, Bloomfield, and Troy; and the southern tier includes Farmington, Southfield, and Royal Oak. The location of this area within Oakland County and in relation, to principal cities of Michigan is shown by figure 1.

Historical sketch of municipal water-supply developments

The first municipal water supply reported in the area was constructed in 1888 when the city of Pontiac installed a group of wells near the Clinton River, at the site of its present Walnut Street plant. Ground-water was obtained from permeable deposits of sand and gravel which are overlain by a relatively thick formation of clay. Initially, water levels in these wells were at land surface or above and the wells were pumped by direct suction. For nearly 30 years this station supplied the water needs of Pontiac. With the rapid growth of Pontiac and the attendant increase in pumping from the Walnut Street wells, ground-water levels in the area declined and the average output per well decreased. Additional wells were installed from time to time in an effort to maintain an adequate supply despite the declining yield per well. By 1917 water levels in the vicinity of the Walnut Street well station had declined below suction limit and it was necessary to install air-lift pumping equipment. With the advent of World War I and attendant increases in water demands, water levels declined further and by 1918 it was decided to abandon the ground-water supply and install a treatment plant to utilize the waters of the nearby Clinton River. A filtration plant was placed in operation in 1921, but was operated for only a few months and then discontinued because of tastes, odors, and high temperatures of the surface water. Since that date Pontiac has been continuously supplied by ground water sources.

In Birmingham a waterworks plant, which was supplied by five flowing wells finished in permeable drift deposits, was placed in operation in September 1890. This plant was on the banks of the River Rouge at the intersection of West Maple Road and Baldwin Street. Since that date, ground water has served as the sole source of supply for the water needs of Birmingham.

In Royal Oak a municipal water supply, using ground water as the source, was constructed near the intersection of Crooks Road and Hustonia Avenue in 1913. As the city grew, it became more and more difficult to obtain sufficient water to meet the rapidly rising needs of this community. Progressive increase in the chloride and hardness content of the ground waters and marked lowering of water levels in the vicinity of the well stations made it necessary to purchase supplementary water from Detroit, after the extension of Detroit water mains along Woodward Avenue in 1930.

Municipal water supplies dependent on wells finished in permeable sand and gravel were developed by the city of Clawson in 1923 and by the city of Berkley in 1925. The cities of Bloomfield Hills and Sylvan Lake and the village of Lake Angelus have no public water supply and residents of these communities depend entirely on private wells which are finished in permeable sand and gravel.

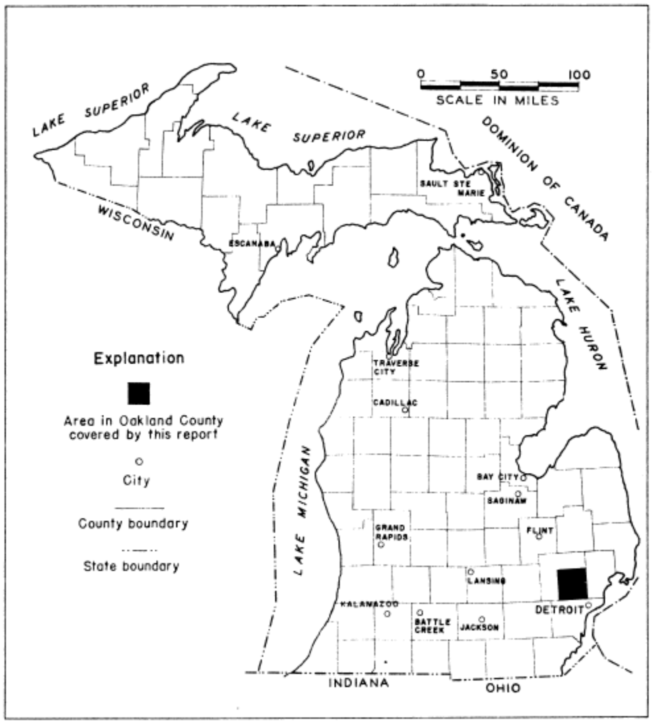

Figure 1. Index map of Michigan showing location of southeastern Oakland County.

The city of Ferndale, bordering on Detroit, constructed a distribution system in 1921 and purchased water from Detroit. Similar arrangements for the purchase of water from Detroit were made by the city of Pleasant Ridge in 1923; Royal Oak Township in 1924, with service to Hazel Park; the city of Huntington Woods in 1930; Southfield Township in 1930, with connection to the city of Royal Oak; and the city of Oak Park in 1936.

Prior to connection with the Detroit water supply, residents of Ferndale, Oak Park, Pleasant Ridge, Huntington Woods, and Hazel Park depended on ground-water supplies from individual domestic wells. Reports of well failures in the area were rather general and in drought years many residents found it necessary to haul water.

In 1895 the city of Rochester developed a public water supply from a group of flowing wells on a branch of Paint Creek in Avon Township. Originally, these wells flowed directly into a reservoir at a head sufficient to furnish water to the city. The wells were finished in permeable deposits of sand and gravel at depths ranging from 65 to 88 feet below land surface.

In 1912 the city of Farmington developed a municipal water supply with two wells finished in sand and gravel at depths of about 170 feet below land surface. These original wells were a short distance south of the present well supply, which lies north of Grand River Avenue near the Shiawassee Trail and the River Rouge.

Previous investigations

Various phases of the geology of this area are described in numerous reports relating to extensive investigations of the geology of the Southern Peninsula of Michigan and appropriate references to these reports are included in the section on References. Detailed investigations confined to specific phases of the geology of this area were made by G. M. Stanley and J. W. Bay. Stanley (1936) reported on the geology of the Granbrook area and the Whittlesey beaches at Birmingham, and Bay (1937 and 1938) did considerable work on the glacial history of the rivers and their associated terraces in Oakland and adjacent counties.

An inventory of municipal water supplies and flowing-well districts including Oakland County was made by Leverett (1904). In 1929, an investigation of the ground-water resources of the Pontiac area was made by F. C. Taylor (1930) of the Pontiac Department of Water Supply. At the time of publication Taylor's report represented the most detailed treatise ever published on the water resources of any area in Michigan. Since 1939, measurements of water level in three observation wells maintained by Pontiac Department of Water Supply have been published in the annual series of water-supply papers of the U. S. Geological Survey entitled "Water levels and artesian pressures in observation wells in the United States". Records for two of these wells extend back to 1931 and the record for the other well which extends back to 1929 are shown graphically in Water-Supply Paper 886, in which the measurements for 1939 are tabulated. In 1952, a brief discussion of the water resources of the southern half of Oakland County was included in a report on the water resources of the Detroit Metropolitan Area (Wisler, et al, 1952).

Well numbering system

The numbering of wells in the cooperative water resources program follows a pattern which was developed by mutual agreement between the Federal and State Geological Surveys. A four-letter code precedes the number of each well and serves as a guide to the general location of that well. The first pair of letters in this prefix designates the county in which the well is located and the second pair designates the civil township, city, or village. The first letter pair consists of a capital and a lower-case letter, which are selected as suggestive of the county name. If the second letter pair indicates a civil township, an upper-case letter followed by a lower-case letter is used. If the second letter pair designates a city or village, both letters are upper-case. The number following the letter code represents the order in which the well was visited during the field inventory. The letter prefixes for the townships and communities for which well-inventory data are reported are shown by table 1. The prefix Oa, for Oakland County, is omitted in this report because all wells described are in the county.

Well Number Prefix	Township	Well Number Prefix	City or Village
Av	Avon	BK	Berkley
Bf	Bloomfield	BR	Birmingham
Fa	Farmington	BH	Bloomfield Hills
Pt	Pontiac	CW	Clawson
Ro	Royal Oak	FE	Ferndale
So	Southfield	OP	Oak Park
Tr	Troy	OL	Orchard Lake
Wt	Waterford	PT	Pontiac
Wb	West Bloomfield	RH	Rochester
		RO	Royal Oak

Table 1. Letter code used as prefix to well numbers in townships, cities, and villages of southeastern Oakland County.
A map showing the relative position and the boundaries of these townships and communities is shown by figure 2.

Through this report on illustrations that show specific boundaries and the names of the civil townships, cities, or villages, the prefix letters are omitted and only the numerical part of the official well number is given. Where some question may arise as to the appropriate code prefix for any well indicated, the second letter pair of the official code number is designated in addition to the numerical portion of the number.

Acknowledgments

Many well logs, records of well performance, and records of well construction were obtained from files of the Michigan Department of Conservation, the Michigan Department of Health, the Huron-Clinton Metropolitan Authority, the cities, villages, and townships in the area, and from local well owners and well drillers. Among the well drillers contacted, especially helpful were Neal Cameron of Farmington, O. O. Corsaut, Jr. of Oak Park, Glen Godby of Big Beaver, the Layne-Northern Company of Lansing, L. L. Oberlin of Pontiac, O. N. Phillips of Rochester, Harvey Tracey of Farmington, Oscar Woodcomb of Pontiac, and many others. Numerous foundation boring records were obtained from the Michigan State Highway Department, the Detroit offices of the Raymond Concrete Pile Company, the Michigan Drilling Company, and the Detroit Department of Water Supply. Considerable information of value was obtained from reports of consulting engineers which were furnished through the courtesy of the various municipalities.

Many chemical analyses of ground waters in the area were obtained from files of the Michigan Department of Health and from well owners in the area. Records of pumping and operational data on well performance were obtained from files of well owners and several well drillers.

Records of stream flow and lake levels, and valuable assistance in the interpretation of these data were obtained from the district office of the Surface Water Branch of the U. S. Geological Survey, which is under the direction of A. D. Ash, District Engineer. Information on the discharge of drains and interceptors was obtained through the courtesy of L. F. Oeming of the Michigan Water Resources Commission, Ralph Main, Drain Commissioner of Oakland County, and D. M. Pierce, Staff Engineer, of the Michigan Department of Health.

Many records of wells and foundation borings were obtained from A. J. Mozola of the Geology Department of Wayne University who was working coincidentally in this area on a study of the glacial geology of Oakland County and his problem for the Doctorate in Geology.

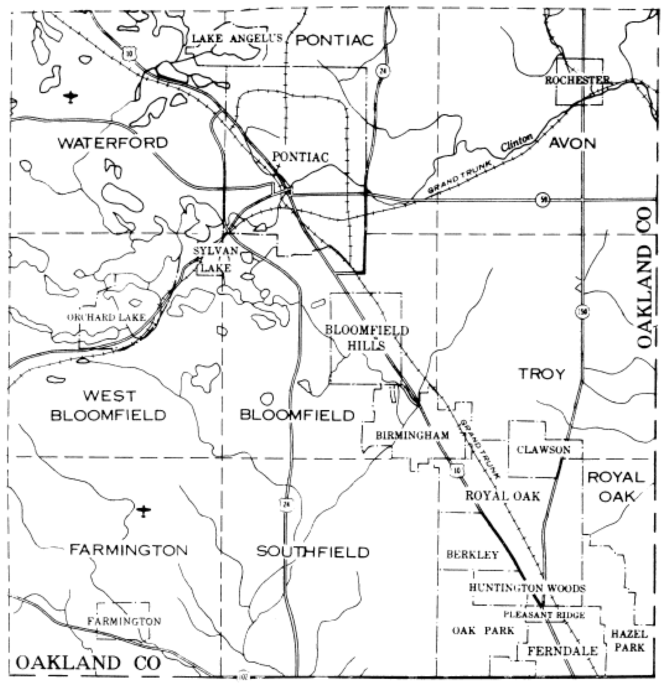

Figure 2. Map showing the location of townships and cities in southeastern Oakland County, Mich.

GEOGRAPHY

Population

According to the 1950 census, the total population of Oakland County is 396,001 and of this total 341,042, or 86.2 percent reside within the nine civil townships discussed in this report. The distribution of population within these townships is shown by table 2.

Township	Population		
	1940	1950	Percent gain
Avon	8,776	13,147	50
Bloomfield	14,248	20,404	38

Farmington	7,205	12,988	80
Pontiac	70,230	79,270	13.3
Royal Oak	86,387	152,070	77.5
Southfield	8,486	18,408	116.9
Troy	6,248	10,062	61.0
Waterford	13,060	25,230	93
West Bloomfield	5,892	9,263	52.7
Southeastern Oakland County	220,532	341,042	55

Table 2. Total population of townships in southeastern Oakland County.

The townships which border Detroit or Pontiac are the more populous and showed the greater gains in population during the decade ending 1950. The trend to suburban living by workers gainfully employed in Detroit or Pontiac is shown by the pattern of net change in rural population of the nine townships. As shown in table 3, the larger gains in rural population occurred in the townships along the principal transportation arteries serving Detroit and Pontiac.

Transportation

Railroads

The Detroit-Grand Rapids Division of the Grand Trunk Western Railroad diagonally bisects the area from southeast to northwest. This line joins the main line of the Grand Trunk Western Railroad system at Durand to furnish service to the west via Chicago, Ill., and to the east via Toronto, Canada. The Jackson-Richmond Division traverses the area from southwest to northeast through Pontiac and a third line of this system extends northward from Pontiac with terminals at Bad Axe and Caseville, Michigan. The northeastern part of the area is traversed by the Detroit-Bay City Division of the Michigan Central Railroad which serves Rochester, Michigan.

Township	Population		
	1940	1950	Percent gain
Avon	5,017	8,878	77
Bloomfield	1,771	3,821	116
Farmington	5,695	10,676	88
Pontiac	3,465	6,038	74
Royal Oak	7,040	20,976	198
Southfield	8,486	18,408	117
Troy	6,248	10,062	61
Waterford	12,019	24,087	100
West Bloomfield	5,597	8,580	53
Southeastern Oakland County	55,338	111,526	100

Table 3. Estimated/1 rural population in townships of southeastern Oakland County.

/1 By Detroit Metropolitan Area Regional Planning Commission.

Highways

The principal federal highways traversing the area are U. S. Highway 10 which coincides with Woodward Avenue of Detroit and diagonally bisects this area, and U. S. Highway 16 which coincides with Grand River Avenue of Detroit and crosses the southwest corner of this area. U. S. Highway 10 connects Detroit with the industrial cities of the Saginaw Bay region and U. S. Highway 16 joins Detroit with Lansing, the Capitol city, and Grand Rapids, a key industrial area. U. S. Highway 24 is principally a belt line bypass which expedites traffic flow from Detroit to Pontiac and the north.

State highways M-24 and M-150 join this area with cities of the Thumb region. Routes M-58, M-59, M-102, and M-218 serve largely as supplementary feeder roads between the principal federal roads.

Airports

The Pontiac municipal airport, about 4 miles west of Pontiac, is the only public airport within this area. The longest runway is 3,000 feet. However, in terms of ground transit time all parts of this area are as convenient to the large Willow Rim airport as is downtown Detroit.

Economic development

Agriculture

Although highly developed as a suburban-residential, industrial, and recreational area, Oakland County also ranks relatively high as an agricultural region. In terms of land area devoted to farming, Oakland County ranks fifteenth among the counties of the state and first among counties of the southeastern district or District No. 9 of the Michigan Department of Agriculture crop-reporting service (Mich. Dept. of Agr., May 1952). In the value of land and farm buildings, it ranks not only second within its district but also second within the state. This high rank in land and building evaluation reflects the influence -of the gentleman farmer or the estate-connected farm. Principal farm enterprises include horticultural specialties, fruit and nut crops, poultry and poultry products, dairy products, and other livestock products.

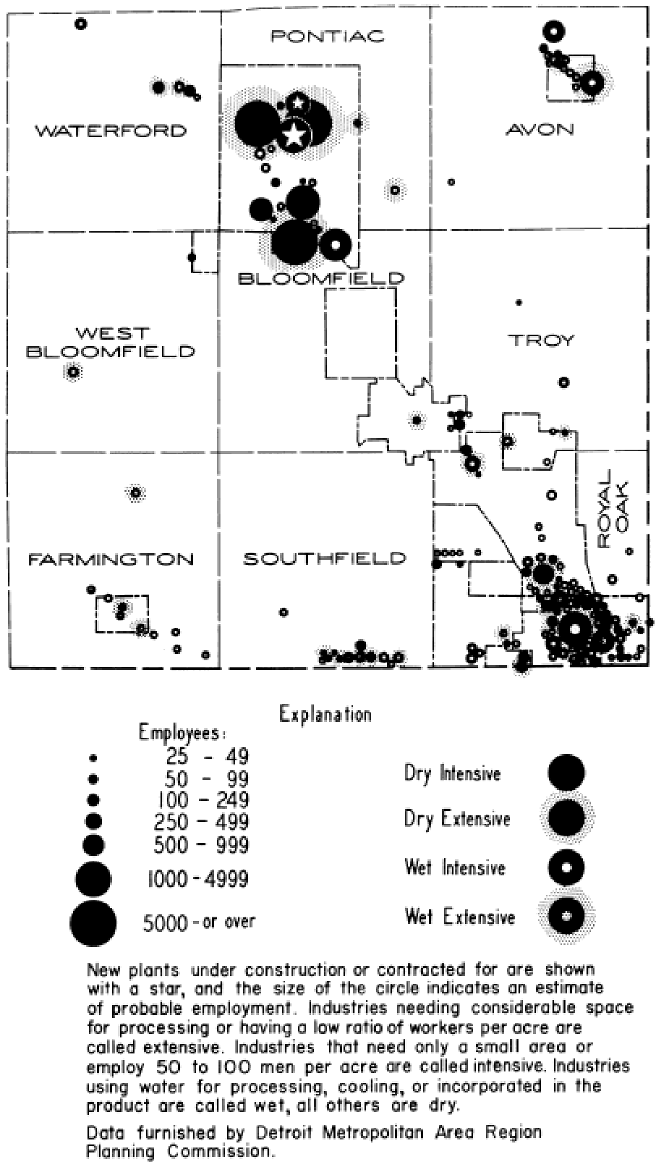

Figure 3. Manufacturing plants in southeastern Oakland County, Mich.

Industry

The U. S. Census of Manufactures shows that manufacturing establishments in Oakland County increased from 132 in 1939 to 567 by 1947 and Oakland County ranked third among Michigan counties in the number of manufacturing establishments and ranked fourth in the number of workers employed. Principal manufactures included transportation equipment, machinery, fabricated metals, chemical and allied products, paper and allied products, and printing and publishing supplies. In terms of the number of establishments and the number of employees, Oakland County ranks among the first ten in the state for all industrial groups tabulated (U. S. Bur. of Census, 1949) and it occupies from second to fifth place within the state for most of these industrial groups. The distribution of industries in this area according to space requirements, water-use types, and workers employed is shown by figure 3, which was developed by the Detroit Regional Metropolitan Planning Commission.

Recreation

The numerous lakes, the rolling topography, and the high degree of park planning and development in Oakland County, and its proximity to the heart of the Detroit industrial metropolitan area have gained for the county top ranking among all counties of the state in the number of recreation-connected commercial establishments in rural or suburban areas. Its rank of first in the number of amusement and dining establishments and the number of gas stations in the suburban and rural areas is a further index of the intensive recreation development in this county.

PHYSIOGRAPHY

Climatology

Precipitation and temperature

The climate of southeastern Oakland County is moderately humid, with about 30 inches of annual precipitation and relatively mild with a mean annual air temperature of 47.2° F. Although in the path of the great cold waves from the northwest, the modifying influence of the Great Lakes tempers the climate of the area. Extremes of temperature which would otherwise accompany the passage of cold waves are greatly reduced in comparison with states of this northerly latitude adjoining Michigan on the west. The greatest continuity of precipitation and temperature observations within the area is the record maintained at Pontiac, Michigan, which extends continuously from 1908 to date, and intermittently back to 1888 when precipitation recording was started at this station. The average annual precipitation, the monthly minimum, maximum, and mean precipitation, and the daily extremes and monthly mean of temperatures observed at this station are shown by figure 4.

Snowfall

The average annual snowfall at Pontiac is 38 inches for the fifty-year period ending in 1951. The average monthly snowfall is distributed as follows: November, 3 inches; December, 8 inches; January, 9 inches; February, 10 inches; March, 6 inches; and April, 2 inches. Minor amounts or a trace have been reported for October and May. The greatest monthly snowfall recorded at Pontiac was 33 inches in February 1908. The maximum snowfall for any calendar year was 62 inches recorded in 1926 and the minimum fall was 13.5 inches in 1906 and a near minimum of 13.6 inches during 1941.

Frosts

The average date of the last killing frost is May 11 and of the first killing frost October 9. The average length of the growing or frost-free season is 151 days. As shown by figure 4, monthly precipitation during the growing season is for the most part above the average rate of precipitation for the year.

Wind, humidity. and sunshine

Records of wind velocity, humidity, and sunshine are not available at the Pontiac station but conditions in this area are very similar to conditions in nearby Detroit where a lengthy and continuous record is available. The prevailing winds at Detroit are from the southwest at an average rate of about 14 miles per hour. Violent windstorms occur infrequently. The number of cloudy days each year about equals the number of clear days. Cloudy days prevail during the winter and sunshine is plentiful during the summer. The relative humidity, averaged on a monthly basis and based on the 8:00 A.M. observation, ranges from 73 percent in July to 85 percent in January, and averages 79 percent during the 55-year period of record.

Evaporation

Records of evaporation in the area are not available, but the evaporimeters maintained at Lansing may be used as an index. Since 1946 the U. S. Soil Conservation Service has maintained a weighing black-pan evaporimeter at Michigan State College, East Lansing, Michigan. In 1951 the U. S. Weather Bureau installed a standard Class A land pan adjacent to the Soil Conservation Service evaporimeter and coincident records are available for the April-October intervals for each year since that date. The minimum, maximum, and average evaporation for the 7-year record of the Soil Conservation Service evaporimeter are shown by table 4 and a comparison with the adjacent Weather Bureau pan is given. To reduce the observed water losses from the Weather Bureau pan to losses from a large water surface a coefficient of 0.70 has been recommended (Rohwer and others, 1934 9 pp. 671-747).

Geomorphology

Topography

Southeastern Oakland County lies within the Huron-Erie morainal and glacial-lake plain areas (Leverett and Taylor, 1915). The regional land surface slopes from northwest to southeast and has a maximum relief of about 360 feet. A generalized topographic map of the area is presented as figure 5.

The northwest third of the area consists of a pitted outwash or gravel plain with a few morainal hills. A succession of moraines and intervening till plains trend southwest to northeast through the middle part of the area. The highest moraine attains an altitude of 1173 feet above sea level. From the moraines a broad lake plain slopes gently to the southeast.

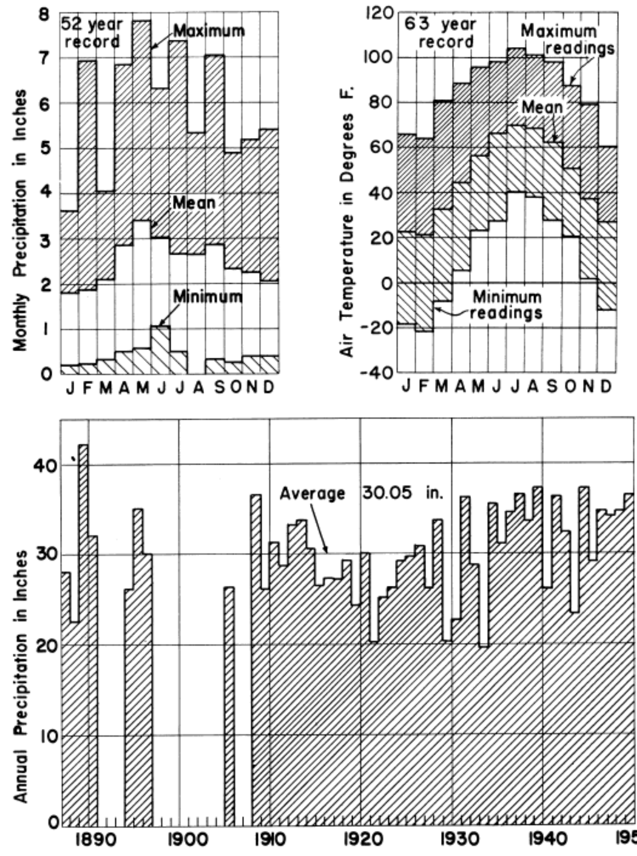

Figure 4. Precipitation and temperature at Pontiac, Mich.

Drainage

Lakes and swamps are numerous on the upland outwash plain and the streams meander because of their small gradients. On the lowland, glacial-lake plain gradients are also small and the streams are but moderately entrenched. The narrow flood plains bordering the channels have been encroached upon by man's urban and industrial development. In the intermediate belt of morainic hills, where gradients are appreciable, the streams locally have cut relatively deep channels down to the base of the morainic ridges, where they are diverted at almost right angles to flow southwest along the course of an early glacial channel and finally turn southeast and flow across the glacial-lake plain (fig. 5).

	Evaporation in inches				
Month	U. S. Weather Bureau Class A land pan [1] 1952	U. S. Soil Conservation black-pan evaporimeter			
		1952	Range and average for period 1946-1952		
			Maximum	Minimum	Average

January	--	1.01	1.62	0.75	1.06
February	--	1.43	1.43	0.86	1.18
March	--	2.74	3.88	2.06	2.66
April	--	5.25	6.61	3.27	4.86
May	5.76	6.70	7.83	5.19	6.42
June	8.75	9.56	9.56	5.82	7.60
July	8.36	9.73	10.60	5.54	8.65
August	6.66	7.63	9.32	6.47	7.66
September	4.84	5.13	7.40	3.86	5.31
October	4.16	4.87	6.04	1.34	4.01
November	--	2.51	2.51	1.32	1.83
December	--	2.90	2.90	0.77	1.48
Total	--	59.46	--	--	52.72

Table 4. Evaporation at East Lansing, Michigan

/1 Observed in frost-free months only.

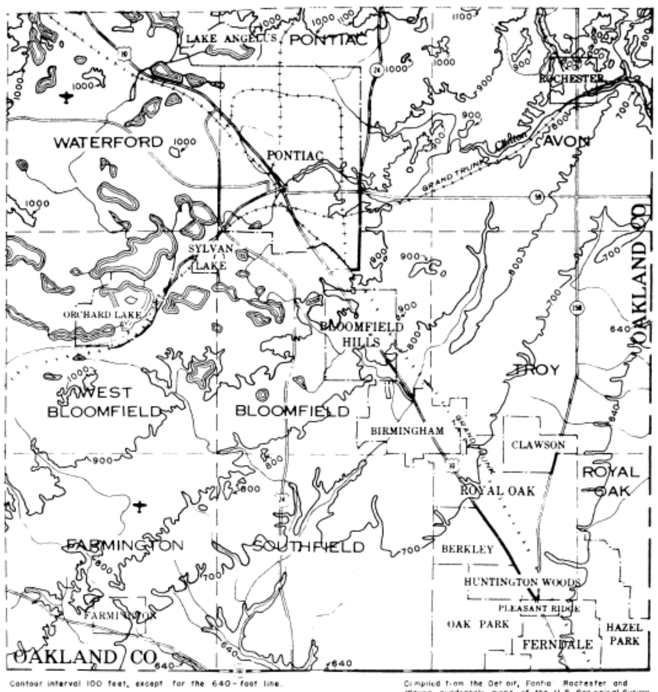

Figure 5. Topographic map of southeastern Oakland County, Mich.

GEOLOGY

Consolidated rocks

At various intervals of geologic time, Michigan was submerged beneath extensive inland seas in which clay, silt, sand, and organic remains were deposited. These seas were shallow and underwent numerous oscillations of sea level that were generally of small magnitude. At times these inland seas were connected to a greater intra-continental sea to the southwest. At other times differential warping of the earth's crust elevated areas adjacent to the Michigan basin on the south and west and thereby isolated the local seas. In some periods the climate of the region was at least as arid as the climate today in the southwestern states. During the arid phases, when water losses exceeded inflow, evaporites such as salt, gypsum, and anhydrite were deposited in these shallow basins.

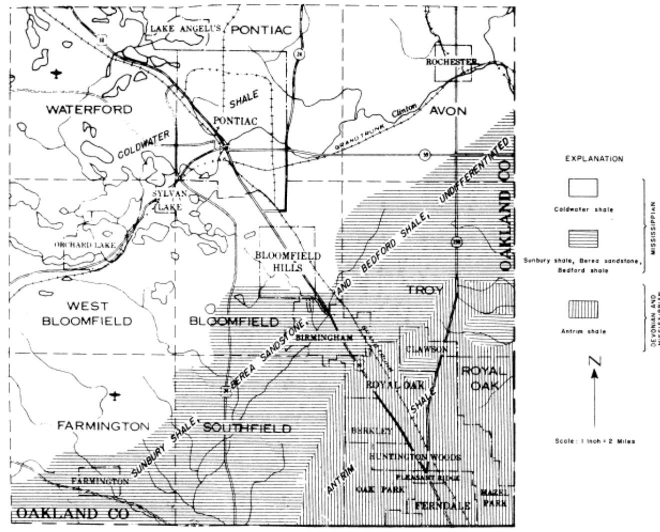

Figure 6. Geologic map of southeastern Oakland County showing areal extent of the bedrock formations

As the weight of sediments within the basin accumulated the clay and silt became consolidated to form shale and siltstone; the sand became indurated to form sandstone; and the limy remains of organisms and precipitated calcium carbonate were cemented to form limestone. The resultant rocks have all conceivable gradations of sandy limestone, limy sandstone, shaly limestone, limy shale, shaly sandstone, sandy shale, and others.

In the shallow seas the sedimentary rocks were deposited in nearly horizontal beds. However, elevation, subsidence, compaction, and warping of the rock formations produced a bowl-shaped or basin-like structure, which is known as the Michigan basin. The classic analogy of this structure has long been to liken the rock strata to a stack of saucers[/1]. This arrangement is only a regional aspect, for in detail the formations were warped into gentle folds which may trend in any direction, but most folds have a northwest to southeast axis. Oakland County lies on the southeast edge of the Michigan basin, and in general, the strata dip to the northwest. However, the Howell uplift which is centered in nearby Livingston County has modified this regional dip so that the beds in the southern and western part of the area dip to the north and northeast. The areal distribution of the bedrock in southeastern Oakland County is shown by figure 6.

The rock formations are everywhere mantled by Quaternary sediments which range in thickness from 20 to more than 350 feet. Thus, the description of the bedrock is based in small part on the examination of meager records of drilling in the area and in large part on the reports of others who have studied these formations at the outcrops. Five concentric bands of rock strata underlie the mantle of glacial drift in southeastern Oakland County. In ascending order and also radially inward toward the center of the Michigan basin they are the: Antrim shale, Bedford shale, Berea sandstone, Sunbury shale, and Coldwater shale. The age, lithology, range in thickness, and water-bearing properties of these formations are summarized in table 5. Underlying the Antrim shale are older sedimentary rocks, but available data indicate that in this area these formations contain only mineralized waters.

/1 A nest of shallow mixing bowls is a better analogy. H.M.M., Michigan Geological Survey editor.

Devonian and Mississippian systems

<u>Antrim shale</u>

The Antrim (Lane, 1901, p. 9) shale is the oldest bedrock formation that crops out beneath the blanket of drift in southeastern Oakland County. This formation underlies the extreme southeastern part of Oakland County and includes nearly all of Royal Oak Township, the eastern part of Southfield Township, and the southern and eastern parts of Troy Township.

The Antrim shale is brown to black and dark grayish-black, carbonaceous, fissile, finely laminated, evenly bedded, and approaches slate in hardness where it is not weathered. It is characterized by an abundance of brown spore cases identified as <u>Sporangites</u> <u>huronensis</u>, which may be the source of the high bituminous content of the shale. In the past, the shale was often mistaken for coal and it has been reported that some of it will burn, but with difficulty. Several thin, gray shale members occur in the lower Antrim. On weathering, the shale becomes gray or rusty brown.

Pyrite and anthraconite concretions are scattered throughout the formation, but are concentrated in the basal part. The pyrite concretions range from 1 to 3 inches in diameter. The anthraconite concretions, composed of brown to greenish, coarse-textured, iron carbonate and bituminous calcite, range from 1 inch up to an extreme of 6 feet in diameter, with an average of about 2 feet. On decomposition these concretions stain the shale with iron oxides and percolating waters in these rocks become highly mineralized. When their drills penetrate concretions in wells drillers commonly report them as "lime" or "hard shell".

Small non-commercial quantities of natural gas have been found in drilling in the Antrim shale and in the overlying drift. This gas has caused trouble in water wells, the two best known examples being the explosions at the Federal store in Ferndale and at one of the early municipal wells in Royal Oak.

<u>Bedford shale, Berea sandstone, and Sunbury shale</u>

Limitations of available data make it impractical to map the Bedford shale, Berea sandstone, and Sunbury shale as separate units so these formations are grouped together in this discussion and on figure 6. These formations crop out beneath the drift in a band which trends across the southern part of Farmington Township; occupy most of Southfield Township; swing northeast across the southeast corner of Bloomfield Township and the northeast corner of Royal Oak Township and continue northeast through Troy Township.

The Bedford (Newberry, 1869, pp. 21, 29) shale lies conformably on the Antrim and is predominantly a soft gray and gray-blue shale, but may -include sandy shale or gray, shaly, limestone beds. Some red shale has been reported.

Overlying the Bedford shale is the Berea (Newberry, 1869, pp. 21, 29) sandstone, referred to also as Berea "grit". In most places it has two or three massive, gray, fine-grained, sandstone members separated by hard, blue-gray shales. In eastern Michigan where the Berea sandstone is thickest, three units can be recognized. The lower unit consists of light gray, dolomitic sandstone which is quite silty and shaly in places. The sandstone is micaceous, in places pyritic, and generally well cemented with silica and dolomite. The middle unit is a friable, fine- to medium-grained, angular to subangular, quartz sand with scattered thin beds of shale and tightly cemented sandstone. The upper unit is similar to the basal unit, but is less shaly and more pyritic. In southeastern Oakland County, the Berea consists mainly of the intermediate unit.

The Sunbury (Hicks, 1878, pp. 216, 220) shale, the uppermost of the three formations, is a brown to black pyritiferous shale somewhat like the Antrim, but has no brown spore cases and is less calcareous. It is dark gray in some places and has several lithologic facies.

Few logs of wells penetrating these strata are available. Estimated thicknesses of the formations are shown in table 5. The formations are considered to be conformable, but evidence is not conclusive as contacts are not exposed in Michigan. No diagnostic fossils have been found in these formations and thus correlation is based on their stratigraphic sequence and lithologic similarity to rocks in Ohio.

<u>Coldwater shale</u>

The Coldwater (Lane, 1895, p. 66) shale crops out northwest of the area of the Bedford, Berea, Sunbury formations. It is quite variable throughout, but consists predominantly of gray, bluish-gray, and bluish shales, with some gray shales which appear black when wet. Subordinate amounts of dolomite, limestone, siltstone, and sandstone are in the formation. Most of the shales are thin-bedded, range from soft to hard, and are brittle and slate-like. Large nodules of "kidney" iron ore are scattered through the formation and drillers often report these as "lime" or "shell". Beds of greenish-gray, purple, purplish-red, and red shale and sandy shale have been reported. Lenticular or "stray", grayish, micaceous, sandy shale and sandstone have been reported near the base and near the top of the formation. In the outcrop areas, these sandy phases may yield fresh water but at depth they almost invariably yield mineralized water.

The contacts of the Coldwater with the Sunbury below and the Marshall above are reported to be conformable. The upper part of the Coldwater is so nearly like the red sandstones and sandy shales of the overlying Marshall formation that it is difficult to distinguish between the two. The upper contact is northwest of the area covered by this report.

Of these formations only the Berea, with the possible exception of some "stray" sandstones in the Coldwater, yields potable water locally and the supply is limited to domestic wells Any intensive development in the Berea would probably soon cause encroachment of mineralized water, because fresh water occurs only in the upper few feet of the formation along the outcrop.

Unconsolidated deposits

During the Pleistocene epoch, at least four major glacial invasions and retreats were made over the northern part of the North American continent. The last or Wisconsin ice invasion and subsequent retreat is principally responsible for the surface features now exposed and is therefore the most thoroughly understood. Surficial features similar to those present today were developed by the earlier ice sheets, but were modified and deformed by later invasions. Antecedent glacial features, as well as the original preglacial surface controlled, to some extent, the movement of subsequent ice invasions and their depositional features. Although the earlier ice sheets probably covered the state as extensively as the Wisconsin, the nature and distribution of their deposition is now obscured by the mantle of Wisconsin glacial debris or drift.

Features of glaciation

In southeastern Oakland County the mantle of glacial drift ranges in thickness from about 20 to 350 feet. In general, the thickness increases in a northwesterly direction and the composition of the glacial material changes from sand and clay to sand, clay, gravel, cobbles, and boulders.

The glacial features of the Southern Peninsula were developed during the Wisconsin stage and are related to three ice lobes which coalesced to form a continental ice sheet at the time of maximum ice extent, but which were more or less distinct during the advance and retreat of the Wisconsin glacier. These lobes were: the Michigan lobe which occupied the present Lake Michigan basin; the Saginaw lobe which extended southwestward from Saginaw Bay; and the Huron-Erie lobe which occupied the Lake Erie basin, the southern part of the Lake Huron basin, and the Ontario peninsula between the two basins. The surficial features of the report-area are related largely to the Huron-Erie lobe and in-small part to the Saginaw lobe.

The most extensive glacial forms in this area are recessional moraines, ground moraines or till plains, lake plains, and gravel or outwash plains. Recessional moraines mark positions of the glacier front subsequent to the building of the terminal moraine (end moraine) and likewise represent times when the forces of ice accretion and depletion were nearly in balance. The recessional moraines of southeastern Michigan are of two types, land-laid and water-laid, the difference depending on whether the deposition was on land or in ponded waters in front of the glacier. In some places the deposits of water-laid moraines were reworked by the ponded waters.

Ground moraines (till plains) lie between successive recessional moraines and mark areas where the waning glacier deposited its load of heterogeneous material without sorting. Locally, till plain deposits were reworked by meltwaters.

Outwash or gravel plains are water-sorted deposits in which gravelly material predominates. Such deposits were laid down by braided meltwater streams that were overburdened with sediments.

Part of southeastern Oakland County was covered by former glacial lakes. Deposits on the old lake beds are lake clays and sands, which locally may be predominantly either clay or sand, or a mixture of both. These deposits are relatively thin and in some places cover deposits of other glacial features, such as the Detroit Interlobate moraine and a part of the Birmingham moraine. The shorelines of these lakes are shown on plate 1.

There is a part of a kame near the northern limit of the area. Kames are ice-contract features which are composed of stratified drift. At least two principal methods of origin have been postulated (Flint, 1947, pp. 147-148). One is the accumulation of debris in or on the surface of stagnant ice which later melts and leaves this accumulation in the characteristic cone-shaped kame. The other method postulates that a deltaic or outwash cone was built out in front of the ice and later the ice melts or collapses in such a fashion as to isolate the kame.

There are numerous kettle lakes in the northwest part of the area. The origin of these lakes is discussed on page 29.

Retreat of the Wisconsin glacier

In most of this area the glacial features were developed by the action of the Huron-Erie lobe which advanced from and retreated to the southeast. The exception is the Drayton gravel plain in the northwest corner of the area which slopes generally to the southeast. suggesting that it was formed by meltwater from the Saginaw lobe (Leverett and Taylor, 1915, p. 198). The drainage from the Saginaw lobe at the time of the formation of the Drayton gravel plain was southeast from the glacier to a master stream that flowed southwest.

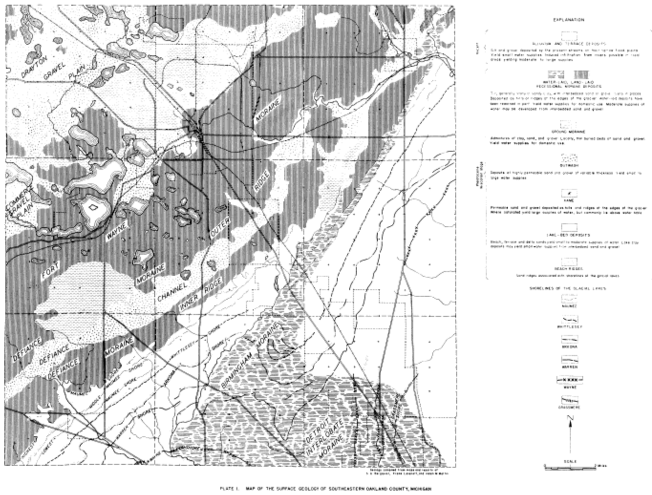

Plate 1. Map of the surface geology of Southeastern Oakland County, Michigan.

Another gravel plain, known as the Commerce plain, is south of the Drayton plain and was formed when the ice front of the Huron-Erie lobe stood on the Fort Wayne moraine. In this area the Fort Wayne moraine is undifferentiated from the outer ridge of the Defiance moraine. The Commerce plain has a northwest sloping surface which, at the time of formations, led the meltwaters into Huron River (Bergquist and MacLachlan, 1951, p. 5).

After formation of the Fort Wayne moraine and the Defiance moraine (outer ridge), the ice retreated in part to the position of the Defiance moraine (inner ridge). During the formation of this ridge, the Defiance channel, which is between the outer and inner ridges, carried the melt-waters to the southwest as far as Ann Arbor, where the drainage continued southward between the Fort Wayne and Defiance moraines through the ancestral channels of the Huron and Raisin rivers and finally reached glacial Lake Maumee near Adrian, Michigan (McGuinness, et al, 1949, pp. 11-12). Further recession of the ice resulted in the development of the Birmingham moraine. The meltwaters of the ice then used the Rochester channel which is between the inner ridge of the Defiance moraine and the Birmingham moraine. During the development of the Birmingham moraine, according to Leverett (1915, p. 285), the Detroit Interlobate moraine was formed beneath the ice in ponded water. Leverett considered it an interlobate feature formed along the line of junction of the Huron lobe and the Erie lobe. This explanation accounts for its trend which is roughly perpendicular to the trend of the other moraines in the region.

After the formation of the Birmingham and Detroit moraines, the Pleistocene history of this area relates the features formed by the glacial lakes. Beaches of six of the glacial Great Lakes are traced in southeast Oakland County. In order of their formation they are lakes Maumee, Arkona, Whittlesey, Wayne, Warren, and Elkton.

Lake Maumee was the earliest of the glacial Great Lakes in this area. The origin of this lake is associated with the eastward retreat of the Huron-Erie lobe away from the Fort Wayne moraine in northwestern Ohio and northeastern Indiana. The waters of the lake were ponded between the Fort Wayne moraine and the retreating ice. As the ice retreated, the lake extended itself northeastward to the vicinity of Adrian, Michigan when the ice front stabilized and built the Defiance moraine. During this, the first and highest stage of Lake Maumee, drainage was through the Fort Wayne outlet near Fort Wayne, Indiana into the Wabash River, the Ohio River, and finally the Mississippi River (Leverett and Taylor, 1915, p. 322).

Eastward retreat of the ice, away from the Defiance moraine opened an unnamed outlet somewhere near Imlay City, Michigan which initiated the second and lowest stage of Lake Maumee. Taylor (1915, p. 322) postulates that the drainageway may have been east of Imlay City and was subsequently destroyed by the readvance of the ice front which marks the beginning of the third or middle stage of Lake Maumee. The discharge of the third lake stage was through the Imlay outlet down the Flint River to the glacial Grand River. In this period the beaches of the lowest stage of Lake Maumee were submerged and reworked.

Lake Arkona came into existence when the ice had withdrawn to a point north and east of the "Thumb" region of Michigan and permitted the waters of Lake Maumee to extend around the "Thumb" and into the Saginaw basin, where they mingled with the waters of Lake Saginaw. Lake Saginaw had a lower outlet through the Maple River into the glacial Grand River and as Lake Maumee declined to this lower stage, Lake Arkona was initiated. The lowering of this lake is recorded by three beaches, each at a successively lower level.

Lake Whittlesey was initiated when a readvance of the ice separated the Saginaw basin from the lower Huron and Erie basins. The water in the Saginaw basin remained at relatively the same level as former Lake Arkona, but the water in the lower Huron and Erie basins was raised above the level of Lake Arkona. These two bodies of water are known as Second Lake Saginaw and Lake Whittlesey. Lake Whittlesey discharged westward into Lake Saginaw through the Ubly outlet near Ubly, Michigan.

The retreat of the ice at the closing stage of Lake Whittlesey initiated Lake Wayne. This lake was the first to drain to the east and not westward to the Mississippi. The drainage flowed past Syracuse, New York into the Mohawk depression and thence to the Hudson River near the site of Albany. A readvance of the Ontario lobe, in the New York region, closed the Syracuse-Mohawk-Hudson outlet causing the water in the Huron-Erie basins to rise and merge with the waters of Lake Saginaw. This change formed Lake Warren whose discharge was westward through the glacial Grand River. Retreat of the ice front resumed and Lake

Grassmere was formed at a temporary halt in the lowering from the Lake Warren level to Lake Elkton[/1].

Three more glacial lakes followed short-lived Lake Grassmere, but their shore features are outside the area under discussion. These lakes were, in order of development, Lake Elkton, Lake Algonquin, and Lake Nippissing (Leverett and Taylor, 1915, pp. 324, 328-332, 399-463).

/1 Leverett renamed Taylor's Lake Lundy to its original name Elkton. A.J.S., Vol. 237 p. 456, 1939.

Origin of Pit Lakes

The lake-dotted upland of pitted outwash, west and north of Pontiac, is of principal importance in an appraisal of the ground-water resources of southeastern Oakland County. Thus the origin of the pit or kettle lakes of this area merits discussion. The explanation for the origin of pit or kettle lakes that is now generally favored implies that ice masses were stranded either on the outwash plain in front of the ice or were buried within the moraine. Later, these stranded or buried masses of ice melted and left the characteristic pit or kettle lake. Many of the smaller depressions are circular, whereas the larger ones are somewhat elongate. They range in diameter from several hundred feet to several miles. The depth of most pits or kettles is of the order of tens of feet but locally depths of some are 100 feet or more (Flint, 1947, pp. 148, 149). In the outwash plain the pits are numerous and many are arrayed in a chain that lies normal to the front of the retreating ice or in arcuate bands that parallel the ice front. Many of the pits dotting the outwash plain were formed by the stranding of ice blocks floated out from the glacier by meltwaters during periods of thaw. This explanation leads to a random distribution of the pit or kettle lakes.

Certain evidence raises considerable doubt as to the validity of the ice block-stranding origin for the deeper lakes in Oakland County. Maps showing contours of the sounded depth are available for many of these lakes. Inspection of the lake-bottom contour maps shows that many of the lakes exceed 50 feet and several exceed 100 feet in depth. In some lakes the bottom contours are symmetrical with the lake shore configuration and show a progressive deepening along the principal axis of the basin. In some lakes the bottom contours indicate one or more major deeps with perhaps several minor deeps, where the terms major and minor refer not to the area enclosed by the deep, but relate to the total depth involved. In some lakes the principal axes of the deeps are aligned and indicate a progressive trend of the sea level altitude from minor to major deeps. In addition, some consistency is evident in the progression of the altitudes of major deeps from lake to lake. These data are summarized by figure 7, which shows the altitude above sea level of the principal deeps in the lakes sounded and the orientation of the deeps in each lake.

The progression of altitudes of the deeps from lake to lake shows a regional gradient directed into the southeast quadrant. Available information shows that the regional slope of the bedrock topography in this area is directed into the southeast quadrant. If these lakes were formed by the stranding of ice blocks, the orientation of the lake-bottom deeps and the progression of bottom altitudes from deep to deep within a given lake or from lake to lake would not be consistent nor would the direction of bedrock drainage and the trends of lake-bottom altitudes agree.

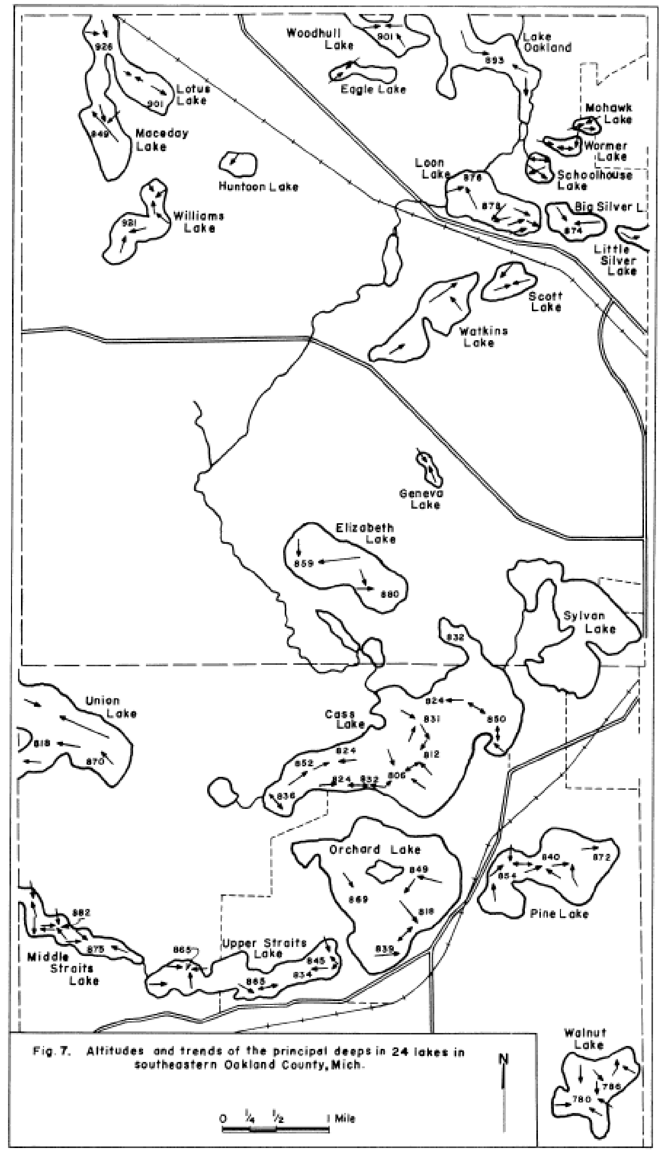

Figure 7. Altitudes and trends of the principal deeps in 24 lakes in southeastern Oakland County, Mich.

Of further Interest is a study of the maximum gradients of the lake bottoms along the periphery of the lake basins and around the small islands in several of the large lakes. Examination of the lake-bottom contour maps shows that in several lakes the maximum gradient observed approaches or equals the slope of the maximum angle of repose for unconsolidated materials when submerged and thus raises some question as to the nature of the sediments in which the lake basins were formed.

The axes of the principal deeps in lakes west of Pontiac and the progression of their bottom altitudes show convergence along an axis which, when projected, nearly coincides with the line of municipal well stations that parallels the course of the Clinton River through Pontiac. In addition, the altitudes above sea level of the deeps in these lakes correspond with the surface of the permeable deposits of sand and gravel that fill the basal section of the preglacial channel in which these wells are located.

A study of the configuration of the major and minor deeps in all lakes sounded reveals that the compass bearings of the principal axes of the deeps fall in a pattern which strikingly resembles the angular joint pattern reported by Rhodehamel (1951, p. 89) for the bedrock topography of the Saginaw Bay region. The distribution and frequency of the compass bearings for the principal axes of the deeps as measured from the lake-bottom contour maps are shown by figure 8. The dominant frequencies for the strike of these lake-bottom deeps are along the compass bearings 60° in the northeast quadrant, 60° and 70° in the northwest quadrant, and the east-west axis, but these directions are also the principal axes of bedrock shear lineations found in Michigan as reported by Kelly (1936, p. 215) and Reed (1951).

In view of the considerable evidence of a consistent regional pattern in the origin and development of the deeper lakes in this area, the postulate of their formation at random, by the stranding of ice blocks that broke off from the retreating Ice front seems untenable. However, an alternative and equally plausible explanation for the stranding of ice blocks may be developed to explain the systematic orientation of the deeps. This alternative explanation involves the probable sequence of events which occurs with the advance and subsequent retreat of glaciation over a land surface of moderate relief. In the advancing phase of each cycle of glaciation, continuing accretion to the ice mass increases its weight and bows down the land surface in front of the advancing ice. Meltwater from the ice sheet and drainage diverted toward the ice front by downwarp of the land surface submerges the topographic depressions in front of the advancing ice. Pre-existent drainage systems in the path of the continental glacier's advance would also be submerged unless their direction of flow was compatible with the direction of ice advance. As the swelling flood of melt-water drainage reversed and otherwise modified former drainage or developed new drainage, the remnants of older drainage were submerged. The prevailing temperatures would freeze any water contained in these depressions before the advancing ice mass covered them.

After the ice advances over a submerged topographic low, the ice contained within, the low becomes an integral part of the regional ice mass and tends somewhat to preserve the form of the low. The low is modified if the movement of the ice is along flow lines which are directed through the topographic low. Any movement of ice through the low tends to enlarge and deepen the basin.

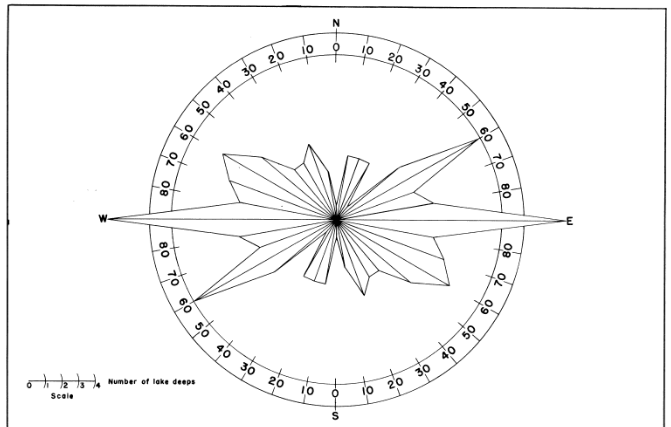

Figure 8. Diagram showing the number of occurrences and direction of lake deeps in 24 lakes in southeastern Oakland County, Mich.

Figure 8. Diagram showing the number of occurrences and direction of lake deeps in 24 lakes in southeastern Oakland County, Mich.

As the glacier melts from the land surface, the total thickness of ice overlying the topographic lows is somewhat greater than the ice thickness left on the areas adjacent to these lows. Thus, after all ice has melted from the adjoining land surface a plug of ice remains in the topographic low, In the course of thawing, large volumes of meltwater run off from the ice front. These meltwater streams transport large quantities of rock debris, which is spread over the landscape and thereby buries the ice plugs left in the former topographic lows. If meltwater streams flowed over the ice plug before it is buried deeply by a blanket of outwash, thawing may be accelerated because of convection set up by the circulation of these waters. Under these conditions the smaller ice plugs may be washed out and the topographic low eliminated by filling with stream debris. In the case of the larger ice plugs, the wash out and subsequent back fill might do more than breach the ice plug and subdivide the former topographic low. Evidence suggestive of this latter possibility was presented by Zumberge (1952, pp. 17-18) for a chain of lakes in Martin County, Minnesota.

As shown by Stefan (Ingersoll, Zobel, and Ingersoll, 1948, pp. 194-196), the time required to thaw a given mass of ice by conduction varies as the square of the thickness of the ice mass. Thus, for twice the thickness of ice the period of thawing is 4 times as great and for 10 times the thickness the time of thawing is 100 times as great. For ice blocks which were buried so deeply that circulation and resultant transfer of heat by convection was prevented, the time of thawing by conduction may be estimated by Stefan's equation. For example, a 50-foot thickness of ice would require as much as 1,000 years to thaw by conduction only. In this estimate the temperature rise premised is in accord with magnitudes generally assigned to the postglacial rise in air temperature in this latitude. Under the same conditions a 100-foot thickness of buried ice would take several thousand years to thaw by conduction.

The time of thawing would be much smaller than indicated by the above estimates, if the glacial debris overlying the ice plug was relatively thin and could settle into the ice mass and thereby expose the ice to thawing by both conduction and convection. With the ice exposed, further thawing would form a layer of water on top of the ice plug. In converting water from the solid to the liquid state, at 32° F, heat in the amount of 80 calories per gram must be supplied to accomplish the thawing. Note also that water is a poorer conductor of heat than most rocks and has a higher specific heat.

Thus, a layer of water would tend to deter further thawing of the underlying ice mass. However, as the layer of water became of appreciable depth, differences in density would develop circulation and permit thawing by convection in addition to thawing by conduction.

From reports of the time of thawing required to remove ice thicknesses ranging from 6 to as much as 30 inches on inland lakes in these latitudes, it was estimated, with the aid of Stefan’s equation, that the influence of convection might decrease the time of thawing to as little as ten percent of the time required where only conduction is involved. Nevertheless, it is apparent that the thawing of ice masses, tens of feet to 100 feet or more in thickness requires considerable periods of time.

It is evident that wherever topographic lows contained ice masses of appreciable thickness and areal extent, the great delay in thawing of the included ice plug tended to protect these lows, particularly where the ice was deeply buried by glacial debris. Thus, for each ice invasion some pre-existent topographic lows may have persisted until the time of ice recession and in modified form may remain as lows in the post-glacial topography. The apparent correlation between certain features of the lake-bottom deeps in Oakland County and similar features found to be indicative of joint patterns in the bedrock suggests the possibility that the origin of the deeper lakes in Oakland County may be in some manner related to the bedrock surface of this area. The importance of bedrock structure in controlling the development of preglacial drainage in the Saginaw Bay region was discussed in detail by Rhodehamel (1951). The importance of structure in the development of surface drainage in Southern Michigan was indicated earlier by Newcombe and Lindberg (Aug. 1935s. PP. H73-H91). Unfortunately no detailed records are available of deep drilling in the vicinity of the deeper lakes of Oakland County. Until such records become available, this suggestive correlation can not be assured.

To the east and south of the lake area municipalities and industries have done a considerable amount of deep drilling in exploring for ground-water supplies. On the basis of the drilling records obtained, it has been the general opinion that drift thicknesses in the area are of the order of several hundred feet or more. Samples of the materials penetrated in the drilling of most of these test wells were not preserved and little information is available except the drillers report. Where drilling progressed to appreciable depth and samples were preserved, it was found that the driller was often unable to distinguish between the bedrock and the overlying drift unless the bedrock formations were highly resistant to drilling. The bedrock underlying the Pontiac area and the lake area to the west consists of shales, sandy shales, and shaly sandstones of the Coldwater.

Records of most of the deeper test holes in the Pontiac area show a relatively thick section of clay and gravel or clay, sand, and gravel at the base of the test hole. From experience elsewhere in the correlation of drilling samples with drillers logs, it has been found that where the underlying bedrock is the Coldwater shale, the recognition of the drift-to-bedrock contact may be considerably in error when based on drilling resistance as an index. Thus, any further study of the origin of the lakes in this area must necessarily be postponed until adequate records of test drilling and drilling samples are available.

Water-bearing properties of Pleistocene and Recent deposits

<u>Till</u>

The moraines and till plains (or ground moraines) are glacial drift that was dropped directly by the melting ice without sorting by meltwaters. These deposits are heterogeneous and component particles may range in size from fine clay to boulders several feet in diameter. Pore spaces between the large particles are filled by particles of intermediate size and pore spaces between these particles may be filled by smaller particles. Locally, isolated lenses of sorted material consisting of silt or sand may occur in the till mass. If such permeable lenses are below the regional water table they may serve as collectors of ground water and yield at least small quantities of water to domestic wells.

Although of small transmission capacity and effective porosity, till deposits are of importance as reservoirs for interception and storage of percolating waters. In morainal areas of moderate to large relief numerous lenticular zones within the till mass may store appreciable quantities of ground water during periods of recharge. Water levels in wells tapping glacial till may rise rapidly during periods of recharge, but decline as rapidly when recharge ceases. Yields of wells in the till deposits of this area range from a few hundred gallons per day to as much as several thousand gallons per day.

<u>Outwash</u>

Glacial outwash deposits are gravels and sands sorted by running water. The porosity and transmission capacity of these deposits may be very large if coarse materials predominate. Sorting may develop large porosity in the finer materials but because of the smaller pore spaces the effective permeability is reduced. In many places the greater percentage of the volume of sediments may be the finer materials and they may be of great importance as the reservoir which furnishes water to the coarser deposits. Water may be obtained in large quantities from the coarser deposits of stratified materials by means of properly constructed and developed wells. The largest lakes and the headwaters of the principal streams are in the glacial outwash deposits.

Lacustrine deposits

During the existence of various glacial Great Lakes in this area, large quantities of material were washed from the ice sheet or from local land surface and deposited in the glacial lakes and along their margins. These materials are termed lacustrine deposits and, for the most part, are well stratified and range in composition from clay to sand or gravel. In this area the most extensive lacustrine deposits are clays and fine sand. Sand and gravel were dropped near the ice front, along the channels of glacial drainage upstream from the lakes or in deltas deposited by streams. Stratification and sorting of the lake deposits made them relatively porous and where particle sizes are appreciable, as in beach deposits, they may transmit water readily. However, many of the more permeable beach deposits of the area are elevated above the general, lake plain so that water is drained from them rather than stored. Groundwater supplies adequate for rural or domestic use can be developed from the lacustrine deposits, wherever permeable zones are below the regional level of lakes or streams.

Alluvium

Wherever streams exist for some time, their running waters deposit clay, silt, sand, and gravel in their channels and upon their flood plains. In and near the principal channel, where stream velocities at sometime or other have been moderate to large, well sorted, relatively coarse deposits of sand or gravel may be found. When stream velocities are smaller, as in periods of low flow, fine materials are laid down in the principal channel. When the stream overflows its channel, relatively coarse materials may be deposited upon the flood plain but when the waters recede fine materials are deposited over the flood plain as the ponded waters slowly drain back to the stream. Wherever well sorted and relatively coarse deposits of alluvium are adjacent to existing streams, very large quantities of ground water may be developed by induced infiltration.

HYDROLOGY

The Hydrologic Cycle

Although the fact is not generally recognized, man's principal resource is water. Like other mineral resources it can be depleted by over development, but water resources are renewable to some extent. Water, the dynamic resource, is ever changing in its position and state. The oceans of the earth are vast reservoirs from which water is evaporated to the atmosphere. The moisture is transported over land and sea by circulating air masses; it is precipitated upon the land as dew, rain, snow, or hail; and then returns to the seas by overland and underground routes. This continuing circuit of the earth's moisture is known as the hydrologic cycle.

At any time or position within the hydrologic cycle the various forces acting on any water particle direct its movement to a region or state of equilibrium. For example, if an air mass is undersaturated, it will absorb moisture in passing over a water surf ace. Later, when this air mass reaches a cooler region, perhaps by rising to some higher altitude, it becomes saturated and moisture is precipitated. If precipitation is directly upon the ocean, the cycle is completed. Moisture carried inland and precipitated on the land surface may be intercepted by vegetation, re-evaporated from plant surfaces, and returned to the atmosphere. Some moisture that falls upon the land surface may run off overland, downhill to the lakes or streams, and be returned to the ocean. Some moisture may enter the soil, percolate downward, and seep down gradient to reappear in surface streams or lakes. Anywhere enroute, moisture may return to the atmosphere by evaporation from the soil or from the surface of lakes and streams.

The amount of moisture intercepted by vegetation, entering the soil, or running off overland varies with the duration and intensity of the precipitation, the antecedent moisture demands of the soil, and the season of the year. For example, a flash storm of moderate to high intensity and of quite short duration produces a relatively large amount of overland runoff, with little time for interception by plants and accretion to the soil. Slow soaking rains, however, may produce little or no immediate overland runoff, but may completely satisfy plant needs and accumulated moisture deficiencies in the soil belt and may result in considerable recharge to underground reservoirs.

Between periods of precipitation the moisture demands of vegetation must be met from water stored within reach of the maze of plant rootlets. Moisture extracted by rootlets is "pumped" by the plant to its leaf surface as a part of the natural circulatory system which enables the plant to maintain life processes. During an extended drought the plant may undergo permanent wilting, if the moisture supply available to the rootlets is sufficiently depleted.

Moisture moves from the soil to the atmosphere through evaporation. When the potential of an overlying air mass to withdraw moisture from the soil or from the plant surfaces is balanced by the forces within the soil or subsoil that tend to retain residual moisture, equilibrium is reached and further evaporation is minimized. However, if plant rootlets reach into the underlying ground-water reservoir or if soil-air tubes from the land surface to the water table are sufficiently short, evaporation will continue depletion until the water level in the underground reservoir is lowered beyond the effective reach of these evaporating systems. In graphic form the hydrologic cycle is illustrated by plate 2, with adaptation to a generalized geologic section through the area of this report.

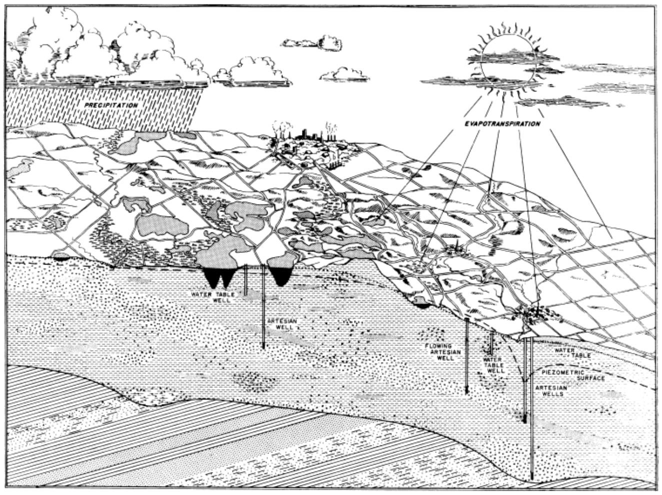

Plate 2. The hydrologic cycle adapted to Oakland County, Michigan.

Within the ground-water reservoir, water moves very slowly owing to the great friction in percolating through the maze of minute interstices between the rock particles. Generally, rates of ground-water movement may range from a few feet per year to as much as several feet per day. The water may travel great distances underground from regions where recharge is received at the surface to areas down gradient where it may once more escape to the surface and join the flow of streams; or appear as a seep or spring; or enter a lake; or perhaps escape directly to the atmosphere by evaporation, or be transpired by vegetation. Movement is always in the direction of the hydraulic gradient just as in surface -flow, but unlike surface flow this gradient may or may not conform to the topographic gradient in any particular area. Where undisturbed by man-made diversions, the water-level surface in an underground reservoir conforms approximately with the general trend of the overlying land surface.

During drought periods, maintainance of stream flow depends on slow seepage from underground reservoirs. For most streams in this area, the overland runoff of any given period of precipitation is carried out of the basin within a few days -- probably not more than two weeks after the precipitation. Stream flow after this brief interval of surface runoff is maintained by seepage from underground reservoirs. People who fish the streams and lakes of Michigan often observe the many seeps or springs which discharge cold, clear, ground water into the lakes or streams. In periods of extended drought, streams function essentially as drainage systems to carry off the outflow of the ground-water reservoirs.

Precipitation is the initial source of recharge to all ground-water reservoirs in this area. No mystic underground conduits lead to or from Canada, the North Pole, the Great Lakes, or elsewhere. On the contrary, precipitation on the upland areas of Michigan recharges ground-water reservoirs to stages a thousand feet or more above the levels of the Great Lakes and the outflow from these underground reservoirs is an appreciable factor in maintaining the steady outflow of the Great Lakes system.

As a consequence of the relatively small thermal conductivity and large thermal storage capacity of the earth's crust, changes in air temperature from season to season and the even shorter cycles of cold waves or heat waves, do not penetrate the land to great depth. At depths of more than 20 feet and less than 100 feet below the land surface, earth temperatures generally vary only a few degrees above or below the mean annual air temperature of the region. At greater depths the temperature rises slowly, an average of 1° F. for every 50 to 75 feet of increased depth. During its slow percolation through the rocks ground water acquires the temperature of its surroundings so that at depths of 20 to 100 feet its temperature is at all times within a few degrees of the mean annual air temperature of the region. Therefore, as a stable cooling medium ground water is particularly advantageous for air conditioning and other cooling purposes. During the winter when air temperatures are considerably lower than the annual average, ground water could be used as a heating medium, where heat-pump systems have recently been installed.

As it percolates slowly through the rocks, ground water dissolves minerals from the rocks. Therefore, although filtered crystal clear, most ground waters are hard. The quality of ground water, unlike the quality of water of surface streams, fluctuates so slightly that treatment schedules but little changed from a standard pattern may be readily established.

Surface Water

The principal streams draining southeastern Oakland County are the Clinton River, which drains about 53 percent of the area; the River Rouge, which drains about 44 percent of the area; and the Huron River, which drains about 3 percent of the area. The headwaters of these streams are in the gravelly uplands west of Pontiac. Few records of stream discharge and lake stage are available for southeastern Oakland County and these records cover relatively short times. The records may be extended somewhat by correlation with simultaneous observations in nearby areas where longer records and more adequate coverage of surface-water data are available. The locations of gaging stations and lake gages in Oakland and adjacent counties are shown by figure 9. The availability of records of stage and discharge for these streams and lakes is summarized by figure 10. Median-year hydrographs and flow-duration curves for each stream, a flood profile of the River Rouge, and a summary of pertinent data on the flood flows and low flows of each stream was reported by Wisler, et al (1952, pp. 11-18).

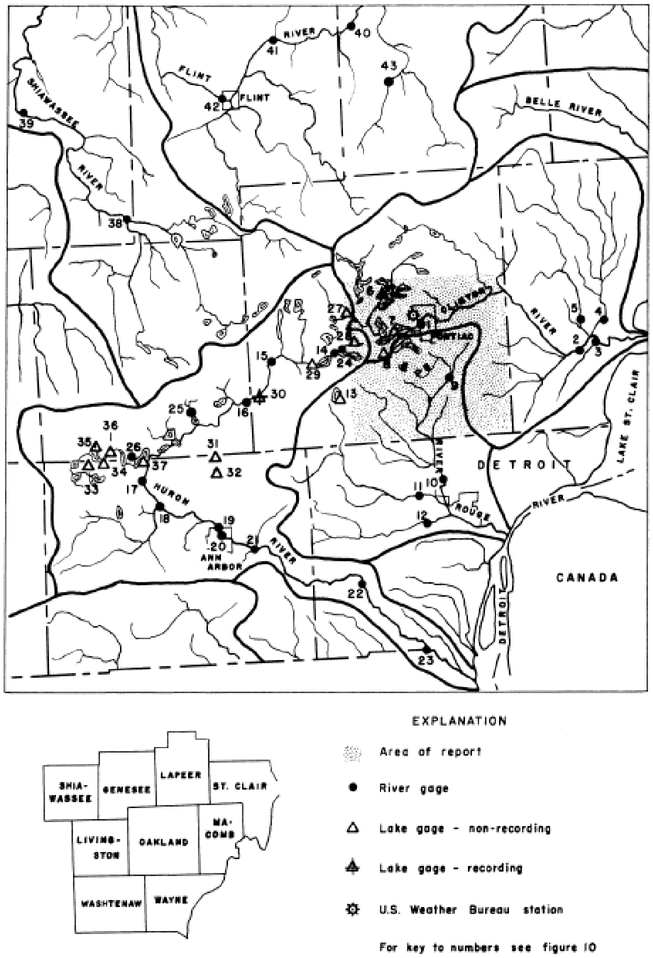

Figure 9. Map showing drainage basins and surface-water gaging stations in Oakland County and vicinity.

Clinton River

The Clinton River rises in Upper Bushman Lake in Independence Township, about 8 miles northwest of Pontiac. It enters the area of this report near Waterford and winds southward through a chain of lakes to Cass Lake. Beyond Cass Lake it flows northeast through Pontiac and Rochester and leaves the area southeast of Rochester. It then traverses Macomb County and empties into Lake St, Clair below Mount Clemens. A principal tributary within this area is Paint Creek which flows south to join the Clinton River at Rochester. Galloway Creek, a lesser tributary, enters the Clinton from the north between Pontiac and Rochester.

The headwaters region of the Clinton is a rolling, hilly, morainal area with intervening gravel plains. Locally, surface altitudes exceed 1,000 feet above sea level. Throughout its upper reaches are numerous small to large natural lakes, many are isolated bodies of water with no surface inlet or outlet. Near its junction with Paint Creek, the Clinton River leaves the morainal area and beyond Rochester flows over a gently sloping, glacial lake plain.

River Rouge

The River Rouge rises east of Pontiac and flows southward along the Rochester channel (glacial). The principal tributaries are the Upper Rouge, which flows southeast through Farmington; Franklin Branch and Pebble Creek, which flow in from the northwest in Southfield Township; and Sprague Branch, which enters northeast of Bloomfield Hills.

The headwater region of the River Rouge is an area of morainal hills and natural lakes. However, the tributaries of the Rouge descend rapidly along relatively steep gradients in cutting through the inner ridge of the Defiance moraine and then flow at much smaller gradients along the Rochester Channel to the lake plains.

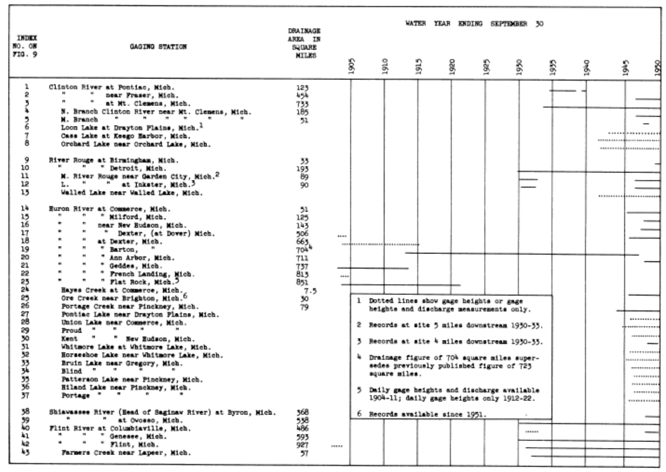

Figure 10. Duration of records at surface-water gaging stations in Oakland County and vicinity.

Huron River

The branch of the Huron River which drains a small part of this area rises in Big Lake. This small part of the Huron River basin is a region of lakes and swamps among morainal hills, whose altitudes approach 1,000 feet above sea level.

Ground Water

Principles of occurrence and terminology

The earth's crust serves as a vast reservoir for the storage and transmission of ground water. The enormous storage potential of this reservoir is not accurately known, but it has been stated (Sayre, Nov. 1950, p. 16) that within our continental borders it probably exceeds the combined storage capacity of all potential and existing surface reservoirs including the Great Lakes. Of course, not all this capacity is usable. A small part of the water is held immobile by capillary forces which retain water in the smaller openings against the force of gravity, when the rocks are drained. Furthermore, the deeper underground reservoirs contain saline waters which many would exclude from any estimate of usable capacity.

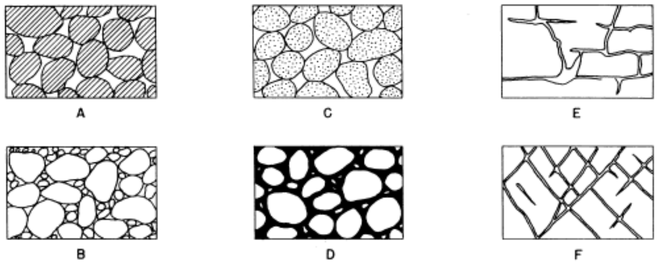

Figure 11. Diagram showing several types of rock interstices and the relation of rock texture to porosity. A, Well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity; D, well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices; E, rock rendered porous by solution; F, rock rendered porous by fracturing. (From O. E. Meinzer)

The rocks of the earth's crust are seldom, if ever, solid throughout but contain numerous interstices or pores which may be filled with water, oil, air, or other natural gases. In the terminology of this report, rocks may refer to consolidated formations such as limestone, sandstone, or shale or to unconsolidated sediments, such as gravel, sand, or clay. Rock interstices vary widely in shape and range in size from microscopic pores to the large caverns found in some limestone regions. Interstitial openings may be isolated and limit the percolation of ground water, but most are interconnected and permit ground water to move from regions of intake to regions of discharge.

Porosity and specific yield

The volume of water which can be stored by a rock depends on its porosity, that is on the number and size of the openings, or pores, in it. In unconsolidated or in pervious, sedimentary rocks the porosity is a function of the size, shape, sorting, and degree of cementation of the component particles. In soluble rocks such as limestone, the porosity is a function of the size and distribution of cavities or channels. In dense rocks of sedimentary, igneous, or metamorphic origin the porosity is a function of the size and distribution of fractures or other crevices. In diagrammatic form the manner in which these factors may influence the porosity of rocks is illustrated by figure 11.

The porosity of rocks generally decreases with depth as the interstices decrease in size partly because of increased pressure and partly because of cementation by mineralized waters. The greater part of the ground water in crystalline rocks is within a few hundred feet of the surface. Water-producing zones have been found in some sedimentary rocks at depths greater than a mile below the surface. In Michigan, fresh waters are pumped from sandstones of the Northern Peninsula from depths of about 1,400 feet and in the Southern Peninsula saline waters are pumped from wells finished in sandstones at depths as great as 6,000 feet below the surface. In most areas, however, little water is found in sedimentary rocks below depths of 2,000 feet.

Although the porosity of a rock is a measure of its capacity to store water, not all of this storage may be recovered by drainage. When drained by gravity some of the water stored within the interstices is retained as a thin film which adheres to the rock particles. Capillary forces hold this pellicular water against the forces of gravity. The quantity of water retained by a rock after gravity drainage is measured by its specific retention, which is the ratio of the volume of water retained to the total volume of material drained. The specific yield is the ratio of the volume that drains out by gravity to the total volume. Together the specific retention and the specific yield equal the porosity.

Permeability and transmissibility

The capacity of a rock to transmit water is expressed by its coefficient of permeability which is a measure of the rate at which a fluid of specified density and viscosity flows through a unit cross sectional area under a unit hydraulic gradient. In the system of units used by many hydrologists in this country the coefficient of permeability is defined by Meinzer (Stearns, 1927, p. 148) as the rate of flow of water in gallons per day at 60° F. through an area of one square foot, under a hydraulic gradient of one foot per foot. The fluid viscosity and density is inherently specified by defining the fluid as water at 60° F. In practice, however, because of the nearly constant temperature of the ground water in a given region, the coefficient of permeability is generally determined at the prevailing field temperature of ground water in each aquifer tested.

Within the past decade the development of certain formulas and field methods for appraising the hydraulic properties of water-bearing formations has resulted in wide adoption of the term coefficient of transmissibility, in lieu of coefficient of permeability. The coefficient of transmissibility was introduced by Theis (1935, p. 520) and may be defined as the rate of flow of water in gallons per day under a unit hydraulic gradient, through a column of water-bearing material which measures one foot in width and extends the full saturated thickness of the formation. Again, formal definition must specify the viscosity and density of the fluid flawing, but field practice generally relates this coefficient to the properties of the fluid encountered in the formation tested.

Although both the specific yield and the permeability of a rock bear some relation to its porosity this relationship is not direct. In clays the pore spaces are generally so small that molecular forces bind the water to the walls of the pore and interconnection between the pore spaces may be non-existent or so limited that only molecular interchange can occur. In the aggregate, the total volume of pore space in clay may approach or exceed the volume of pore space in sand and indicate about the same total porosity. However, the permeability of clay would be considerably less than sand because of the great impedance offered to the movement of water. The specific yield of clay is considerably smaller than the yield of sand.

Reservoir capacity

The significance of storage or reservoir volume provided by fine-grained materials is too often overlooked in developing ground water supplies, because it is overshadowed by the importance attached to the search for coarse-grained materials in which the well screen is to be placed. Although it is advisable to place the well screen in the coarsest material available to reduce entrance losses at the face of the well, it does not follow that isolated lenses of coarse material in an aquifer, composed predominately of fine-grained material, will greatly enhance the performance of the well. The withdrawal of ground water for any prolonged period is possible only to the extent of the regional or over-all capacity of the water-bearing formation, and is little influenced by isolated lenses of coarse material, except insofar as these coarse materials represent a fraction of the total reservoir volume.

Aquifers, artesian and water-table

A water-bearing formation that yields water in usable quantities is termed an aquifer. In areas where ground water is difficult to obtain, a formation yielding less than a gallon per minute to wells of moderate to large diameter may be classed as a principal aquifer. In other areas where wells of similar diameter in other formations may yield several hundred gallons per minute, a formation from which wells obtain less than a few gallons per minute might be classed as non-productive.

On the basis of water occurrence, aquifers may be classified as water table or artesian. In a water-table aquifer, ground water is confined and is in contact with the soil atmosphere. The static water level in a well finished in a water-table aquifer stands at the level at which water first entered the hole when the formation was penetrated. The surface formed by connecting the heights of gravity ground water, shown by the water levels in a closely-spaced pattern of wells which tap an unconfined aquifer, is termed the water table. In an artesian aquifer, ground water is confined under pressure by an overlying formation of relatively small permeability. The water level in a well that is finished in an artesian aquifer and is tightly cased through the confining bed stands above the level where water was first encountered. The overlying capping formation is sometimes termed an aquiclude, a confining bed, or an aquitard. The surface formed by connecting the heights to which water levels would rise in tightly cased wells that tap the artesian aquifer is termed the piezometric surface. Contours on this surface are referred to as isopiestic lines. A generalized section illustrating this terminology is shown by figure 12.

Coefficient of storage

In an artesian aquifer, unlike a water-table aquifer, ground water may be withdrawn from storage without draining the water-bearing rocks. Thus, the storage properties of an artesian aquifer might be likened to a pneumatic natural-gas holder except that the magnitudes of vertical displacement by the aquifer are infinitesimal compared to the gas holder. However, just as in the gas holder, where a decline in storage pressure is accompanied by settlement of the containing shell, so too in the artesian aquifer compaction of the rocks occurs with a decline in hydrostatic pressure.

The term specific yield which refers to the storage property of the uppermost foot of water-table aquifer is not applicable to the artesian aquifer, because by definition of the artesian condition all pore spaces are filled as long as artesian head exists. The storage property of the artesian aquifer is referred to as the coefficient of storage and is the quantity of water yielded by a column of water-bearing material with base of one square foot and with height equal to the thickness of the water-bearing material, when the water level declines one foot. This definition also permits application of the term coefficient of storage to water-table aquifers and to a degree that includes more than the specific yield which to the material drained. The storage coefficient includes also the contribution gained by elastic deformation of the saturated material that underlies the sediments drained. For artesian aquifers, the coefficient of storage ranges from 0.0005 to perhaps 0.005 as compared to a range of 0.03 to 0.35 for water-table aquifers. Values intermediate between the artesian and water-table range generally indicate leakage from overlying or underlying beds.

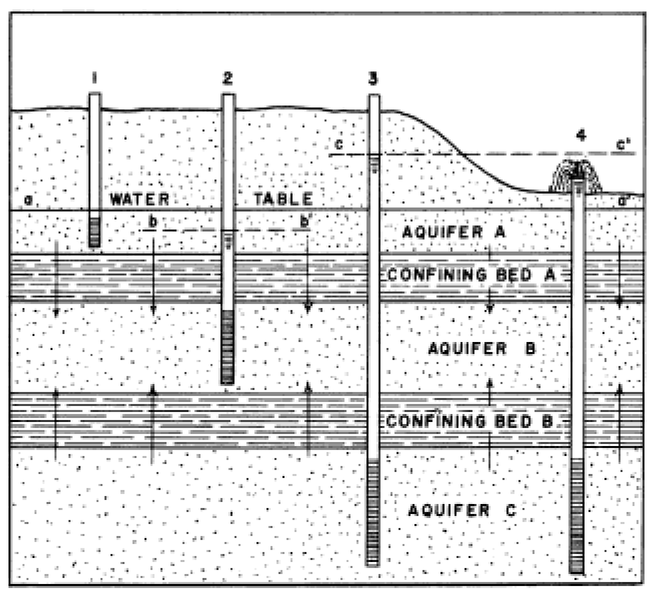

Figure 12. Section showing hydrogeologic conditions for water-table and artesian aquifers. a-a' is the water table in aquifer A and well 1 is a water table well. b-b' is the piezometric surface in aquifer B and well 2 is an artesian well. c-c' is the piezometric surface in aquifer C and wells 3 and 4

are artesian wells. Well 4 is in an area of artesian flow. The arrows indicate the direction of cross-bed leakage.

Vertical leakage

The existence of fine-grained and compact aquicludes of great thickness and areal extent has fostered a popular but fallacious belief that underlying artesian aquifers are insulated formations which contain only connate waters. If such insulation were general, many of our intensively developed artesian aquifers would be dry today. It should be recognized that the terms permeable or impermeable are only relative. Consider that a township of 36 square miles contains more than a billion square feet of surface area. Thus, when the small unit rates of percolation in fine-grained materials are multiplied by the astronomical number of square feet of percolating area available the vertical seepage through so-called confining beds becomes quite significant. The direction of cross-bed leakage depends on the heads above and below the confining beds (fig. 12).

Cone of influence

When a well is pumped ground-water levels in the vicinity are drawn down in the shape of an inverted cone with its apex at the pumped well. The depth of this cone and the rate of growth of its base depend on the coefficients of transmissibility and storage of the aquifer and on the rate of pumping. Initially, the water pumped by a well is drawn from storage in the vicinity of the well. As pumping continues the cone expands and continues to do so until it intercepts sources of replenishment that will satisfy the pumping demand. In water-table aquifers the cone of influence may grow initially at rates ranging from several hundred to perhaps several thousand feet per day, but subsequently its rate of advance will decline to tens of feet or several feet per day. In artesian aquifers, coefficients of storage are a hundred to a thousand times smaller than in the water-table aquifers and the cone of influence must grow much more rapidly in order to encompass regions that are of sufficient storage capacity to satisfy the demands of the pumped well. In the artesian aquifer the initial rate of advance of the cone of influence may approach the speed of sound in the saturated medium, but limitations of physical measurement rule out observation. Measurable influences of pumping travel at rates ranging from several thousand to several tens of thousand of feet per day, but subsequently decline to rates of perhaps tens of feet per day.

Sources of water to wells

As pumping continues and ground water is withdrawn from storage, the cone of depression expands until sources of recharge are reached which will satisfy the demands of the pumped well. Perhaps a stream or lake may be intercepted by the cone of influence. If infiltration from such a source can keep pace with the demands of the pumped well, further growth of the cone of influence will cease. After intercepting the stream or lake, the cone will depart from its original shape because most of its further advance will be as a fan-like enfolding along the axis of the surface source. If a stream or lake is not intercepted, the growth of the cone might be curtailed by the interception of an area of seeps or springs from which flow may be diverted. Perhaps an area of evapotranspirative discharge may be intersected. As ground water is diverted from discharge areas, the flow of seeps or springs and the evapotranspirative use of soil or vegetation may be eliminated or greatly reduced, depending upon the extent to which these former discharges may be captured by the cone of influence. In the absence of a surface source or the possibility of salvaging evapotranspirative discharge, the cone expands until it intercepts sufficient base area to satisfy the demands of the pumped well at the prevailing rates of ground-water recharge whether from precipitation or by leakage from other beds. In some instances the cone of influence may advance beyond the original divides of the ground-water reservoir and divert water from adjoining drainage basins. A generalized diagram illustrating this possibility for .a water-table aquifer is shown by figure 13.

The cone of depression undergoes continuing change in areal extent and in depth as it responds to changing influences of recharge and discharge within the reservoir. In long periods of drought the cone deepens and expands as it withdraws additional water from storage to meet the continuing demands of the pumped well. When a period of recharge occurs, the cone shrinks to a degree dependent on the amount of recharge received.

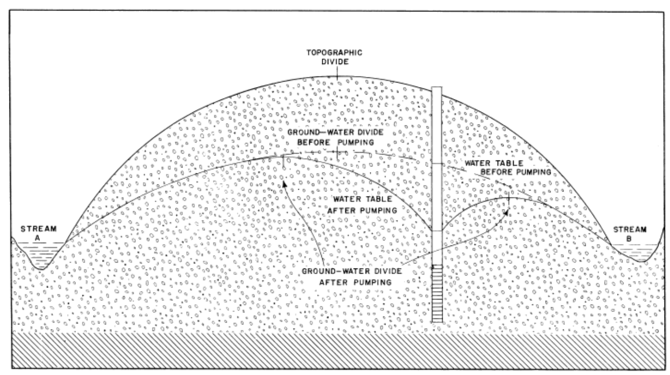

Figure 13. Generalized section showing the shift in the drainage divide as a result of pumping.

Mutual interference

Where intensive development has taken place in ground-water reservoirs, each well superimposes its individual cone of depression upon its neighbor. The resultant development is a regional cone of depression, When the cone of depression of one well overlaps the cone of a neighboring well, interference occurs and a part of the area of drainage which formerly was tributary to each well must then be shared by all interfering wells. In diagrammatic form the results of mutual interference between wells are shown for the simple case of two wells by figure 14. The amount and extent of interference depends on the rate of pumping by each well, the spacing between wells, and the hydrologic regimen of the aquifer in which the wells are finished.

In any aquifer, as wells are added or the yields of existing wells are increased, the amount and extent of interference between wells increases. With each added well installation and each new increase in existing well yield, water levels in the area must decline to provide the increased hydraulic gradient necessary to move the required amount of water from outlying areas of recharge to the area of withdrawal.

Most well users are interested only in the quantity aspect of well performance and seldom give attention to whether the output is delivered at the initial stage of drawdown or if water levels in the vicinity of the well have declined. Before use of deep-well pumps, wells were pumped by suction with operating depths limited generally to less than 25 feet below the pump. To keep pace with declining water levels it often became necessary to lower pumping equipment into a pit to maintain suction lift within operating limits. The air-lift pump made it possible to pimp water from greatly increased depths. This type of pumping equipment was once widely used, but its application was somewhat limited because it required a large degree of submergence for successful operation. Development of the deep-well turbine pump made it possible to pump water from great depths and from formations of limited head. The head-discharge characteristics of the deep-well turbine pump permit operation at nearly peak capacity until the pumping water level declines to a few feet or more below the pump bowls. Beyond this point, pumping capacity declines markedly until the pump breaks suction. Generally, a decline in stage from a few feet to not more than ten feet below the pump bowls results in the loss of suction. Thus, well yield provides little or no index of the rate of water-level decline or of impending well failure.

<u>Pumping test methods</u>

Field methods now used for comparing the relative performance of aquifers or well sites are grouped under the general term, pumping tests. For the convenience of this discussion pumping tests are further divided into specific-capacity and aquifer-test methods.

SPECIFIC-CAPACITY METHOD

The term specific-capacity method is not now in general use, but is assigned by the authors to identify this method. The terms well-performance test or well-acceptance test were considered as alternatives but are not entirely synonymous. This method is the oldest and still the most widely used even though generally inadequate and subject to criticism. A well is pumped and its rate of discharge and the accompanying drawdown are observed. The specific capacity of the well is computed as the rate of discharge per unit drawdown of water level. It is often tacitly assumed that the specific capacity is constant and may be extrapolated over a wide range. Frequently, the pumping follows no consistent pattern. Often the well is pumped at its maximum rate until it breaks suction and then is throttled down in a series of trial steps until delivery is maintained at a steady rate. This throttling of output permits the well to recover and produces an artificially stabilized pumping level, which is often mistaken as a condition of equilibrium.

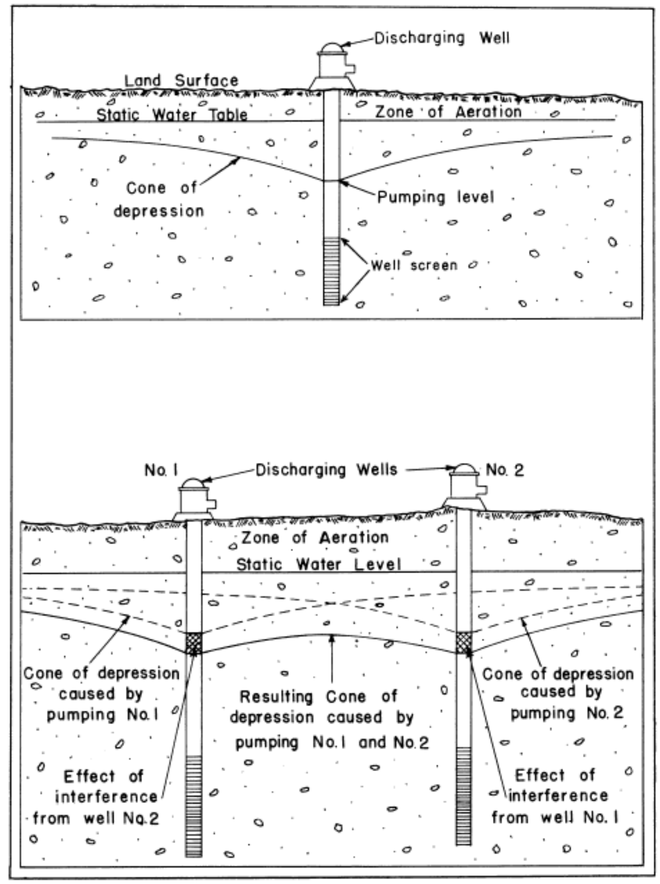

Figure 14. Mutual interference between wells.

Generally, the test extends for 8 to 24 hours. A popular misimpression is that the drawdown of pumping level is directly proportional to the time since pumping started and that leveling off of the rate of decline indicates stabilization of the well at a constant yield. On the contrary, the pumping level declines in proportion to the logarithm of time and this apparent leveling off after several hours reflects the logarithmic relation and may have no bearing on the capacity of the well or aquifer. For example, it may be found that during an 8-hour test, in which pumping levels were observed to the nearest foot, no change in operating level occurred from the 6th to the 8th hour. Water-level observations to the nearest foot are typical in tests of this type because generally air-line measurements of the depth to water are made with gages calibrated at only 2-foot intervals. Assume that in this test the operating level declined 0.2 foot between the 6th and 8th hour, which would pass unnoted if air-line readings were made to the nearest foot. If the pumping level should continue to decline at this rate, by the end of the first year the operating level in the well would have declined an additional 876 feet, or a far cry from stabilization. Large-capacity pumps throttled to small discharge rates on wells of moderate to small capacity today stand as mute testimony to the fallacy of forecasting well performance by extrapolation of specific-capacity data. A point in favor of the term pumping test as applied to this method is that at least the connotation is correct because for the most part the information gained from tests of this type and probably the original intent of this method is that it can serve as an effective method of testing the pumping equipment.

Aquifer-test method

Although aquifer-tests are a relatively recent development, they are rapidly gaining favor because these rational procedures have already demonstrated in practice that the performance of ground-water installations can be forecast within limits comparable to forecasts made in other phases of water-supply design. As in the specific-capacity method a well is pumped, but in the aquifer-test method the rate of discharge is carefully controlled at a constant value or is regulated stepwise at several values with each held constant for a known interval. Precise measurements of water level are made in the pumped well and if possible in one or more observation wells. Generally, the recovery of water level is also measured after pumping stops. The program of water-level measurement requires the use of continuous recording instruments or an adequate crew of technicians to obtain the necessary detail of water-level trends with a high degree of precision. Equally accurate measurement of discharge is required at frequent intervals to insure that the rate of pumping is always maintained at the specified magnitude.

The resultant time-drawdown data for each observation well and the pumped well are analyzed by methods described by Brown (1953, pp. 844-866), Jacob (1950, pp. 321-386), Wenzel (1942) and others. With the use of the nonequilibrium formula of Theis (1935, pp. 510-524), the coefficients of transmissibility and storage are determined for that part of the aquifer sampled during the test period. This equation can then be used to forecast the performance of the well or groups of wells proposed. In addition, the efficiency of the well construction can be appraised.

Within recent years hydrologists, engineers, and contractors in ever-increasing numbers are adopting the aquifer-test method of pumping test because of its proved superiority over the older but less adequate methods. As the name implies, the aquifer-test method determines the hydraulic characteristics of the aquifer. From these data, questions relating to the well efficiency and its probable performance can be answered and the adequacy of the supply can be evaluated with the aid of other hydrologic data.

Induced infiltration

From underground sources

The regional lowering of ground-water levels in the vicinity of a well development disturbs the initial condition of hydrodynamic equilibrium between the aquifer which is being developed and the overlying and underlying aquifers or confining beds. For example, figure 15 shows the nature and extent of ground-water gradients that may exist before and when pumping ground water from a water-table aquifer that overlies a formation of shales, sandy shale, and sandstone. Initially, the water in the water-table aquifer stands at a higher level than the piezometric surface in the underlying formations of shale and sandstone. As a consequence of the higher head, ground water may percolate from the sand and gravel formation into the underlying shale and sandstone, as indicated by the leakage vectors in figure 15.

When ground water is pumped from the water-table aquifer at rates sufficient to lower water levels below the piezometric surface of the artesian formation, leakage gradients will be reversed and ground water now percolates upward from the artesian formation and enters the water-table aquifer. In diagrammatic form the degree and extent of such vertical percolation is indicated by the leakage vectors of figure 15. In areas of extensive development, where a large regional lowering of ground-water level may occur, vertical leakage may be induced from underlying or overlying formations at appreciable rates and over a quite large area. Under these conditions, as development continues and increases in magnitude, the contribution of ground water from adjacent formations also increases. If the ground waters contained in overlying or underlying formations are of different chemical composition than those in the aquifer in which development occurs, there will result noticeable changes in the quality of ground water pumped from the aquifer developed. The rate of vertical leakage is proportional to the rate of pumping from wells in the aquifer of development. Thus, it would appear from this observation that changes in chemical quality will be most marked in the wells or in the areas where withdrawals are greatest. Although this generalization may be appropriate for many wells, for some wells it may be modified by other conditions such as differences in the degree of penetration of the pumped wells, differences in the vertical permeability from area to area, and the effects of differential density of the several ground waters involved.

From surface sources

Where an aquifer is intersected by a perennial stream, large ground-water supplies may be developed by the installation of wells or other types of subsurface intakes, which parallel the course of the stream and are at sufficient depth below the stream to permit the development of adequate gradients from the stream to the subsurface intake. As ground water is withdrawn, water levels are drawn down in the vicinity of the intake. As pumping continues, the cone of depression deepens and the area of interception expands. When the piezometric head in the reservoir, adjacent to and underlying the stream, is lowered below stream stage, water from the stream moves down gradient into the aquifer and toward the center of withdrawal, as shown by figure 16.

The interception and diversion of surface water by induced infiltration takes advantage of the slow sand filter provided by Nature's reservoir, as contrasted to the more widely used and more costly procedure of direct surface intake, which requires the construction of extensive filter beds. Of course, Nature did not provide adequate filtering media everywhere adjacent to the streams and in many places the only choice is to construct filter plants. Unfortunately, man's awakening to the availability and practical usefulness of ground-water reservoirs as natural filters has been rather slow, and even at this late date is still not complete. As a consequence, it is not uncommon to find monumental filter plants constructed by man with their foundations seated in natural filter media that dwarf man's limited efforts.

In using a ground-water reservoir as a filter medium, careful consideration must be given to the proper location of the underground intakes in order to take full advantage of local hydrogeologic conditions and at the same time obtain adequate filtration. At first consideration, it may appear advisable to locate the subsurface intake as close to the stream bed as possible, because this would develop the maximum gradient and result in peak performance. However, such procedure would reduce to a minimum the volume of filter material between the stream and the underground intake and thereby minimize filtration benefits. It would also limit benefits gained in modulating the temperature of inflow water as it moves through the earth. Although the filtration and temperature benefits increase as the underground intake is located at progressively greater distances from the stream, the increased distance reduces the gradient from the stream to the intake and thereby reduces the hydraulic performance of the intake structure. Thus, the optimum design for an induced infiltration system requires a comprehensive study of the hydrogeology and the engineering economics of each site under consideration.

Many of the larger ground-water installations developed in this country are of the induced infiltration type. It has been indicated by Jeffords (1945, p. 151), by Kazmann (1948, p. 419), and by Rorabaugh (1951, p. 173) from observation of such systems, that essentially complete filtration can be effected and many other advantages gained. Among these advantages are the elimination of short-term fluctuations in turbidity, temperature, and other phases of water quality that are so characteristic of many surface streams. Inasmuch as ground-water movement from the stream bed to the intake structure would be generally of the order of a few feet to perhaps tens of feet per day, the time of travel from the stream to the ground-water intake may be of the order of several days to as much as several months for intakes within a few hundred feet of the stream. As a consequence of these long times of contact with the reservoir media, the infiltrated stream water absorbs heat from or delivers heat to the reservoir particles. Thus, in effect, the ground-water reservoir serves not only as a filtering medium, but also as a heat exchanger.

In periods of flood when the stream is very turbid, the method of direct-surface intake requires continual vigilance on the part of the filter plant operator, but where a subsurface intake is used, as in the induced infiltration method, much of this burden is eliminated. Where chlorination or water softening is necessary, operation schedules can be planned from weeks to months in advance. Under continued operation and with moderately to highly permeable connection to the stream, the average quality of water produced by an induced infiltration system approximates the average quality of the surface source, except that its variations in quality and temperature are greatly reduced as a consequence of the lengthy times in transit through the aquifer.

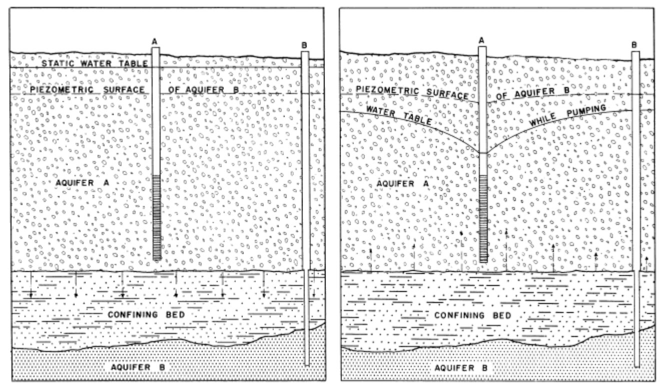

Figure 15. Interformational leakage reversed by pumping.

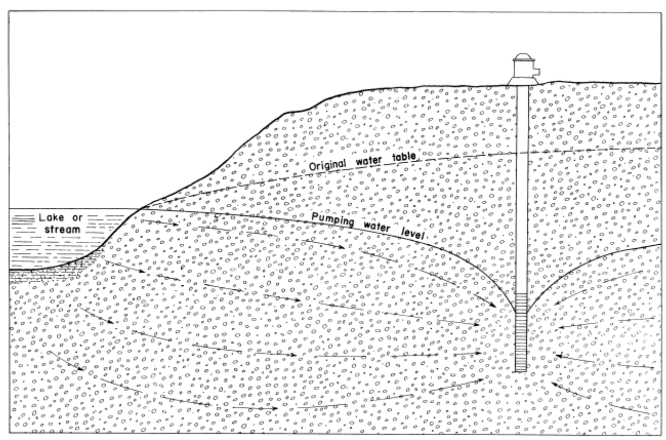

Figure 16. Generalized diagram showing how water can be induced to flow from a source of water to a well.

Intake structures for obtaining ground water

Types of intake structures

The extraction of ground water from the rocks of an area may be accomplished by the use of any one of several types of intake structures, such as wells; pits; infiltration galleries, shafts or tunnels; radial collectors; or subsurface dams and appurtenant collecting works. The selection of the appropriate structure for the withdrawal of ground water from some areas is readily apparent, but for other areas it may involve a detailed economic study of the installation and maintenance costs of several types of intake structures. The magnitude of the supply required, the availability of land for development, and local geologic conditions are principal factors in such an appraisal. Frequently, limitations imposed by one or more of these factors make the selection obvious without the need for appraisal of other types of intake structures. For example; .for domestic ground-water supplies, where the magnitude of the supply is small, all structures but the well may be ruled out of consideration. Where land availability is limited, even though the magnitude of the supply required may be large, all structures may be ruled out except the well or radial collector. Where the water-bearing formation is at great depth and is overlain by consolidated rocks of appreciable resistance, the choice of withdrawal structure may be limited to the well.

Wells

Wells are the most widely used and probably the earliest form of intake structure for the extraction of ground water. On the basis of the method employed in their construction, wells may be classified as dug, bored, jetted, driven, and drilled, either by percussion or by rotary methods.

DUG WELLS: The dug well is the oldest known method of construction and formerly was the most widely used type. Dug wells range in diameter from several feet to as much as several tens of feet. Generally, dug wells are finished at relatively shallow depth, 50 feet or less, but in some places, as in the northern part of the Southern Peninsula of Michigan, they have been constructed to depths as great as several hundred feet.

Most dug wells are constructed in areas where the depth to the water table is relatively shallow and where the materials overlying the water-bearing formation will stand in an open excavation without the use of shoring or sheeting. In other places a lining may be used and in some wells a cutting shoe is installed. Excavation is generally made with hand tools, but in the larger diameter wells a power-driven clam-shell bucket could be employed. Where a lining or curbing is installed, the curbing is extended as it settles during excavation. The lining or curbing may consist of masonry, wood sheeting, or steel tubing.

The depth of penetration into the water-bearing formation is limited, because of the danger of collapse, despite the use of curbing. As a consequence of such limited penetration into the saturated zone, most dug wells are of small yield and many fail during periods of extended drought. The large circumference of curbing used, the difficulty of adequately sealing the excavation outside the well curbing, and of sealing the well curbing itself makes it difficult to eliminate surface contamination. Advances in other methods of well construction now have largely ruled out the use of dug wells in this country.

BORED WELL: The bored well ranges in diameter from 2 to about 36 inches. Bored wells are finished at depths ranging from about 10 to not more than 50 feet. They may be constructed with either hand-operated or power-driven equipment. This type of construction is limited to deposits that will stand without casing for a sufficient period of time to complete the boring and subsequently install a suitable tubing or casing. The bored well is not widely used in Michigan and would be limited to areas where the water table is at relatively shallow depth.

JETTED WELL: The jetting method is limited generally to wells of diameter or less. Although jetted wells have been constructed to depths of more than 1,000 feet, for the most part, the jetting method is used where the depth to water is less than 50 feet. The small diameter of this well type limits its use to domestic, stock, some irrigation, and the smaller industrial or public supplies.

In this method of construction, water is forced under pressure to a jetting bit, or, the leading edge of the casing may be fashioned to function as a cutting tool. An alternative procedure uses a conductor pipe with a smaller jetting pipe inserted. The conductor pipe is rotated by hand and forced down as the jet stream washes the cuttings up between the jet pipe and the conductor casing. When resistant materials are encountered, the jet pipe or bit is lifted and dropped as a percussion tool to loosen these materials. When the water-bearing formation is penetrated to a sufficient depth, a small-diameter well pipe with suitable screen is lowered into the hole and the jet casing is removed. An alternative method is often employed wherein the well tube and attached screen is used as the jet casing. In this method, the screen section contains a spring-leaded poppet valve in the nose of the jetting point. Under the pressure of the jet stream, the poppet valve opens during the jetting process and closes under the action of the spring, when the pressure of the jet stream is removed.

The jetting method of construction is best adapted to areas where the water table is at relatively shallow depth and where the water-bearing formations are principally fine to coarse sands. Under these conditions, wells of 30-foot depth or less may be jetted into position in a few minutes. Where highly resistant formations are encountered, jetting may be exceedingly slow or impossible. Where very coarse materials are encountered, the jetting water may be carried off so rapidly that it becomes difficult to establish any appreciable pressure in the jet pipe, and it may be necessary to abandon the hole. In Michigan, the jetting method is used by the State Conservation Department to construct wells for forest-fire suppression (Stewart, 1934).

DRIVEN WELLS: Driven wells range in diameter from 1 to 3 inches and are generally constructed at depths of 50 feet or less, but may be driven to depths of more than

100 feet. In this method, a drive point with screen and sufficient casing attached, is driven into unconsolidated material either by hand or with power-driven equipment. A maul or sledge hammer may be used or a tripod with a pulley or windlass is used to run a drop line and weight. Power equipment may be adapted to the tripod and windlass to raise and trip the drive weight or a pneumatic hammer could be used.

The driven well is limited to areas where the water table is relatively shallow and where the water-bearing formations and the overlying materials are loose unconsolidated deposits relatively free of cobbles or boulders. Since the casing used is of small-diameter a driven well is limited to capacities suitable for domestic, stock, and the smaller irrigation, industrial, or public water supplies.

DRILLED WELLS: Drilling may be accomplished by percussion or by hydraulic rotary methods. Although both methods are used in Michigan, at present only a few water-well drilling contractors use hydraulic rotary equipment. Drilled wells range in diameter from 2 to as much as 60 inches. The depths reached in drilling of oil and gas wells, proves that depth presents no limitation in obtaining water supplies. In unconsolidated materials the drilled hole is finished with iron, steel, concrete, or plastic casing and with a screen, perforated pipe, or porous concrete liner in the water-bearing zone. In relatively fine-grained materials the drilled hole may be reamed oversize and gravel may be packed around the well screen.

In the percussion method of construction a chisel-like bit is alternately lifted and dropped to cut or chip the rock into fragments which are periodically removed from the drill hole by a bailer or sand pump. In unconsolidated deposits, the well casing is driven as the drill hole advances, whereas in consolidated materials it may not be necessary to set casing until the hole is completed. In Michigan, most drilled water wells of 3-inch diameter or less are drilled by the so-called self -cleaning or hollow-rod method of percussion drilling whereas most larger wells are drilled by the cable-tool method. Details of the equipment used and the technique of drilling by these methods are described by Bowman (1911, pp. 32-102) and in a technical manual issued by the War Department (November 1943, pp. 37-172).

In the rotary method of drilling, a cutting bit is revolved on the end of a hollow-drill string through which drilling mud is forced under pressure and ejected from the bit. The drill cuttings are washed through the space between the drill rods and the wall of the hole. The drilling mud and any fine-grained sediment penetrated by the drill, is plastered on the walls of the hole by the drill pipe which seals the wall of the drill hole and prevents caving. Generally, casing is inserted into the drill hole after drilling is completed. When strata are penetrated that cannot be sealed by drilling mud, drilling must be done by casing the drill hole.

In an alternative method of rotary drilling, circulation is reversed by pumping the drilling water out of the hollow drill stem and returning it by gravity down the space between the drill stem and the drill hole. In this method, mud is not added to the drilling fluid, but is removed when clays are penetrated during the drilling, in order that the drilling fluid be maintained as clean as possible. In the reverse-rotary method the wall of the drill hole is maintained by the head of water in the hole. Thus, unlike the conventional rotary method, in which it is necessary to later remove the mud seal from the drill hole, in the reverse-circulation method sealing is held to a minimum and subsequent development of the water-bearing formation adjacent to the finished well is more rapidly effected.

Pits

Where the depth to the water table is quite shallow and the water-bearing formation is unconsolidated, pits are sometimes used for the withdrawal of ground water. A dragline or scraper is used to excavate a shallow sloping pit near a stream or in a low-lying swale where the depth to water is quite shallow. A sump may be installed for the pumping equipment, or, it may be floated or rafted. The large surface area exposed and the development of local drainage toward the pit subjects it to a high degree of contamination and for the most part, the use of pits for the development of ground water is limited to irrigation and stock supplies and for certain industrial uses, particularly as in sand and gravel-pit washing operations.

Infiltration galleries, shafts, or tunnels

In areas where the water is at shallow depth in unconsolidated deposits, ground water may be obtained through infiltration galleries. A trench is excavated through the water-bearing deposits and perforated pipe, tile or a masonry conduit is installed below the water table. The infiltration line is laid with a slight pitch toward a central sump or collecting well in which the pumping equipment is installed. The excavated material may be graded or otherwise sorted and then back filled around the collecting line. Above the water-bearing formation the back fill is replaced without grading or sorting and is tamped or puddled to restore the original grade, with appropriate surface drainage away from the collecting area. When labor costs were relatively small, gallery installations were in more common use. Recent advances in the development of earth-moving equipment make galleries practicable again in some areas, but the problem of surface contamination remains, just as in other shallow depth installations. However, with appropriate treatment for the control of water quality, the infiltration gallery is a practical method for the development of ground-water supplies from unconsolidated water-bearing formations at relatively shallow depth.

The use of shafts or tunnels for the withdrawal of ground water is limited generally to quite shallow depth in unconsolidated deposits, because of the costs of shoring or sheeting the excavation. The great cost of excavation rules out this type of structure in some consolidated formations, except where existing mine or other shafts or tunnels may be utilized. A few abandoned iron, copper, and coal mine shafts and tunnels have been utilized in Michigan as intakes for the development of ground-water supplies.

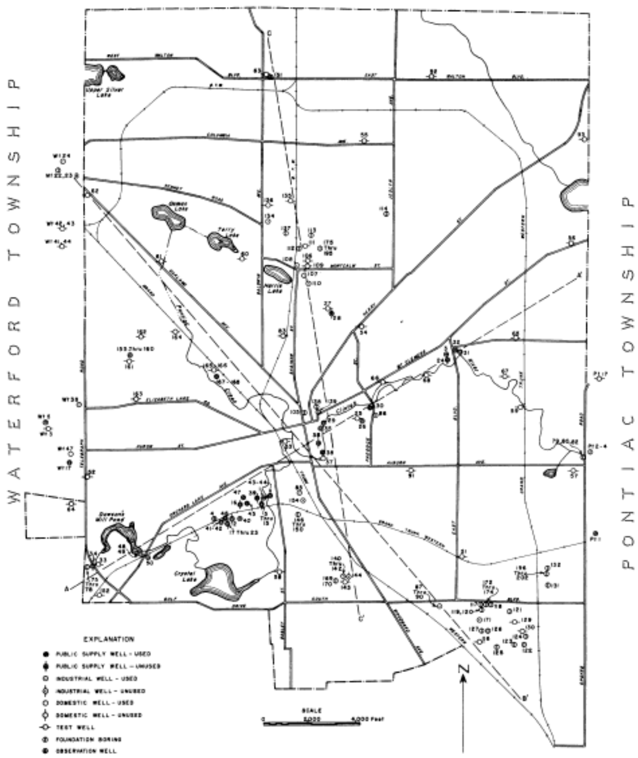

Plate 3. Map of Pontiac, Michigan, showing location of wells, foundation borings, and geologic cross sections.

Radial collectors

When dug wells were used in this country on a large scale, it was often the practice to jet or drive perforated pipes or well points radially outward from the base of the dug well in order to increase or restore its yield. Now a method has been developed to construct radial collecting wells at appreciable depth and further improve upon the older procedure. In the radial collecting method a central caisson of reinforced concrete is set upon a circular, steel, cutting shoe. Excavation is made within the central caisson by means of a clam-shell bucket. As excavation proceeds the caisson settles and is periodically extended. In the base of the caisson section provision is made to later insert perforated pipe. When the caisson has reached the appropriate depth in the water-bearing formation a concrete plug is poured to seal the hole. After dewatering the caisson, perforated pipes are jacked and jetted radially outward from the central shaft.

This method of construction may be used in unconsolidated formations to depths as great as several hundred feet. In some wells the perforated pipes have been projected radially outward from the collector to distances of a few hundred feet. This type of installation combines certain features of the gallery and the well structure.

Subsurface dams

The use of subsurface dams for the collection of ground water is quite limited and generally is feasible only in areas where the depth to the base of the water-bearing formation is small and where the ground-water reservoir is underlain and flanked by impervious deposits. In this method of construction, excavation is made through the water-bearing formation into an underlying impervious stratum. An impervious core wall is constructed to bound the subsurface reservoir and cut off all underflow. The core wall or subsurface dam is extended to and above the surface to a height sufficient to store available underflow, except perhaps during extreme periods of recharge. Details of this type of construction were described and illustrated by Slichter (1902, pp. 76-78) and by Schuyler (1897, pp. 693-695).

GROUND-WATER CONDITIONS IN PRINCIPAL AREAS OF DEVELOPMENT

Pontiac and environs

Nature and extent of water-bearing formations

Surficial outwash and alluvium

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

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

Numerous other examples equally conflicting are shown by the graphic logs on figures 17 to 19, inclusive.

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

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

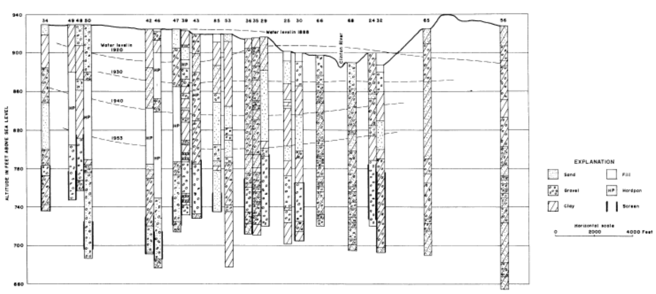

Figure 17. Geologic section and profile of piezometric surface along line A-A' shown on plate 3.

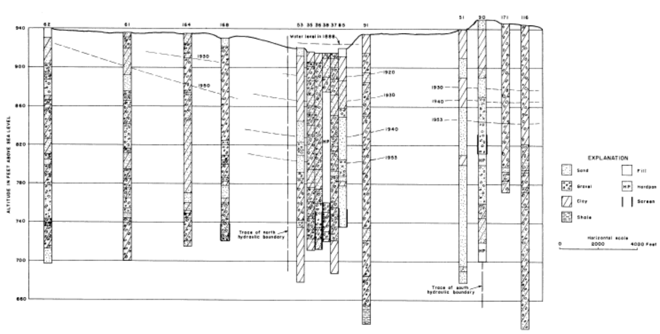

Figure 18. Geologic section and profile of piezometric surface along line B-B' shown on plate 3.

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

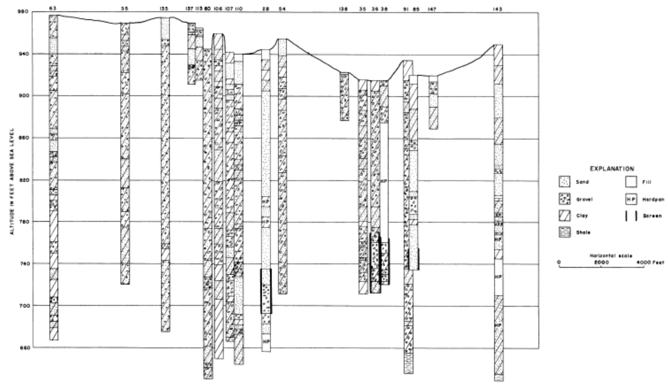

Figure 19. Geologic section along line C-C' shown on plate 3.

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

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

<u>Buried outwash</u>

A thick section of clay and gravelly clay underlies the surficial outwash and the morainal and till plain deposits throughout Pontiac. Some drillers refer to this section as hardpan. Along the Clinton River this hardpan reportedly ranges from 60 to more than 100 feet in thickness. Nearly everywhere the hardpan is recorded as clay, sandy clay, or gravelly clay. In contrast, however, the logs of wells PT 24, 25, 30, 32, 34, 53, and 85, shown on figure 17, record this hardpan section as clay, sandy clay, and gravelly clay that is interstratified with sand and gravel, clayey sand, and clayey gravel. These logs suggest that the hardpan section consists of a tripartite sequence beginning at the top with clay and gravelly clay, about 30 feet in thickness; overlying sand and some gravel about 40 feet or more in thickness;

which is underlain by a basal member of clay and gravelly clay, about 20 feet in thickness. This tripartite sequence approximates the thickness and correlates with the position of the hardpan section recorded in the other logs. Well PT 90, shown on figure 18, is of interest in this regard because it was screened in the gravels that correspond in stratigraphic position to the intermediate and permeable zone of the tripartite sequence.

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

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

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

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

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

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

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

Coldwater shales

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

Where the Coldwater shale is overlain by thick deposits of permeable glacial drift, as in the Pontiac area, small to moderate quantities of potable water might be obtained by wells tapping the Coldwater at shallow depth. Joint systems may exist where the Coldwater is comprised of resistant sandy shales^ shaly sandstones, or shaly limestones. Where such joint systems are at the contact with the drift mantle ground water from the drift deposits may be stored and to some degree transmitted to wells. For the most part, water obtained from such wells would be potable and essentially equivalent to the waters from the drift. Although data available are meager and inconclusive, it is probable that some of the deeper wells in the north and northwest part of Pontiac penetrate the Coldwater and obtain a little water from it. Although of little value as an aquifer, the Coldwater shale plays an important role in influencing the quality of ground water obtained from the overlying drift aquifers as shown by subsequent discussion.

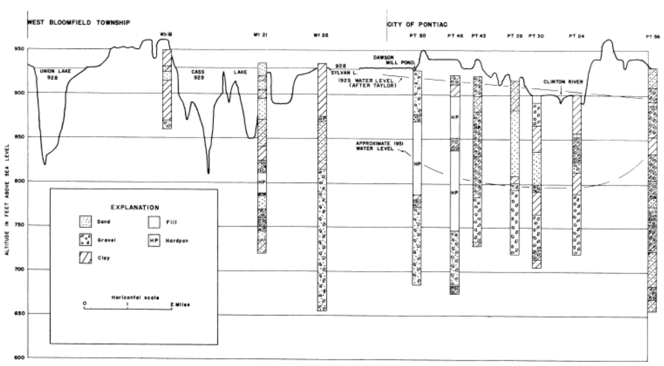

Figure 20. Generalized section and profile of piezometric surface along line X-X' shown on plate 4.

Source and movement of ground water

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

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

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

To date, the collection of data on ground-water levels in this area has been limited to a few wells within the heavily pumped area of Pontiac. These observation wells are so greatly influenced by interference from the operation of nearby municipal and industrial wells that the effects of natural influences of recharge or discharge are masked completely. However, records of ground-water level are available for an observation well which taps the surficial deposits and an area where nearby pumping is moderate to small and intermittent. This well, number BH 2, is in Bloomfield Township. A hydrograph showing the fluctuation of water level in 1951 is shown by figure 21. Well OaBH 2 is finished at a depth of 65 feet. During 1951 the water level ranged from 12 to about 16 feet below land surface. The hydrograph of well GeBu 303 near Flint, Michigan, is shown for comparison. This well also is finished in surficial outwash but at a depth of only 8.4 feet below land surface. During 1951, the water level ranged from a few inches to about four feet below land surface. Insofar as general trend is concerned., the hydrographs of the shallow and the deep well conform, but in detail the shallow well shows earlier and more pronounced response than the deeper well. As a result of the greater depth to water at the deeper well, more time is required for recharge from the surface to reach the water table. In comparing the hydrograph of observation well OaBH 2 with the hydrographs of the other hydrologic stations shown on figure 21, it should be remembered that several wells are within a few hundred feet of well OaBH 2 and the intermittent pumping of these wells influences the water level in the observation well.

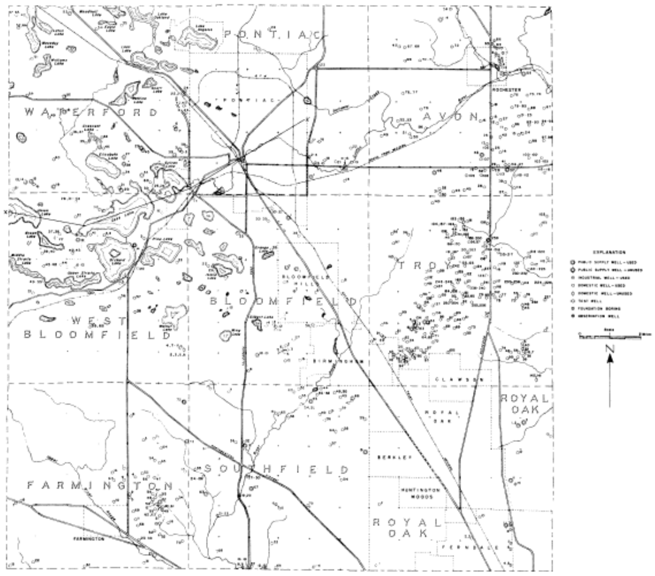

Plate 4. Well-location map of Southeastern Oakland County, Michigan.

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

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

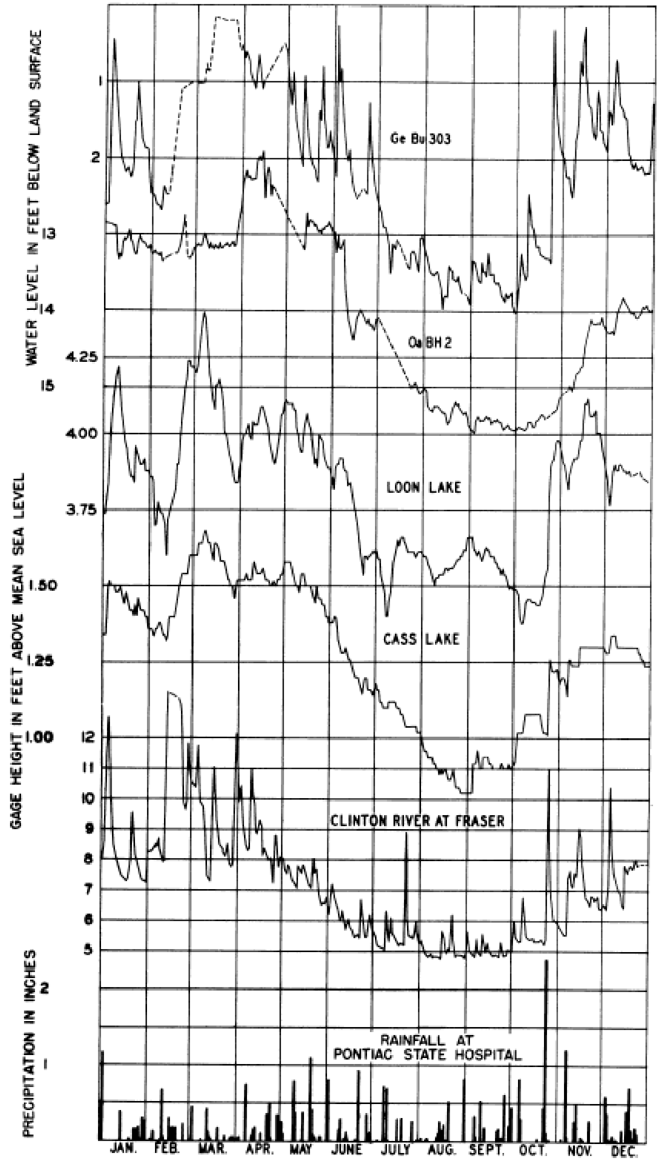

Figure 21. Relation between rainfall, river stage, lake stage and ground water levels during 1951.

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

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

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

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

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

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

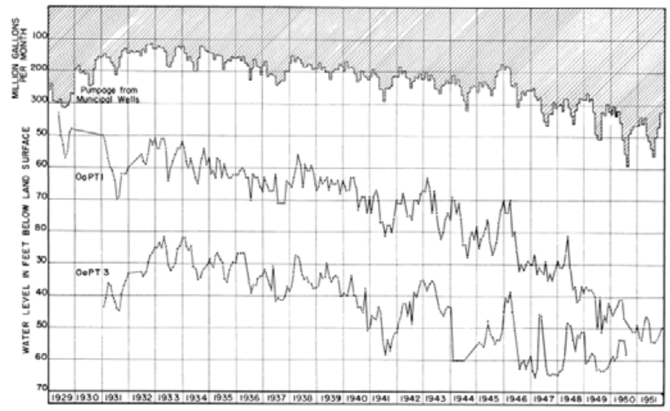

Figure 22. Hydrographs showing the relation between pumpage and decline of water levels in wells at Pontiac, Mich.

Hydraulic characteristics of principal aquifers

<u>Surficial outwash</u>

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

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

<u>Buried outwash</u>

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

Specific capacity reports

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

Pumping tests

Specific-capacity tests: The first test for which records are available was conducted by C. W. Hubbell, consulting engineer, who investigated the water problems of Pontiac and appraised the potential of the buried outwash for development of additional water supply. The test, run February 12 5 1918 p consisted of about a 4-hour period of steady pumping from 3 air-lift wells near the Walnut Street station with a combined output of 2830 g.p.m. The rate of pumping was maintained constant through the test period and water levels were observed in 4 nearby observation wells.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where:

T = coefficient of transmissibility, in g.p.d. per foot
Q = rate of pumping in g.p.m.
s = drawdown or recovery of water level, in feet
W(u) = well function of u

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

or

and

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

r = distance from pumping well, in feet
t = time since pumping started or stopped, in days
S = coefficient of storage

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

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

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

If the aquifer is of infinite areal extent and if all other conditions assumed in the development of the Theis equation are met, the field data for this test should follow the trace of the type curve W(u). From figure 25, it is noted that although the first observations match the type-curve trace 9 subsequent observations rise at a steeper rate and lie above the type curve. An increase in the rate of drawdown might imply that the rate of withdrawal from the aquifer increased. However, it is known that pumping from the airlift wells was maintained at a steady rate throughout the pumping period and that no other large ground-water developments existed in the area at this time. Thus, in the absence of other pumping only one other possibility remains as an explanation for the increased rate of drawdown. It has been shown by Jacob (1950, pp. 354-355), Ferris (1949, pp. 247-259) and others that where an aquifer is made semi-infinite by a bounding plane of impervious sediments the hydrologic effect of that boundary is comparable to the influence of a competing well, which discharges at a rate equivalent to the real pumped well and lies at an imaginary position symmetrical about the boundary plane. Thus, the effect of the image well is to double the rate of drawdown caused by the discharge of the real well. From the log-log graph of figure 25, note that the increased rate of drawdown in the observation well is twice the initial rate as shown by the evidence that the second part of the log-log graph matches the type curve at twice the drawdown intercept of the initial match for the corresponding value of W(u). A procedure that might be followed with greater clarity, is to plot the departures of the field observations from the extrapolated trace of the original type-curve match on the log-log graph. Then match the departure data to the type curve and note that it will match at the same drawdown intercept as the solution for the initial data.

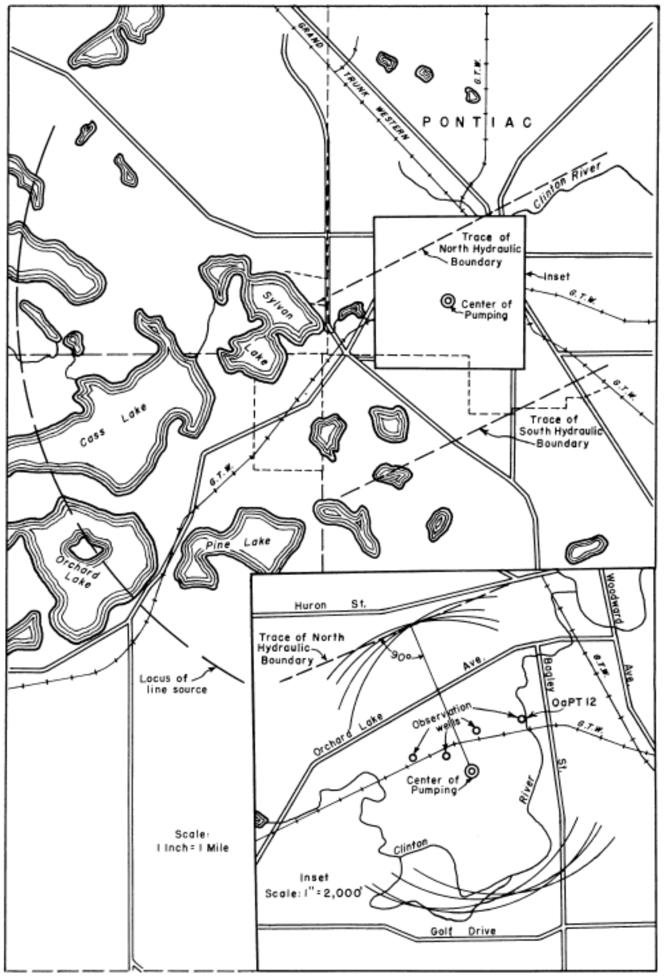

Figure 23. Location of wells and trace of hydraulic boundaries as determined from Pontiac pumping tests.

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

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

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

Coordinates of initial match point:

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

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

from equation (1)

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

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

from equation (3)

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

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

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

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

$T = P\,m$

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

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

m = saturated thickness of aquifer, in feet

then

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

$P = 2300$ g.p.d. per square foot

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

Daily measurements of water level were made in several observation wells through the two months preceding the week of peak withdrawal. Numerous but somewhat sporadic, measurements of water level in the observation wells were made through the last week of the test. Some difficulty arises in the interpretation of the antecedent water-level trends because of a 6-hour shutdown of all pumping just prior to the start of the final week of pumping at the higher rate. Within this shutdown period, water levels in the area recovered appreciably and the water levels prior to the 6.1 m.g.d. test were several feet above the stages that had obtained for most of the antecedent period. In analyzing the drawdown data for the final week, this brief period of recovery was ignored and the drawdown corresponding to the 2.8 m.g.d. increase in pumping rate was computed from extrapolation of the stage which had prevailed in each observation well during the 10 days preceding the step increase in pumping rate. This method of analysis involves some error in the drawdown values for the first few hours, but after pumping has continued for a period comparable to the 6 hours of recovery the influence of the recovery interval is minimized and subsequent drawdown data show little or no residual effect.

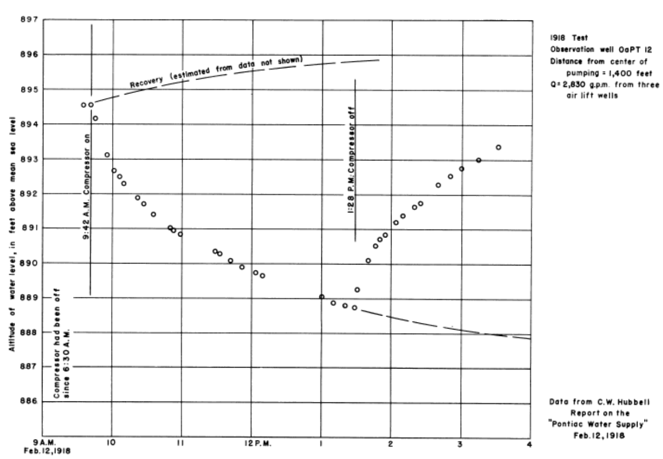

Figure 24. Fluctuation of water level in well OaPT 12 produced by pumping wells at the Walnut Street Station at Pontiac, Mich.

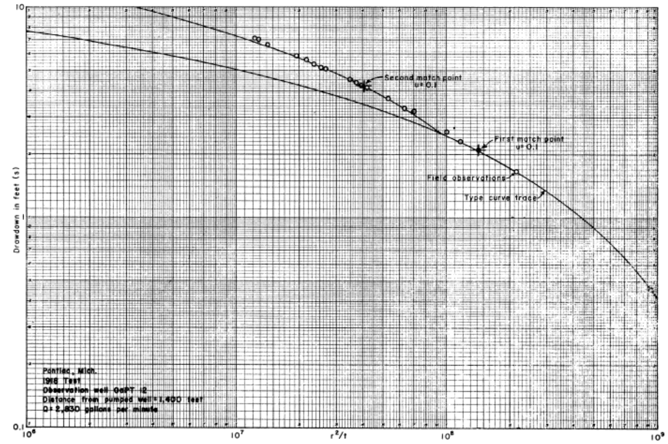

Figure 25. Logarithmic graph of the drawdown in well OaPT 12 produced by pumping wells at the Walnut Street Station at Pontiac, Mich.

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

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

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

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

Thus, it is demonstrated that the first 15 hours of drawdown in well PT 7 can be reproduced in both magnitude and slope on the log-log plot of figure 27 by using the hydraulic boundary positions of figure 23 with their related images and the T and S values from the 1918 test. Beyond this time, however, the observed data show a marked decrease in drawdown trend. As in the 1918 test, interference from other wells or a change in pumping of the air-lift wells can be ruled out on the basis of records available. The possibility remains that an image recharge well may account for the reduction in drawdown. As shown by Muskat (1937, pp. 175-181) and by Theis (1941, pp. 734-738) a recharging image well represents the hydraulic influence of a line source, such as a stream or lake recharging the aquifer.

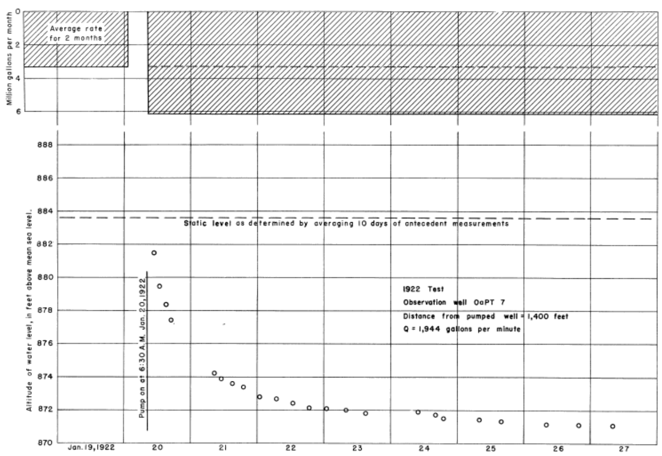

Figure 26. Fluctuation of water level in well OaPT 7 produced by pumping the air-lift wells at the Walnut Street Station at Pontiac, Mich.

From departures of the observed data below the trend computed for trial 29 the distance to this line source is estimated at about 23,000 feet. Although several observation wells were measured in the 1921-22 test, all were less than 2,000 feet from the center of pumping and thereby were of little added value in fixing the position of the recharge source. An arc describing the locus of the recharge boundary is scribed on the map of figure 23. Theoretically, the recharge area may be anywhere on the circumference of the boundary circle, but the data available are not adequate to pinpoint its location. However, to a large extent the geologic evidence rules out the eastern half of the boundary circle and points westward to the vicinity of the deeper lakes. It was previously stated that the deeper lakes in this area are of sufficient depth to intersect the buried outwash deposits and that the origin of these lake basins may be correlative with the buried channel of outwash.

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

Knowing the coefficients of transmissibility and storage and the effective hydraulic width of the channel aquifer, the underflow through the buried channel can be calculated by Darcy's law (Wenzel, 1942, pp. 3-4) if the gradient along the channel is determined. In the 1918 and 1921-22 tests, the observation wells used were relatively close to the pumped wells and influenced by their spacing geometry. Data presented by Taylor (1930, p. XIII) provides a basis for determining the regional gradient from the line source to the pumping locale. In the period November 1929 to March 1930, water levels in the Orchard Lake well (PT 48) were observed while this well was out of service and its average stage was 881 feet above sea level. The total withdrawal from wells in the buried outwash average 6.5 m.g.d. The distance from the Orchard Lake well to the line source is about 20,000 feet. The altitude of lake level in the recharge area is 929 feet above sea level or 48 feet above the ground-water stage at the Orchard Lake well. From Darcy's law the following relation is developed:

$$Q = T\ I\ W \qquad (5)$$

where

Q = underflow in g.p.d.
T = coefficient of transmissibility, in g.p.d. per foot
I = gradient of piezometric surface
W = width of underflow channel, in feet

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

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

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

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

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

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

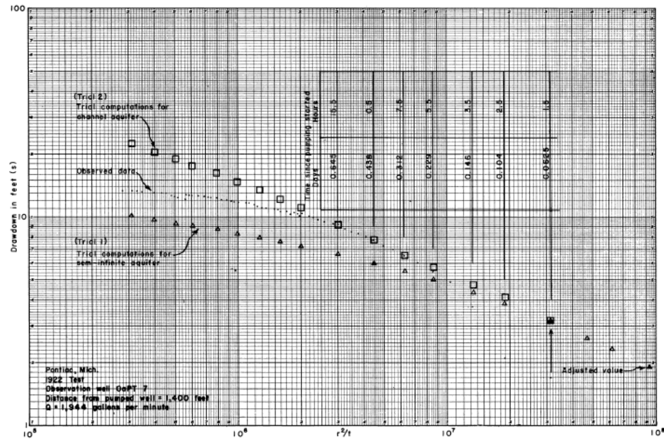

Figure 27. Logarithmic graph of the observed and computed drawdown in well OaPT 7 produced by pumping the air-lift wells at the Walnut Street Station at Pontiac, Mich.

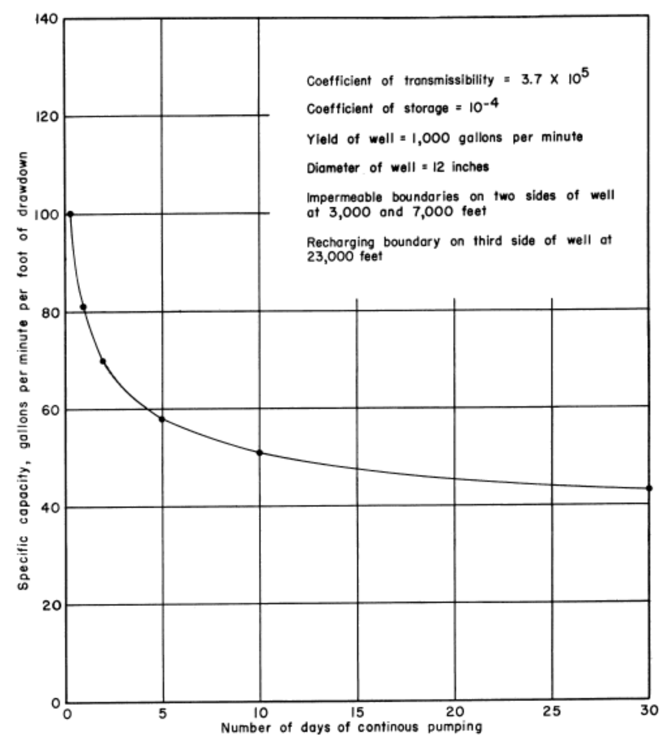

Figure 28. Variation of computed specific capacity in a hypothetical well at Pontiac, Mich.

Quality of water

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

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

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

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

As an aid to illustrate the areal distribution of ground-water quality the hardness, sulfate, and chloride content for each recent analysis are shown on plate 5, adjacent to the well sampled. With reference to Pontiac and vicinity, observe the range in hardness from 155 p.p.m. for well OL 14 to as much as 632 p.p.m. for well Av 58. Well OL 14, which represents the softest water reported in table 7, is finished in the surficial sand and gravel at a depth of 80 feet and is adjacent to Orchard Lake. The soft water indicates that recharge to the formation tapped by this well is from the immediate vicinity, perhaps from the nearby lake. Well Av 58 is reportedly finished in surficial sands at a depth of 35 feet, but the extreme mineral content reported raises some question as to the source of the water. With the exception of these two extremes, the hardness for the balance of the wells in or near Pontiac shows the much narrower range from 205 p.p.m. in well Tr 259 to 450 p.p.m. in well PT 29. The chloride content ranges from 2 to 124 p.p.m. and the same wells again mark the extremes of range. Note also that wells Wt 13 and 49 for which chloride content is reported at 100 p.p.m., are among the wells of higher hardness. An equally wide range in sulfate content is indicated from the 2 to 3 p.p.m. evidenced by wells Tr 259, OL 14 and Wb 4, to the 142 p.p.m. reported for well BH 2. Again the extremes are marked by the wells with extremes of hardness or chloride.

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

Well BH 2 with high sulfate and well Av 58 with high chloride and total hardness are both on a topographic ridge, most of which was mapped by Leverett as the Birmingham moraine. As shown by plate 1 and figure 6, this topographic high coincides in general with the contact of the Coldwater shale and the Berea-Bedford-Sunbury formations. The few drilling records along the ridge report relatively thick drift. However, if this topographic high reflects an underlying high on the bedrock surface, such as an escarpment of Coldwater shale, Sunbury shale, or Berea sandstone, the quality of water from these wells may indicate induced infiltration of mineralized water from the underlying bedrock. High sulfate suggests infiltration from the shales of the Coldwater or the Sunbury, whereas high chloride suggests infiltration from the sandstones of the Berea.

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

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

Nature and extent of ground-water developments and their effect

Past and present development

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

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

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

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

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

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

Effect on water levels

Prior to 19009 water levels in the buried, outwash deposits at the Walnut Street station were several feet above land surface or more than 920 feet above sea level. However, with the steady uptrend in ground-water use, water levels declined steadily through the year, as shown by figure 29. By 1952, ground-water levels in the Walnut Street area had declined to about 120 feet below land surface or 800 feet above sea level. In the summer of 1953 water levels in a number of the municipal wells were at or slightly below the top of the perforated pipe that was used in lieu of a screen. Thus, in the vicinity of some wells the aquifer has been dewatered. However, through most of the area ground-water levels still remain above the aquifer and artesian conditions prevail.

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

From detailed study of the water-level reports, generalized profiles of the piezometric surface were constructed along the lines of the geologic section A-A' and B-B' (figs, 17 and 18) through Pontiac. The profile along line A-A' nearly parallels the coarse of the channel of buried outwash deposits. A rather extensive depression of water level is shown by the several profiles of water level for each year noted. In general, the lowest water levels are between the Walnut Street station and the secondary pumpage concentration of the Perry-Paddock Street group of municipal wells. The effective center of over-all ground-water withdrawal in Pontiac lies between these centers of municipal pumping concentration.

The water-level profile shown by figure 18 follows the axis of geologic section B-B' and reflects the influence of the hydraulic boundaries which are identified on this section. Note that water levels reported for wells north of the north hydraulic boundary are at considerably higher stages than water levels in the outwash channel. Most of these wells were drilled to sufficient depth to completely penetrate the buried outwash deposits of the channel aquifer if they extended into the north part of

Pontiac. If these wells are finished in glacial drift as reported by the drillers, the permeable deposits apparently are a few scattered thin beds, or beds poorly connected hydraulically with the buried outwash in the principal channel. Whatever the nature of the water-bearing deposits north of the north boundary, the water-level gradient indicates that some water moves from this direction toward the buried channel in response to the greatly lowered water level in the channel aquifer.

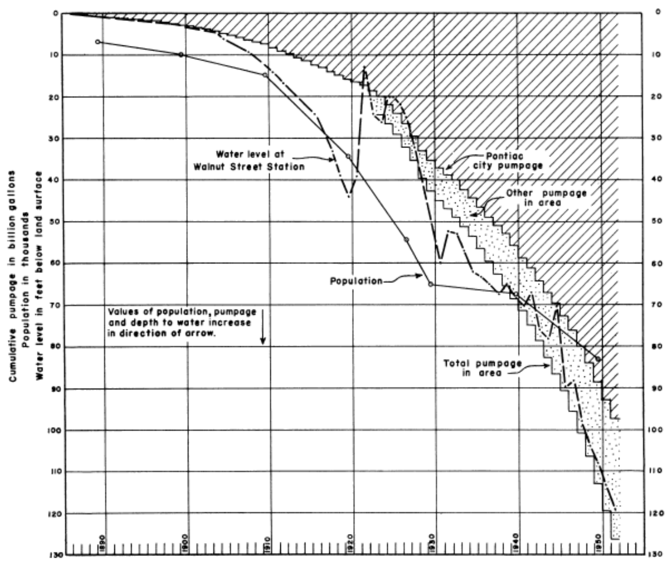

Figure 29. Relation between population, cumulative withdrawal, and water level in Pontiac, Mich.

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

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

Future trends of water level in the area cannot be extrapolated from the trend of the graph shown by figure 31, because of the imminence of extensive dewatering of the aquifer. When dewatering occurs, the coefficient of storage for the channel aquifer will increase from the present artesian value of 0.0001 to a water-table value of 0.20 to 0.30 and the amount of water available to wells from storage will increase several thousand times. As a result of the greatly increased storage release near each pumping well, ground-water levels in the area will appear for some time to stabilize at or near existent levels. However, as pumping rates increase and new well installations are added, further declines of water level will dewater the aquifer and reduce its saturated thickness. The coefficient of transmissibility of the aquifer is proportional to its saturated thickness and as the saturated thickness is reduced the coefficient of transmissibility is correspondingly reduced. As the coefficient of transmissibility decreases, the capacity of the buried channel to transmit water at the rate and gradient which formerly prevailed is reduced. Decreased transmissibility requires increased drawdown to maintain a constant withdrawal rate, but greater drawdown further decreases the transmissibility. As this vicious cycle continues, pumps must be set at successively deeper stages in order to keep pace with the declining water level. Before long, pumps must be throttled to maintain well output commensurate with the saturated thickness required for that rate of well yield. Thus, unless remedial measures are adopted, extension of the seemingly straight-line correlation of figure 31 may continue for some time at its present slope; then seemingly level off for some time; and later renew its decline at a much more rapid rate than previously.

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

<u>Effect on water quality</u>

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

11 it is low in waters that have not been in contact with the Coldwater.

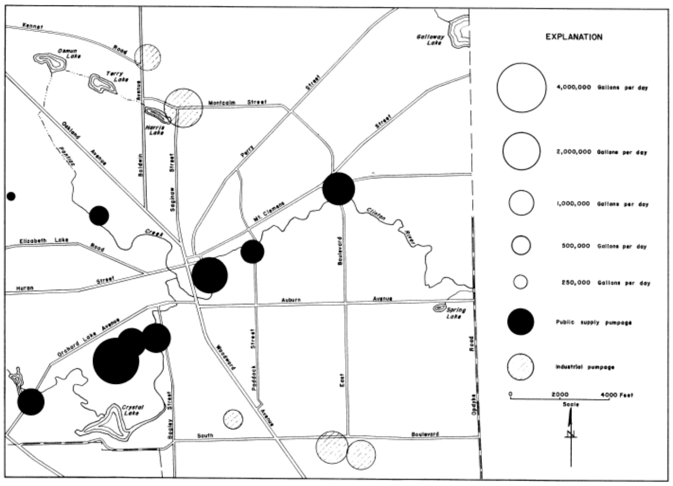

Figure 30. Areal distribution of ground water withdrawals in Pontiac during 1952.

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

Greater sulfate content in the several municipal wells in May 1952 compared to January of that year confirms the interrelation between sulfate content and the lowering of water level in the buried outwash aquifer. The over-all rate of ground-water withdrawal was much larger in May and consequently water levels throughout the area were lower at this time. Thus, a larger head differential existed between the buried outwash aid the underlying Coldwater shales or other deposits of small permeability that bound the buried outwash channel. Under this condition the rate of leakage from adjacent strata was increased.

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

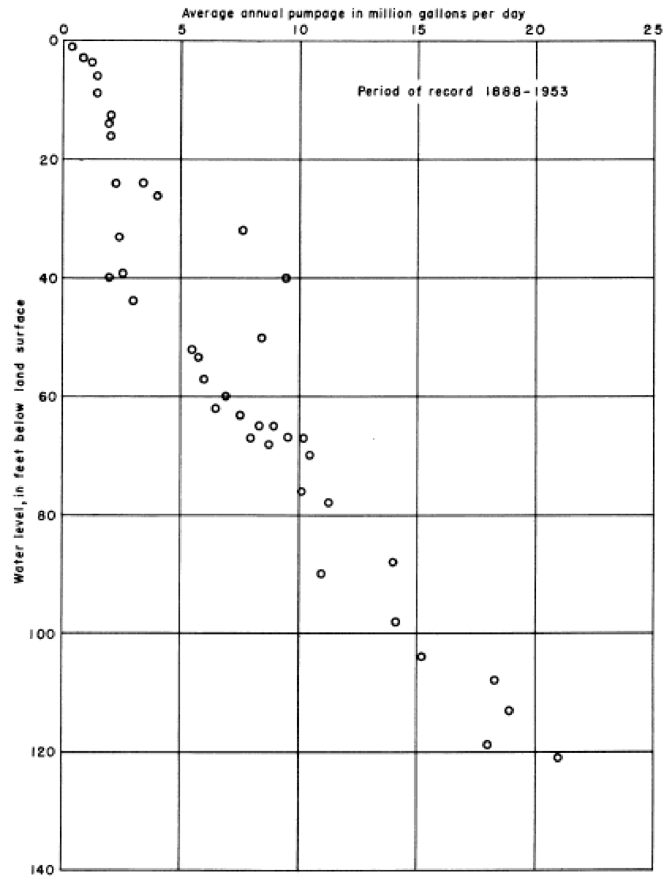

Figure 31. Pumpage and decline of water levels at the Walnut Street Station at Pontiac, Mich.

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

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

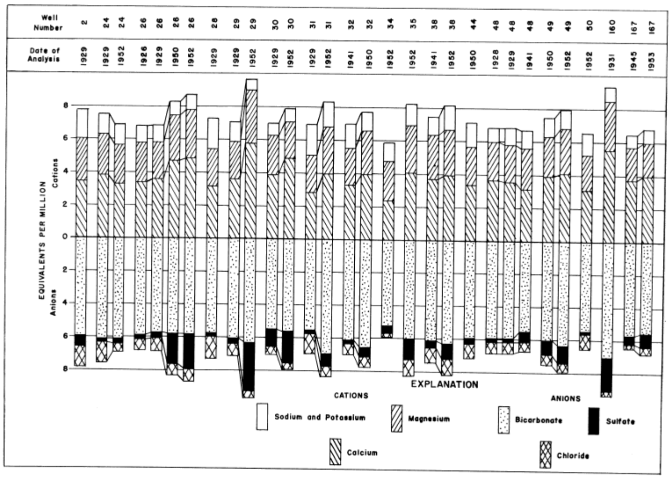

Figure 32. Composition of ground water in Pontiac, Mich.

Birmingham-Royal Oak area

Nature and extent of water-bearing formations

<u>Surficial deposits</u>

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

Many residents of the area formerly obtained domestic water supplies from shallow wells which tapped the sandy lenses of the lacustrine deposits or the "roots" of the beach ridges. By the 1920s, residents of Hazel Park, Ferndale, Oak Park, Pleasant Ridge, and Huntington Woods were troubled each summer with water shortages because of failure of their shallow domestic wells. Water haulage was general in the area at that time. During the 1920ss and 19308s these communities contracted with Detroit to supply water to the area.

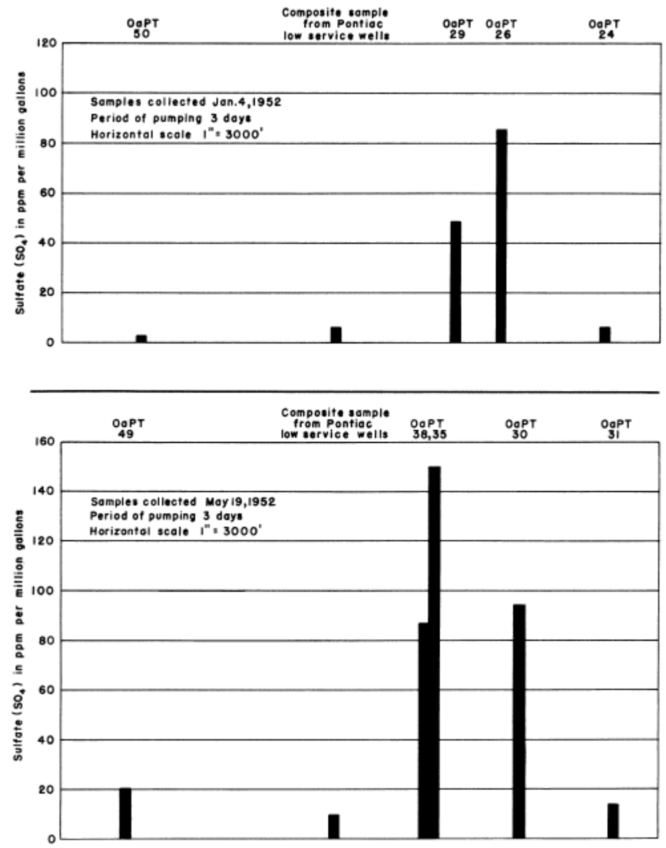

Figure 33. Relation of sulfate and pumpage in the Pontiac municipal wells.

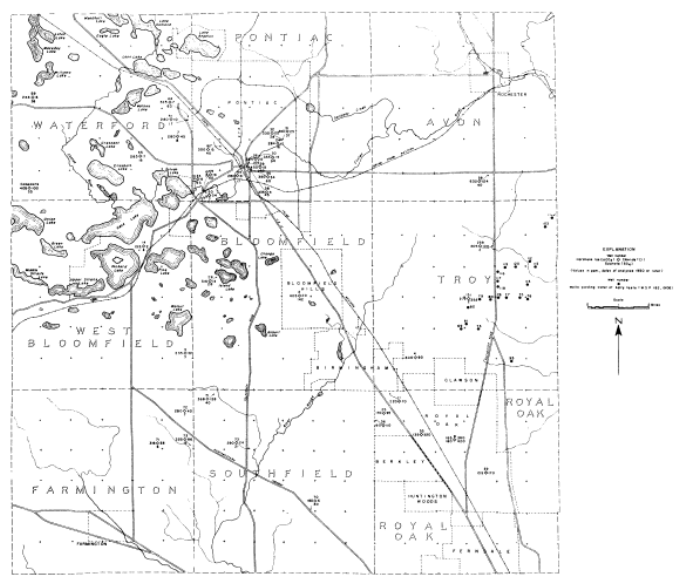

Plate 5. Composition of selected samples of ground water in southeastern Oakland County, Michigan.

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

Buried outwash deposits

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

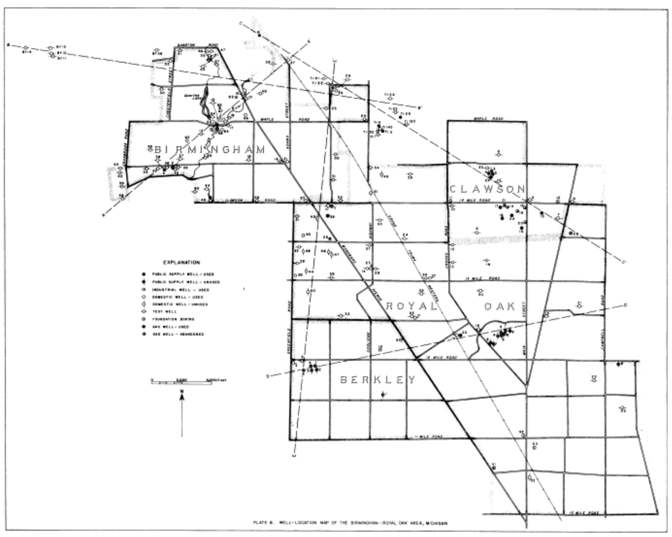

Plate 6. Well-location map of the Birmingham-Royal Oak area, Michigan.

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

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

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

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

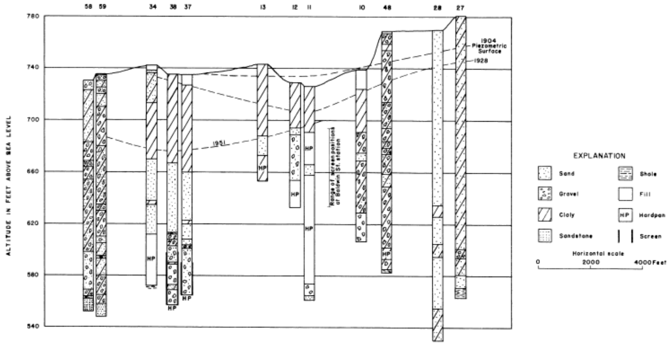

Figure 34. Geologic section and profile of piezometric surface along line A-A' shown on plate 6.

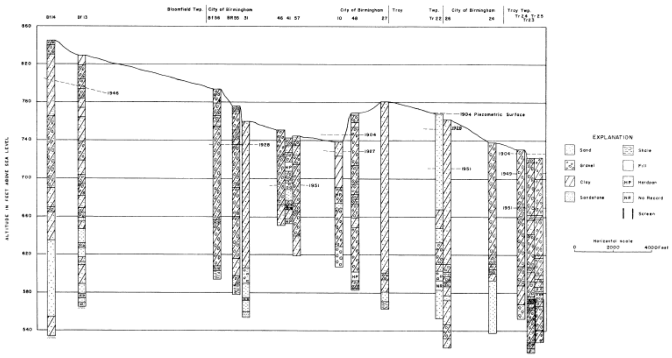

Figure 35. Geologic section and profile of piezometric surface along line B-B' shown on plate 6.

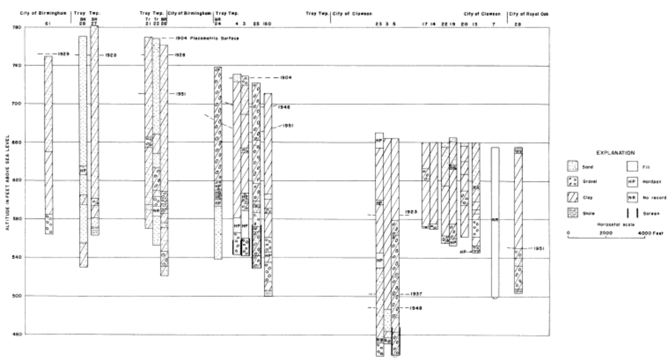

Figure 36. Geologic section and profile of piezometric surface along line C-C' shown on plate 6.

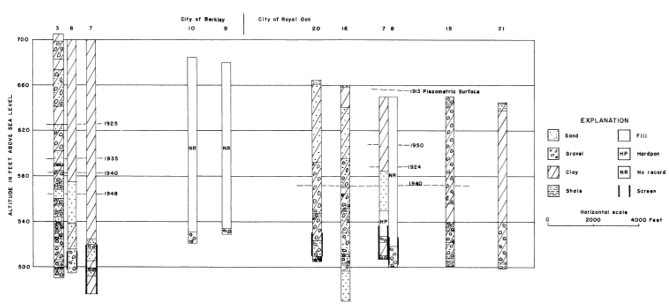

Figure 37. Geologic section and profile of piezometric surface along line D-D' shown on plate 6.

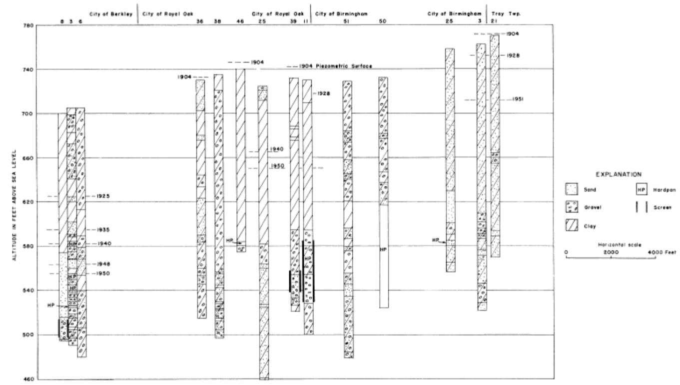

Figure 38. Geologic section and profile of piezometric surface along line E-E' shown on plate 6.

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

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

<u>Bedrock formations</u>

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

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

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

Source and movement of ground water

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

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

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

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

Hydraulic characteristics of buried outwash

Specific-capacity reports

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

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

Pumping tests

SPECIFICS-CAPACITY METHODS

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

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

AQUIFER-TEST METHODS

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

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

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

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

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

Quality of water

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

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

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

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

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

Nature and extent of ground-water development and their effect

Extent of past and present development

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

Effect on water levels

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

Until about 1948, water-level stages in the Lincoln, West, East, and South wells of Birmingham, were relatively steady from year to year, although considerable seasonal fluctuation occurred. As shown by figure 39, the total annual withdrawal of ground-water by the Birmingham municipal wells was slightly larger in the years 1944 through 1951 than in the years 1940 through 1943, but not much greater than in the years 1937 through 1939. Thus, the relatively steady annual stage of ground-water level preceding 1948 is in agreement with the equally steady annual rates of total withdrawal. Since 1948, however, the water levels in the 6 wells observed show a marked downtrend in contrast to the relatively steady pumping rate by the Birmingham wells. In the 4-year period ending 19519 ground-water levels in the Lincoln, West, East, and South wells declined from 20 to 30 feet. The water level in the Baldwin well declined little more than 15 feet but did not reach stages as low as in the 1936-40 interval because it had been out of service for about 7 years and a considerable recovery of stage had occurred, by 1948. By 1951 the new Walker well showed a decline in water level from the initial level of about 70 feet.

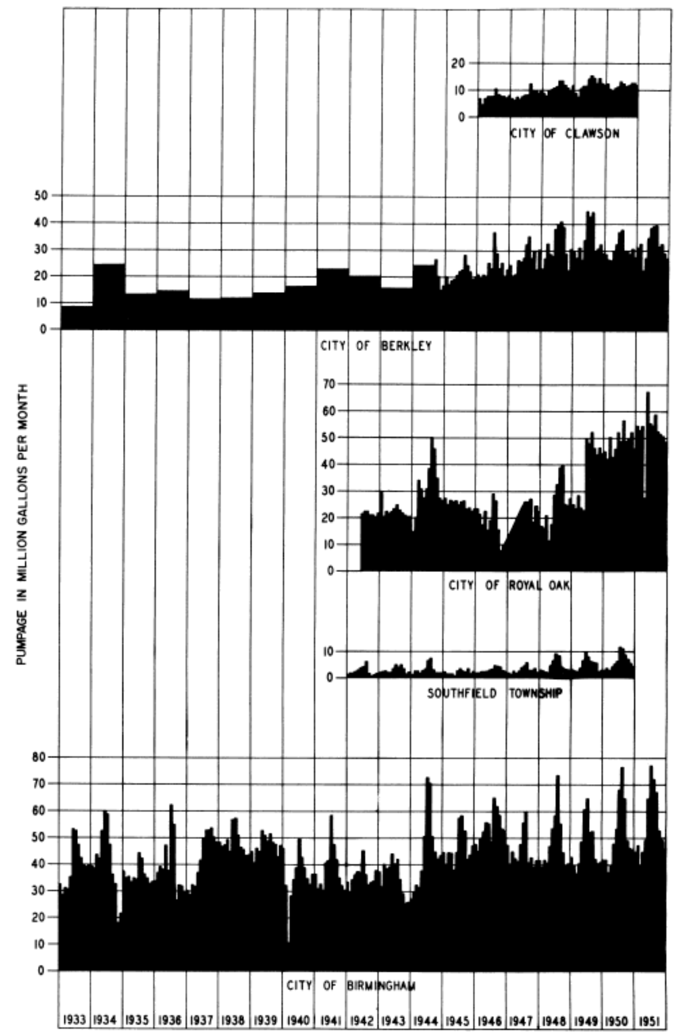

Figure 39. Ground water pumpage for public supply by the cities of Berkley, Birmingham, Clawson, Royal Oak, and Southfield Township.

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

The water-level records from the Birmingham wells indicate that drawdowns as much as a few tens of feet have occurred over distances of several miles as a result of intensive ground-water development in the corner of Troy Township that adjoins Birmingham and Royal Oak. Although drawdowns of this magnitude over so large an area are significant, they are not necessarily indicative of over-development. In the vicinity of any new ground-water development some progressive drawdown of ground-water level must always occur after the start of pumping or following each increase of pumping. This initial, phase of drawdown represents the deepening and expansion of the cone of depression as the ground-water reservoir adjusts to the new pumping regimen. Regional drawdown of water level must occur to provide the gradient necessary to move water from the outer regions of the underground, reservoir to the focal centers of pumping. If pumping continues at a steady rate and if that rate of withdrawal, can be furnished by the salvage of rejected recharge, by decreasing natural discharge, or by increasing the area of recharge, and. without appreciable reduction of saturated thickness, then the downtrend of water level will decrease and ultimately stabilize at stages commensurate with that condition of pumping rate and distribution. The downtrend of water level in 1951 (fig. 41) was markedly smaller than in the preceding 3 years. Considering that from one-third to perhaps one-half of the total withdrawal in this area did not occur until 1950, it is evident that the adjustment of the cone of depression in the region was effected in a relatively short time as in any artesian aquifer of finite extent. Further increases in pumping from this area are to be expected and further drawdown of water level throughout the area must-accompany increased withdrawal.

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

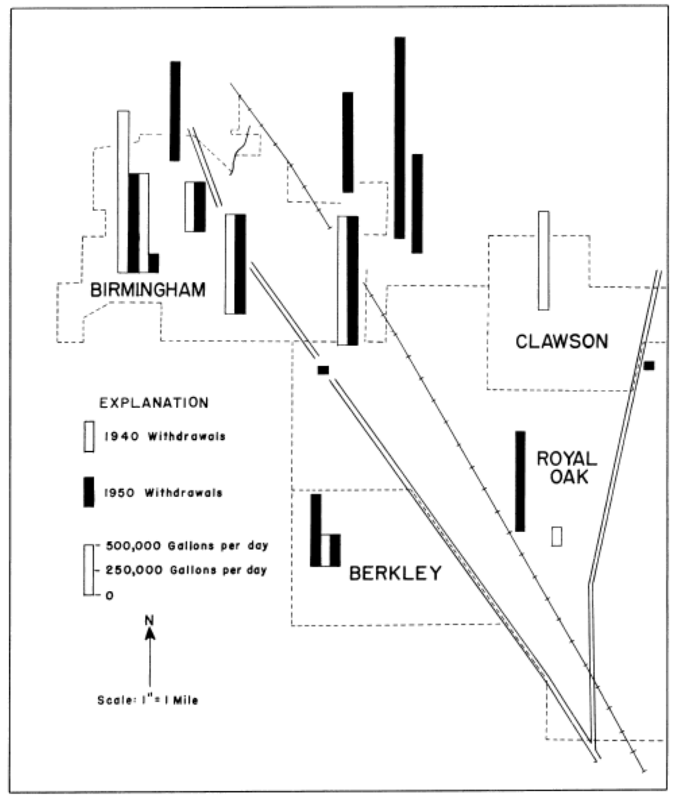

Figure 40. Map of Birmingham-Royal Oak Area showing municipal pumpage in 1940 and 1950.

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

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

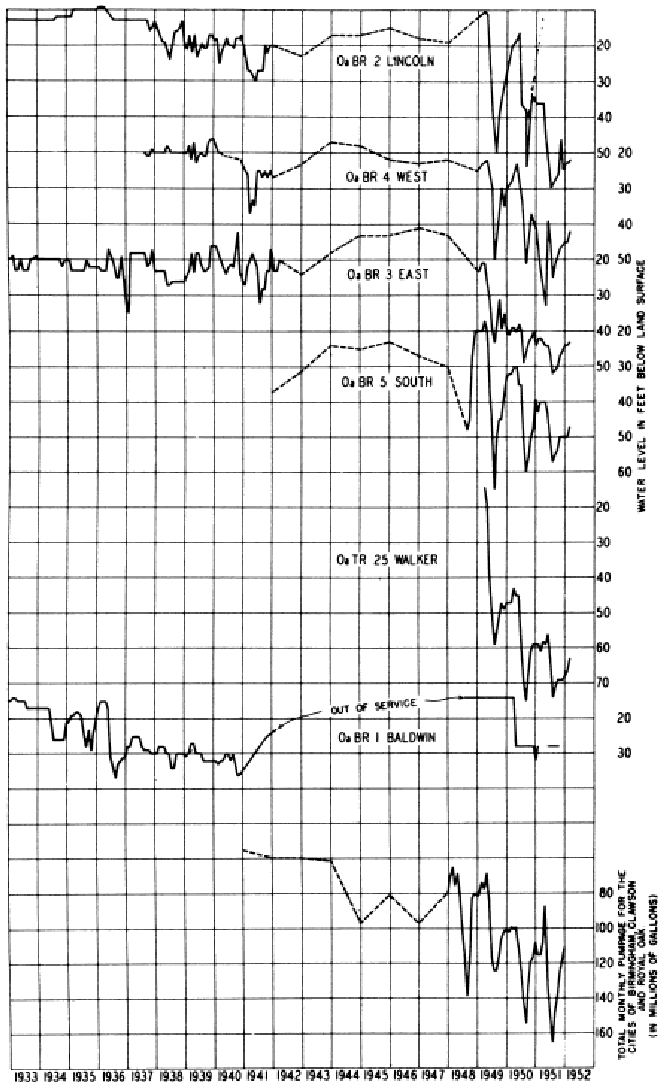

Figure 41. Hydrographs showing monthly fluctuations of water levels in the city wells at Birmingham, and total monthly pumpage for the cities of Birmingham, Clawson, and Royal Oak, Mich.

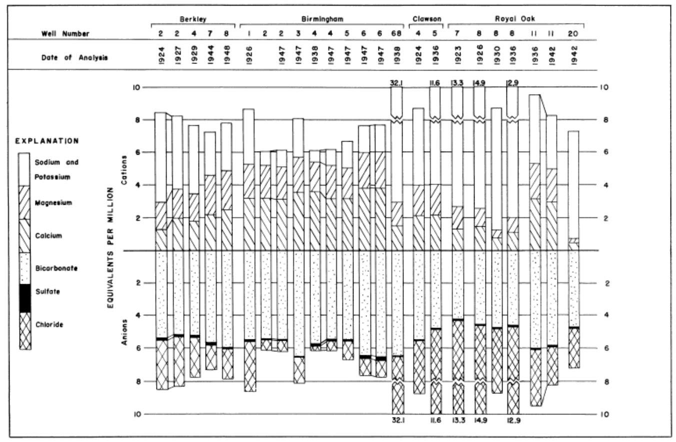

Figure 42. Composition of ground water in Berkley, Birmingham, Clawson, and Royal Oak, Mich.

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

Effect on water quality

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

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

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

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

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

The relatively large amounts of chlorides reported for wells Tr 3 and 4 and RO 11 as shown by tables 7 and 8 are of particular significance. The recent intensive development by several communities of the buried-outwash aquifer, near the southwest corner of Troy Township, has resulted in marked water-level declines in this area and has created the potential condition for equally marked rises in chloride content. Chlorides in this area in 1945, before much of the present development existed, were already appreciable as shown by well Tr 39 and confirmed by well BR 3 to the west. The marked declines of water level in the area suggest a small aquifer and a considerable distance to the source of recharge. If development is further intensified water quality may deteriorate appreciably. Therefore, immediate steps should be taken to establish adequate programs of water-quality, pumpage, and water-level observation to provide a basis for forecasting trends in the area.

POTENTIAL YIELD OF GROUND-WATER RESERVOIRS

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

Ground-water recharge

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

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

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

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

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

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

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

Ground-water runoff

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

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

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

The distribution of total runoff at Mt, Clemens determined for the 9-year period was 4.2 percent ground-water runoff and 58 percent overland or storm runoff. For the 1946 water year, the distribution was 36 percent-ground-water runoff and 64 percent storm runoff. These estimates are rounded off to 40 percent, ground-water runoff and 60 percent storm runoff. On this basis, storm runoff at Mt. Clemens is estimated at 5.2 inches for the 1930 water year and the balance of 3.4 inches represents ground-water runoff.

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

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

The flow-duration data indicate that runoff per unit area, from the North Branch and Middle Branch of the Clinton River above Mt. Clemens is much smaller than the contribution from the Clinton River through Pontiac. The mantle of glacial drift on the Clinton River basin above Pontiac is much more permeable and is of greater average thickness than on the North Branch or Middle Branch basins. Thus, it is to be expected that ground-water flows per unit area at Pontiac will be considerably larger than at Mt. Clemens. The ratio of flow-duration curves at Pontiac and Mt, Clemens provide supporting evidence and an index for appraising the hydrogeologic differences. The ratio of ground-water runoff to total runoff at Mt. Clemens, when applied to the total runoff measured at Pontiac, yields 4.7 inches of ground-water runoff for the 1930 water year. To adjust for hydrogeologic differences between the two areas, the estimate of 4.7 inches is increased by one-third in accord with the flow-duration index noted above and the ground-water runoff at Pontiac becomes 6.3 inches. Subtracting 6.3 inches ground-water runoff from, the total runoff of 11.7 inches, there remains 5.4 inches of overland runoff as compared to the previous estimate of 5.2 inches. All estimates of total runoff and its distribution are in good agreement for the several methods employed.

Recharge or Discharg e	Gain or loss in inches			Total gain or loss (perc ent)
	Subsurface	Surface	Total	
Recharge	21.4	--	27.63[/1]	100
Discharge				
/apotranspiration	13.5	0.9	14.4	52.2
unoff	6.4	5.3	11.7	42.4
version by wells	1.5	--	1.5	5.4
Total			27.6	100

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

/1 Total rainfall for 1930 water year

Water budget

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

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

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

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

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

Management of water resources

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

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

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

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

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

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

The basin method of artificial recharge and other surface spreading methods are restricted to areas where the aquifer to be recharged is overlain by moderate to highly permeable formations with sufficient unsaturated depth available to recharge water at acceptable rates. For artesian aquifers, the capping formations limit benefits from surface application of recharge unless the confining beds are removed or are pierced by wells or shafts. If the artesian strata crop out within moderate distance of the area of use, surface methods of recharge may be used on the outcrop area and the gradient produced by withdrawals at the focal centers of use will induce migration from the recharge area to the centers of use.

Figure 43. Photograph showing Rockaway Road recharge basin, Garden City, New York. (Courtesy of Department of Public Works, Nassau County, New York.)

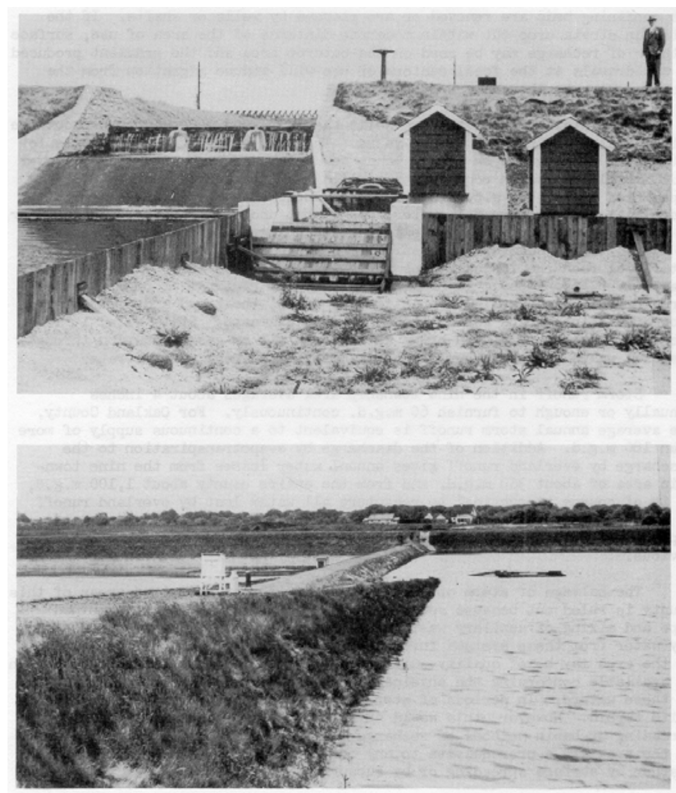

Figure 44. Photographs showing the overflow spillway and the embankment between the north and south units, Rockaway Road recharge basin, Garden City, New York. (Courtesy of Department of Public Works, Nassau County, New York.)

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

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

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

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

A large part of the lake-dotted upland of permeable outwash lies beyond the limits of the nine township area, but would logically be included in any long-range planning for resource management in Oakland County. The importance of these lakelands to the economy of Oakland County as recreation and suburban development areas raises a considerable problem concerning the priority of water rights. Equally important water rights are held by agricultural developments. These rights and others, of course, must be integrated in any over-all plan of water-resource management. The recreational use is seasonal and reaches its peak at about the same time as the evapotranspiration demands and the peak of public, industrial, and domestic water supply needs. However, the needs of recreational interests for the maintenance of lake levels pertain generally to the summer months only. Through the balance of the year, lake stages need not be high and through the ice season might even be lowered advantageously to reduce ice thrust damage. Thus, it may be feasible to withdraw ground water in the recharge area near the lakes at peak rates during one-half or more of the year and use the excess, beyond immediate demand to replenish aquifers nearer to the urban areas. Proper planning based on adequate water-resource data could schedule the timing and distribution of these withdrawals to take advantage of the periods of peak runoff in order to insure replenishment of the lakes before the recreational season. In the summer months of peak water demand withdrawal could be made from wells distant from the lakes and from aquifers in the urban areas that were artificially recharged during the fall, winter, and spring seasons.

Competition between urban and agricultural needs for water could be minimized by the same method of seasonal redistribution of the withdrawal centers. It is noteworthy that present land-drainage practices in places have an adverse effect on the dry-season supply of moisture. In many cases, agricultural drains are designed to handle the extreme spring runoff and no consideration is given to the conservation of soil moisture after this peak as evidenced by the fact that the drains are left wide open throughout the year. It is general practice to limit the number of drains and thereby minimize the need for bridge building. To compensate for the loss of effectiveness because of the wide spacing, the drains are carried to appreciable depth to accomplish drainage at mid-field. Through late spring and summer, when moisture needs of the crops are large, the continued discharge of water by open drains lowers the regional water table below the soil layer and thereby greatly reduces the moisture supply. It is not uncommon during extended drought to observe clouds of powder dry top-soil carried off by the winds from farmlands that are deeply drained. In recent years, however, farmers in increasing numbers are closing drains after each period of runoff and conserving ground water for subirrigation.

In addition to the salvage of overland or storm runoff and evapotranspiration discharge by vegetation, an appreciable part of the ground-water now discharging into streams may be captured by ground-water installations. Again, however, competition is involved because the flow of most streams cannot be entirely diverted without damage to other water users. Locally, a large part of stream flow might be used and returned downstream. The possibility of beneficial diversions of stream flow should be carefully investigated. Reuse of water in its transit through an area has been developed to a high degree in some places. In time, as competition for water increases, some of our densely populated areas undoubtedly will make more effective use of available water.

Prior to the industrial age, man's water needs were very small and Nature's bounty seemed limitless. In humid regions of the United States, water resources are so vast that despite increasing use, no limit was apparent until recently. Now unprecedented water demands in areas of intensive industrial development bring home forcibly the fact that more efficient development of water resources is essential. In many areas, undoubtedly including some in Michigan, regional planning based on exhaustive and detailed water facts will prove necessary. The increasing need for water in this area is illustrated by the experience of Pontiac where annual withdrawal by municipal and industrial wells has increased 3,500 percent since 1900 in contrast to a 750 percent increase of population or, water use has increased at an average rate nearly 5 times as great as the population trend.

Experience gained in the past half-century of low-cost development of our water resources may paradoxically deter progress in the solution of present water problems because it is responsible for the current philosophy of what might be termed a "cheaper than dirt" water economy. For example, the present cost of water delivered to the point of need at any time of the day or night ranges from 2 to 4 cents per ton in this area, as compared to the local cost of fill dirt which ranges from 1 to 2 dollars per ton. The very small cost for water develops a natural resistance to acceptance of the concept of higher water costs for a managed water economy. Nevertheless, in Michigan as well as elsewhere, it seems likely that in the future state and local agencies will be charged by the public with increasing responsibility in the development and management of water resources.

NEED FOR FURTHER HYBROLOGIC INFORMATION

The limited water-resources data now available for Oakland County presented a considerable handicap through the course of this investigation. Frequent reference has been made to deficiencies of information on the quantity and quality of the water resources of the area. The only systematic collection of basic water records now in progress are the water-level measurements in wells by a few municipalities and the cooperative federal-state program of water-level measurement in several wells; maintenance of several lake gages and stream-flow stations; and periodic collection of water samples from selected well installations.

Prerequisite to further development of the water resources of the area is a more adequate program for the continuing and systematic collection of basic water-resource data. The program should be coordinated to meet immediate and anticipated needs of all water users in the area; it should be integrated in appraisal of all phases of the hydrologic cycle, and should be patterned in accord with the regional hydrogeologic controls and the distribution of water use.

Compilation, study, and interpretation of a comprehensive countywide inventory of available geologic and hydrologic data would make possible the planning of a program of geophysical, and test-drilling exploration to identify and map the important aquifers. Adequate water-level and water-quality studies should be a part of the exploratory program and aquifer tests would be needed in selected areas.

Pilot areas selected for intensive studies of evapotranspiration discharge and overland runoff would serve as a basis for developing practical methods of salvaging part of these water losses. Significant differences in ground-water runoff and recharge from place to place throughout the county should be identified. Stream flow losses and gains should be determined and their significance appraised. The interrelation of lake stages, stream flow, and ground-water levels should be studied. The consumptive use of water by various types of cover vegetation on different soils should be determined. Water-use trends and distribution throughout the county should be studied in detail as a basis for predicting future patterns of use. Problems of well development and yield stability should be investigated.

SUMMARY OF RESULTS AND CONCLUSIONS

Within the nine township area, the principal aquifers are the surficial outwash and the buried outwash in the 100- to more than thickness of glacial drift which covers the area. The surficial outwash attains its greatest development in areal extent, thickness, and degree of connection with the deeper outwash deposits in the lake-dotted upland of sandy and gravelly outwash on the Commerce and Drayton gravel plains in West Bloomfield and Waterford townships. Elsewhere, it is thinner and developed only along glacial drainageways, many of which are occupied by streams. The buried outwash deposits are alluvial fills in preglacial and interglacial drainageways. Information concerning the nature and extent of the buried channels is limited to the urban areas where exploratory drilling for water-supply development has penetrated to considerable depth and has been intensive enough to reveal these deposits.

In Pontiac a buried channel of outwash underlies the city along an axis that parallels the general course of the Clinton River from southwest to northeast. More than 100 feet of permeable sands and gravels fill the basal part of the channel for an effective width of about 2 miles. From 80 to more than 100 feet of clay and some interstratified sand and gravel cap the buried outwash deposits and confine the ground water under artesian pressure, except where intensive development has dewatered the aquifer locally.

Intensive development of the buried-outwash aquifer by industrial and municipal wells in Pontiac and in adjoining townships has lowered ground-water levels more than 100 feet through a large part of the city and locally more than 130 feet below the stages reported early in the century. In the central part of the city, the large lowering of water level in the buried outwash has induced upward migration of sulfate-bearing waters from the underlying Coldwater shales. Progressive trends of sulfate and total hardness content of the water pumped from the buried outwash correlate with the progressive downtrend of artesian head, which in turn reflects the marked and continued uptrend of ground-water withdrawal in the area.

Analyses of pumping tests made in Pontiac indicate that the buried channel of outwash constitutes an aquifer of large permeability and transmissibility. The geologic and hydraulic evidence indicate that this buried-outwash aquifer extends westerly to merge with the thick outwash deposits of the lake-dotted uplands in Waterford and West Bloomfield townships. Many of the larger lakes are deep enough to intersect the earlier outwash deposits and evidence suggests that the alinement of the principal lake deeps may reveal the location of buried channels.

Withdrawals of ground water in Pontiac and adjoining townships averaged about 30 m.g.d. during 1952 and most of this quantity was pumped for public water supply. In the Pontiac area, many, if not most of the problems of water-level decline or decreasing well yield, are the outgrowth of mutual interference arising from the concentration of wells within the urban reach of the buried-channel aquifer.

In the Birmingham-Royal Oak area, the buried outwash deposits are the principal aquifer and, as in the Pontiac area the buried outwash is probably alluvial fill in preglacial and interglacial stream channels. Test drilling to considerable depth has been done in several, localized but intensively explored areas of municipal or industrial well development. However, information is not adequate to define the extent and pattern of the buried channels. The most dominant permeable feature is a broad belt of buried outwash which extends westerly from the southwest corner of Troy Township through Birmingham and into Bloomfield Township. Lesser aquifers of buried outwash are developed in Royal Oak and Berkley.

Intensive development by industrial and municipal wells, particularly in Troy Township, Royal Oak, Clawson, and Berkley has lowered ground-water levels more than 30 feet throughout a large part of the area and more than 100 feet in localized areas. Progressive uptrends of sodium, chloride content indicate that intensive development of the buried outwash has induced upward migration of saline waters from the underlying Bedford-Berea-Sunbury sequence and the Antrim shale.

The study of meager records of well performance and two brief pumping tests in the area indicate that in Birmingham and westward, the buried outwash is of large transmission capacity and of considerable width and thickness. In Royal Oak, Berkley, and Claws on, it is relatively thin, of smaller areal extent, and of smaller transmission capacity.

Withdrawals of ground water in the Birmingham-Royal Oak area averaged 10 m.g.d. in 1952. Most of this quantity was pumped from municipal wells. Local problems of water-level decline, decreasing well yield, and increasing mineralization of water are largely the result of mutual interference arising from concentration of well developments in small areas.

Analysis of the hydrology of the Clinton River watershed above Pontiac indicates that in the areas of highly permeable outwash, the effective average rate of annual ground-water recharge may be as much as 22 inches or about 75 percent of the average annual precipitation. Elsewhere, however, the rates of ground-water recharge are probably smaller. Most of the ground-water recharge is discharged by evapotranspiration from streamside and lakeside lands of shallow water table and from lake and stream surfaces. Evapotranspiration discharge is many times greater than the combined use of all ground-water developments in the nine township area. The annual discharge by overland storm runoff also exceeds the total industrial and municipal water use in the area.

Large and immediate increases in ground-water development could be realized by well installations in the areas of permeable outwash to the west of the urban areas, but competition of interests by other water users presents a problem -- one however. which is believed to be amenable to solution by proper planning. Substantial increases in ground-water use could be effected by more effective use and reuse of ground-water runoff now carried out of the area by stream flow. Locally, surficial outwash deposits present potential sources of water not now utilized. The water-resource potential of the area is many times greater than present or contemplated use, but regional quantitative appraisal of the resource is prerequisite to its effective development and management.

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System	Series	Formation	Lithology	Approximate thickness (feet)	Water-bearing properties
Quaternary	Recent and Pleistocene	Alluvium, glacial drift	Clay, silt, fine to coarse sand, gravel, and boulders.	20-350	Yield small to large supplies of water of generally good quality although relatively hard and are the source of water for most wells in the area.
Mississippian	Lower[/1] Mississippian	Coldwater shale	Predominantly gray, bluish-gray, and bluish shale and some green, purple, and red shale. Subordinate amounts of sandstone, siltstone, limestone, and dolomite.	0-400	Locally sandstone lenses yield small supplies of fresh water to wells.
		Sunbury shale	Brown to black shale.	0-50	Yield little or now water to wells. When water is encountered at appreciable depth it is highly mineralized.
		Berea sandstone	Predominantly gray massive fine-grained sandstone with interbedded hard blue-gray shale.	0-100	Generally yield small supplies of water, fresh to highly mineralized.
		Bedford shale	Soft, gray and blue-gray shale.	0-100	Yield little or now water to wells. Where water is encountered at appreciable depth it is highly mineralized.
Mississippian and Devonian	Lower Mississippian [/1] and Upper Devonian	Antrim shale	Black and brown carbonaceous shale.	70-170	Locally yield small supplies of water moderately to highly mineralized.

Table 5. Principal rock formations in southeastern Oakland County, Michigan and their water-bearing properties.

/1 Used by the Michigan Geological Survey as a formal series of the Mississippian system.

Well Number	Owner	Date	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium and Potassium (Na + K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Dissolved solids	Total Hardness (as $CaCO_3$)	Specific conductance in micromhos at 25° C	pH
Part A - Pontiac															
PT 2	Pontiac Dept. of Water Supply	Mar. - 1929	4.8	1.1	70	31	40	316[/1]	28	45	--	376	300	--	--

24	do.	Jan. – 1929	16	.9	77	30	28	372	8.2	45	--	380	315	--	7.3
24	do.	Jan. 4, 1952	13	--	67	28	29	373	16	17	.5	354	284	450	7.7
26	do.	June 17, 1926	12	--	68	27	23	358	13	24	--	340	--	--	--
26	do.	Jan. – 1929	11	.79	72	27	23	351	15	28	--	350	292	--	7.2
26	do.	Oct. 10, 1950	8	1.8	94	34	18	354	87	23	.5	460	372	--	--
26	do.	Jan. 4, 1952	12	.6	98	36	20	360	105	20	.5	492	394	605	7.5
28	do.	Jan. – 1929	7.2	.95	64	27	43	350	9.6	47	--	369	270	--	7.4
29	do.	do.	13	.86	73	28	28	368	11	31	--	362	295	--	7.3
29	do.	Jan. 4, 1952	14	2	116	39	15	385	140	15	.3	558	450	660	7.5
30	do.	Jan. – 1929	17	1.4	78	29	17	332	55	16	--	364	314	--	7.3
30	do.	May 19, 1952	11	1.6	98	27	20	340	90	14	.3	446	355	540	7.4
31	do.	Feb. 7, 1929	10	1.5	57	27	42	338	9.9	44	--	350	253	--	7.3
31	do.	May 19, 1952	13	1.3	80	34	34	428	37	23	.5	432	340	485	7.5
32	do.	July 3, 1941	9.2	.72	67	27	33	371	11	24	--	370	278	--	--
32	do.	Sept. 25, 1950	12	1.2	80	32	27	400	28	22	.6	400	330	--	--
34	do.	May 19, 1952	7.1	.95	48	29	25	317	23	9	.6	300	240	425	7.7
35	do.	do.	13	1	82	35	30	366	60	34	.5	456	350	600	7.6
38	do.	July 3, 1941	15	.92	75	32	25	371	22	32	--	387	320	--	--
38	do.	May 19, 1952	12	.6	80	33	34	381	45	34	.5	430	335	525	7.6
44	do.	Oct. 19, 1950	7.2	1	68	28	34	361	17	31	.5	372	280	--	--
48	do.	Feb. – 1928	tr.	.72	74	28	19	361	11	24	--	337	300	--	7.3
48	do.	Jan. – 1929	10	1.3	72	27	23	361	12	24	--	336	288	--	--
48	do.	July 15, 1941	12	1	64	30	25	334	29	20	--	342	280	--	--
49	do.	Sept. 26, 1950	8	1.3	79	29	27	367	40	22	.6	386	325	--	--
49	do.	May 19, 1952	13	1.4	82	33	26	386	50	19	.5	416	345	580	7.4
50	do.	Jan. 4, 1952	14	1	62	25	31	337	7.4	34	.6	336	258	460	7.7
160	Pontiac State Hospital	June 23, 1931	12	7.3	111	36	20	429	99	10	--	510	425	--	--
167	do.	Feb. 23, 1945	11	1.3	75	24	17	348	23	10	.5	356	285	--	--
167	do.	Mar. 17, 1953	13	1.2	80	24	19	339	40	15	.5	370	300	680	7.7
	Clinton River at Dawson Mill Pond	Feb. 18, 1928	--	--	46	17	4.6	190	24	5	--	176	185	--	--
		Part B – Berkley, Birmingham, Clawson, and Royal Oak													
BK 2	City of Berkley	Aug. 1, 1924	12	.48	31	19	123	323	tr.	110	--	461	--	--	--
2	do.	May 9, 1927	10	.63	42	21	101	315	4.8	105	--	447	190	--	--
4	do.	Aug. 24, 1929	11	tr.	39	21	92	316	4.6	86	--	408	180	--	--

7	do.	Mar. 16, 1944	13	.5	45	27	64	342	5.2	55	.8	378	224	--	--
8	do.	Feb. 10, 1948	7.2	.8	52	29	66	364	2.3	65	.8	396	248	--	--
BR 1	City of Birmingham	Apr. 9, 1926	24	3.2	65	25	77	333	6.2	107	--	473	264	--	--
2	do.	Nov. 16, 1938	14	1.0	66	24	19	326	2.3	25	--	306	263	--	--
2	do.	Jan. 9, 1947	10	1.2	64	24	23	332	2.6	23	.5	330	258	--	--
3	do.	Jan. 14, 1947	11	1.1	72	26	54	394	4.6	56	.5	430	288	--	--
4	do.	Nov. 16, 1938	7.2	2.1	74	24	12	352	4.6	11	--	300	283	--	--
4	do.	Jan. 14, 1947	8.8	1.2	65	24	20	332	2.8	20	.5	319	258	--	--
5	do.	do.	9.6	.9	65	23	35	334	1.3	42	.5	342	255	--	--
6	do.	do.	20	1.3	77	27	37	392	7.6	38	.4	418	305	--	--
6	do.	Oct. – 1947	15	1.7	78	27	37	395	10	37	--	406	308	--	--
68	do.	Nov. 16, 1938	9.6	.3	31	18	670	392	3.3	900	--	1,824	151	--	--
Composite	City of Birmingham	Oct. 9, 1923	20	5.2	75	27	33	349	25	41	--	387	--	--	--
do.	do.	Apr. 5, 1927	15	tr.	78	26	45	351	38	51	--	404	298	--	--
CW 4	City of Clawson	Apr. 10, 1924	18	.9	44	23	108	332	2.0	116	--	463	--	--	--
5	do.	May 1, 1936	8.8	.23	44	23	172	289	1.6	240	--	638	200	--	--
RO 7	City of Royal Oak	Dec. 20, 1923	14	tr.	28	16	245	251	6.8	332	--	740	--	--	--
8	do.	May 10, 1926	13	--	29	14	283	274	5.0	365	--	846	128	--	--
8	do.	July 17, 1930	9.6	tr.	16	5.6	172	286	2.6	140	--	474	60	--	--
8	do.	Sept. 23, 1936	12	.3	23	11	250	280	4.6	290	--	736	100	--	--
11	do.	Sept. 23, 1936	13.6	.7	64	26	96	366	2.6	120	--	500	262	--	--
11	do.	July 6, 1942	6.8	.8	60	24	76	355	7.2	80	--	437	250	--	--
20	do.	July 6, 1942	7.6	tr.	8	3.4	150	288	3.7	80	--	402	34	--	--
Part C – Remainder of southeast Oakland County area															
BH 2	Cranbrook School	Apr. 28, 1953	8	2.0	112	30	13	317	142	20	--	532	405	750	7.4
OL 14	St. Mary's College and Seminary	do.	12	1.0	40	13	10	217	3	2	.2	186	155	400	7.8
Composite	Village of Rochester	Jan. 26, 1923	18	2.0	84	27	10	378	20	8	--	340	--	--	--
	do.	Apr. 16, 1928	12	.68	83	27	13	370	22	14	--	310	318	--	--
BF 5	Bloomfield Village	Oct. 3, 1945	8.8	1.1	68	23	23	342	7.6	18	.5	323	264	--	--
Fa 72	Franklin Hills Country Club	Apr. 28, 1953	14	1.15	70	26	33	361	6.6	40	.2	380	280	700	7.7
73	Sarah Fisher Children Home	do.	13	1.8	80	30	57	388	15	86	.2	490	325	850	7.6
So 73	Lancaster Hills Country Club	do.	14	1.6	68	29	20	345	21	24	.3	396	290	670	7.5
Tr 3	City of Clawson	Sept. 12, 1945	11	1	78	27	107	390	6.6	150	.55	570	305	--	--
12	Troy Township	Jan. – 1947	8.8	1.4	68	28	70	342	8.2	105	.7	460	285	--	--

13	do.	do.	7.2	--	65	25	21	345	6	15	.45	326	262	--	--
259	Sylvan Glen Golf Club	Apr. 28, 1953	12	.9	36	28	90	323	2	100	.8	434	205	810	7.8
Wt 7	Waterford Township	Mar. 17, 1953	14	1	64	29	37	358	8	45	.5	386	280	730	7.7
17	do.	Jan. – 1948	7.2	1.6	75	35	13	405	15	7	.8	360	330	--	--
41	Oakland County Infirmary	Mar. 17, 1953	14	1.1	70	26	18	348	17	10	1	352	280	640	7.6
44	do.	do.	14	1.6	80	30	17	349	63	7	1.1	426	325	680	7.5
45	Waterford Township	do.	13	2.	70	22	10	323	15	7	.4	296	265	550	7.7
Composite	Oakland County TB Sanitarium	do.	13	2.2	108	33	24	345	35	100	.1	574	405	900	7.4
Wb 4	Knollwood Country Club	Apr. 28, 1953	13	.5	52	27	45	356	3	32	.4	350	235	660	7.7

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

/1 CO_3 = 23 p.p.m.

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

20	do.	Mar. 3, 1945	--	--	115	
20	do.	Aug. 17, 1945	103	--	--	
20	do.	Jan. 29, 1948	110	--	120	
20	do.	July 7, 1948	120	--	165	
20	do.	Jan. 24, 1949	--	--	145	
22	do.	Jan. 23, 1951	170	--	155	
25	do.	Jan. 10, 1951	95	--	170	
27	do.	Dec. 30, 1949	925	--	270	
36	do.	May 22, 1950	110	--	190	
55	do.	May 22, 1950	320	--	135	
Av 58	Gulf Service Station	Jan. 19, 1952	124	40	632	Calcium 162. Magnesium 55.
Bf 29	J. R. Davis	Jan. 21, 1952	14	28	316	Calcium 75. Magnesium 31.
Sodon Lake		Feb. 3, 1949	--	40	--	
do.		do.	--	20	--	
do.		do.	--	44	--	
do.		do.	--	40	--	
do.		Apr. – 1949	--	16	--	
do.		do.	--	38	--	
Fa 71	Gulf Oil Company	Jan. 21, 1952	58	6	316	Calcium 78. Magnesium 29.
So 70	do.	do.	6	40	160	Calcium 40. Magnesium 15.
71	H. Huetter	Jan. 22, 1952	158	40	368	Calcium 99. Magnesium 29.
Tr 4	City of Clawson	Feb. 14, 1950	90	--	300	
151	Mrs. Pretzhow	Jan. 21, 1952	252	2	272	Calcium 59. Magnesium 30.
Wt 59	Richardson Farm Dairy	Jan. 19, 1952	6	38	244	Calcium 59. Magnesium 23.

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