PROGRESS REPORT NUMBER SIXTEEN

# STATE OF MICHIGAN

## DEPARTMENT OF CONSERVATION
GERALD E. EDDY, DIRECTOR

## GEOLOGICAL SURVEY DIVISION
W. L. DAOUST, STATE GEOLOGIST

# GROUND WATER RESOURCES OF SOUTHEASTERN OAKLAND COUNTY, MICHIGAN

BY

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G. J. STRAMEL AND E. G. CROSTHWAITE,
U. S. GEOLOGICAL SURVEY



PREPARED IN COOPERATION WITH THE
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
1954

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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 1,000 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 area; 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 1900, 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.

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

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 Bloomfield |
| Pontiac | |
| 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.

## 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 attendent 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

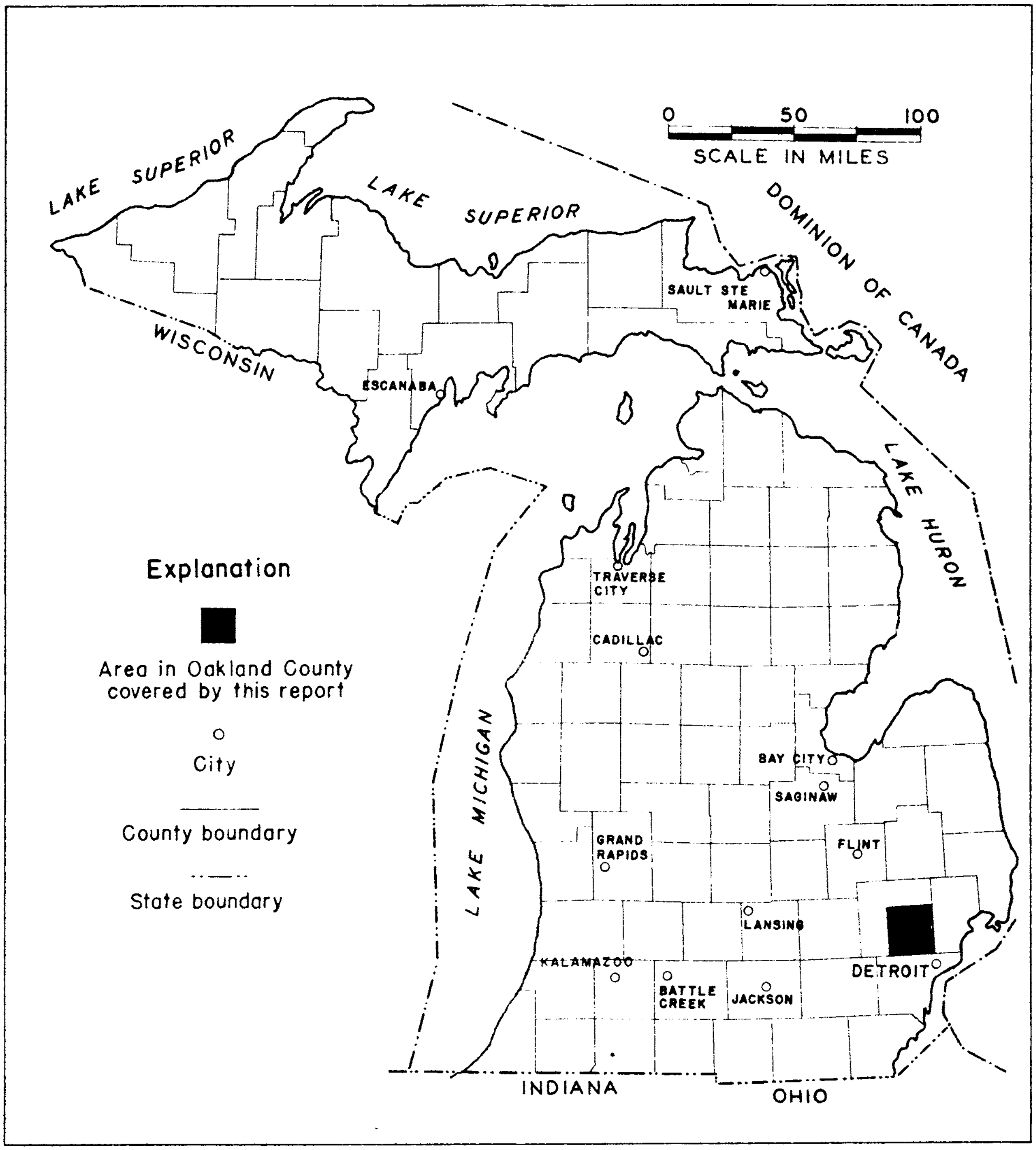



Figure 1. Index map of Michigan showing location of southeastern Oakland County.

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.

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 Cranbrook 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.

Table 1. - Letter code used as prefix to well numbers in townships, cities, and villages of southeastern Oakland 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 |

A map showing the relative position and the boundaries of these townships and communities is shown by figure 2.

Throughout this report on illustrations that show specific boundaries and the names of the civil townships, cities, or villages, the prefix letters are ommitted 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.

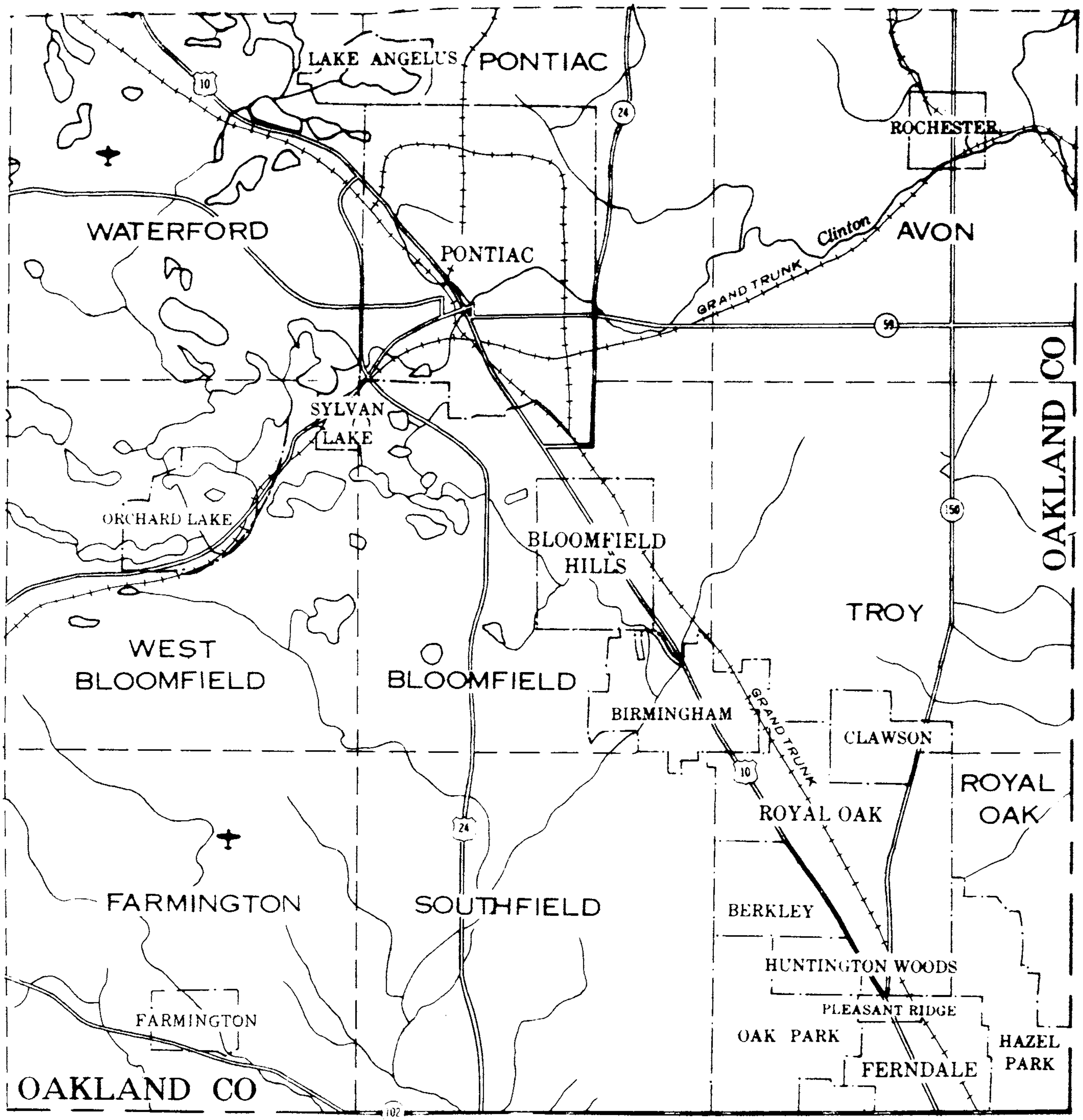



Figure 2. Map showing the location of townships and cities in southeastern Oakland County, Mich.

## 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.

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

| 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 | 57.2 |
| Southeastern Oakland County | 220,532 | 341,042 | 55 |

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.

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

| Township | Rural 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 |

Highways

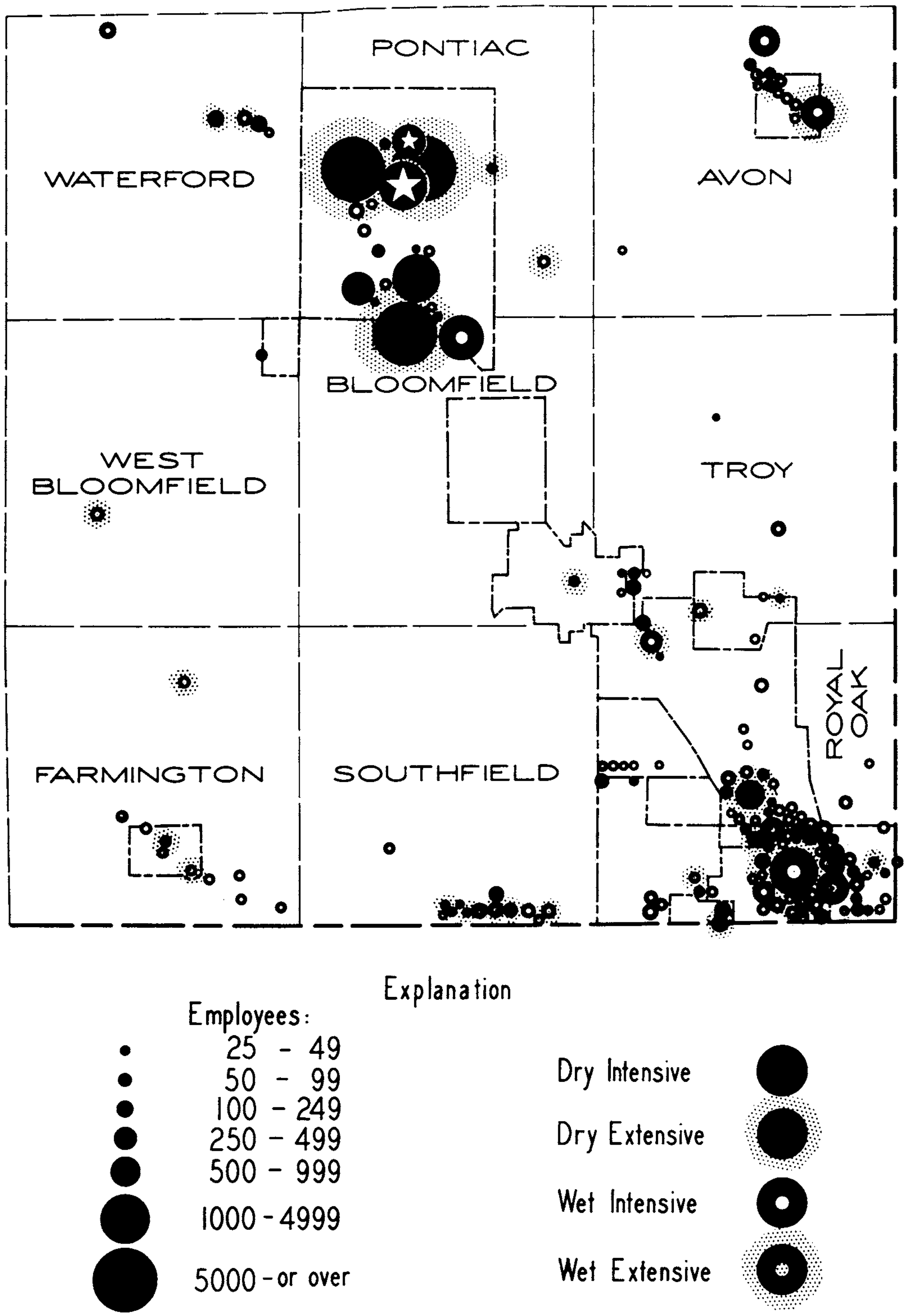
The principal federal highways traversing the area are U. S. Highway 10 which coincides with Woodward Avenue of Detroit and diagonally bisects this area, and U. S. Highway 16 which coincides with Grand River Avenue of Detroit and crosses the southwest corner of this area. U. S. Highway 10 connects Detroit 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 Run airport as is downtown Detroit.

/1 By Detroit Metropolitan Area Regional Planning Commission




New plants under construction or contracted for are shown with a star, and the size of the circle indicates an estimate of probable employment. Industries needing considerable space for processing or having a low ratio of workers per acre are called extensive. Industries that need only a small area or employ 50 to 100 men per acre are called intensive. Industries using water for processing, cooling, or incorporated in the product are called wet, all others are dry.

Data furnished by Detroit Metropolitan Area Region Planning Commission.

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

# 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.

## 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.

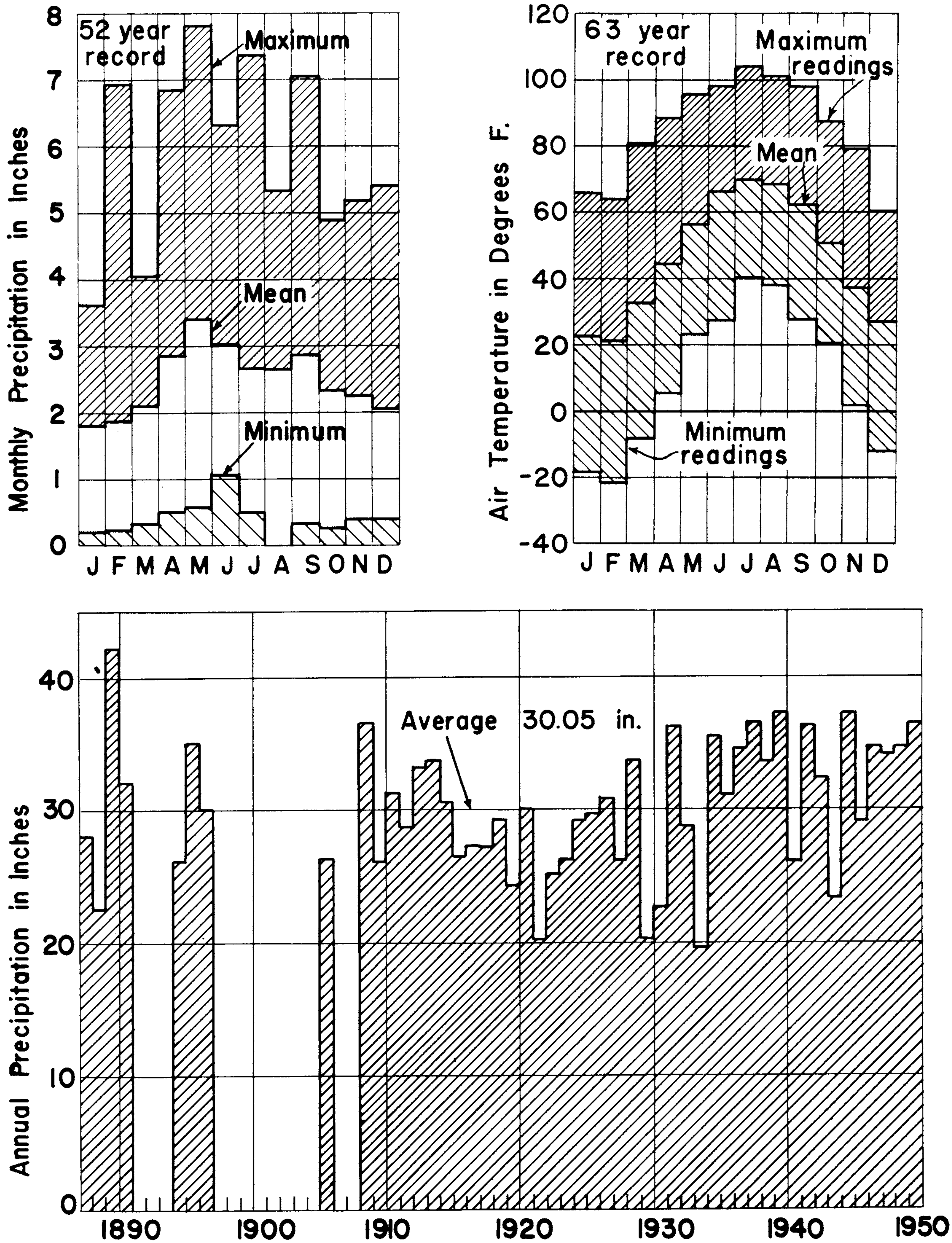



Figure 4. Precipitation and temperature at Pontiac, Mich.

### 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, 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.

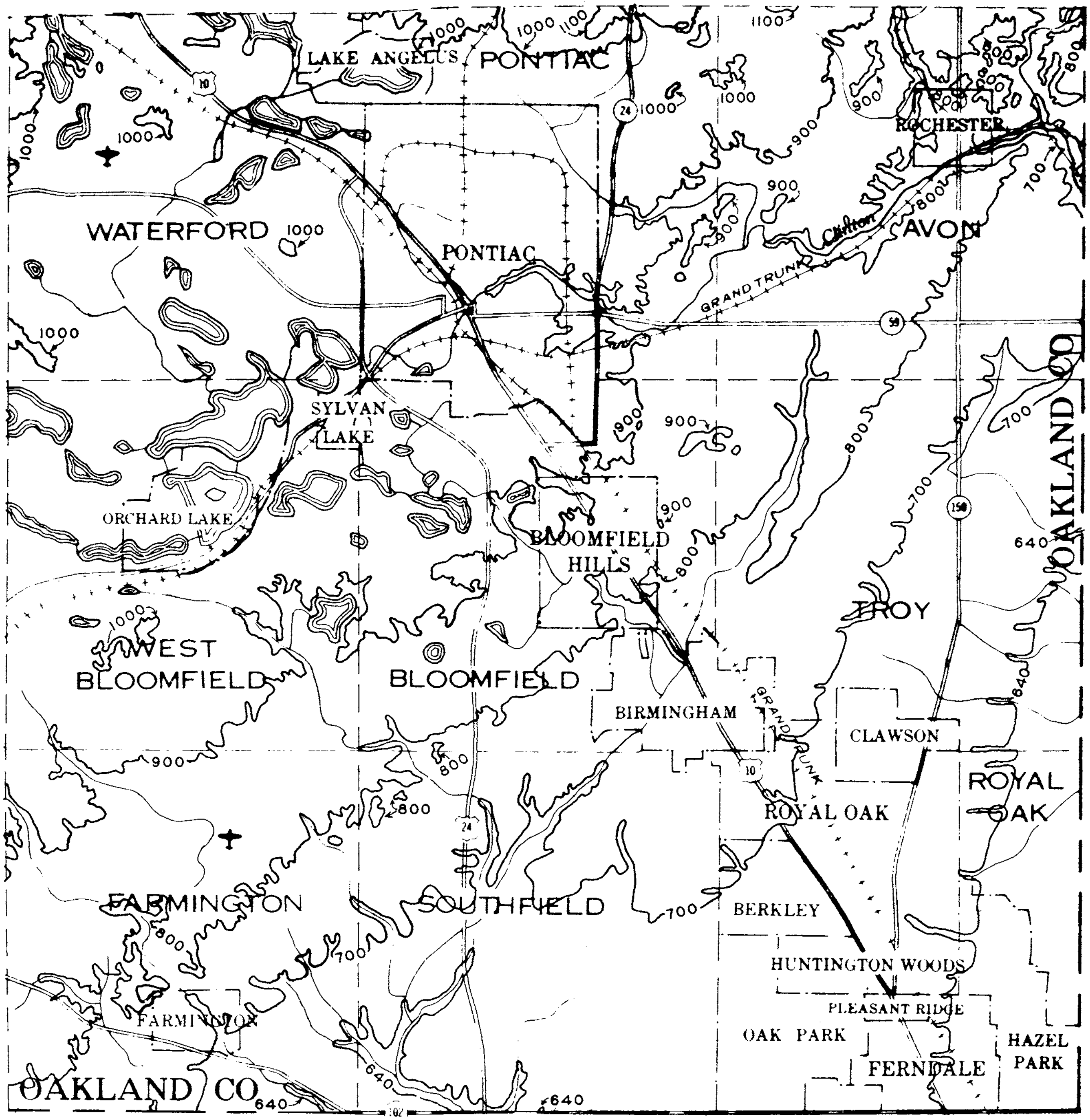
### Drainage

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).

Table 4. - Evaporation at East Lansing, Michigan

| Month | Evaporation in inches | | | | |
|---|---|---|---|---|---|
| | 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 |

/1 Observed in frost-free months only.




Contour interval 100 feet, except for the 640-foot line.

Compiled from the Detroit, Pontiac Rochester and Wayne quadrangle maps of the U S Geological Survey.

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

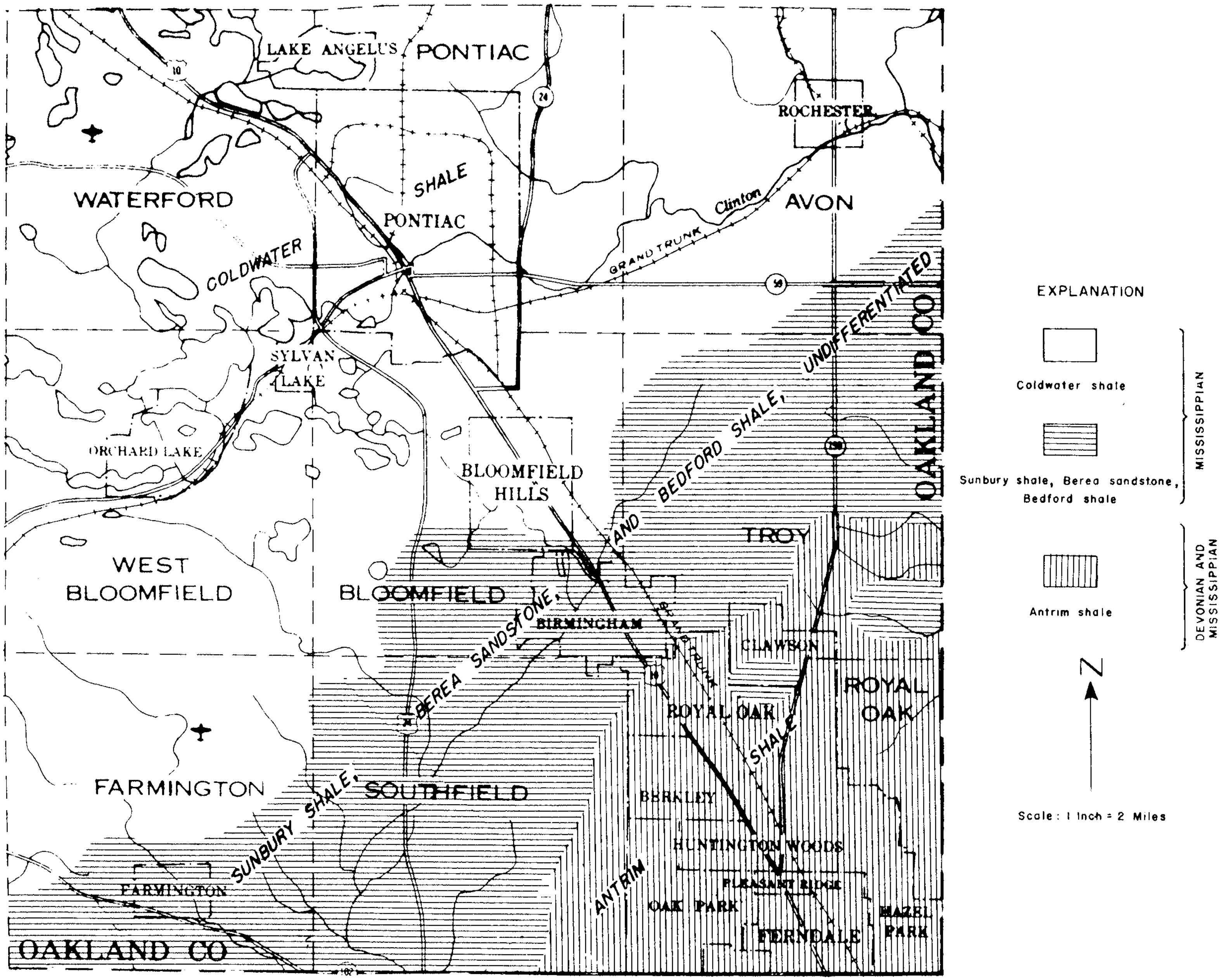



Figure 6. Geologic map of southeastern Oakland County showing areal extent of the bedrock formations.

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.

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.

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

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

| 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 no 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 no 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. |

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

## Devonian and Mississippian systems

### Antrim shale

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 Sporangites huronensis, 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.

### Bedford shale, Berea sandstone, and Sunbury shale

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.

Coldwater shale

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.

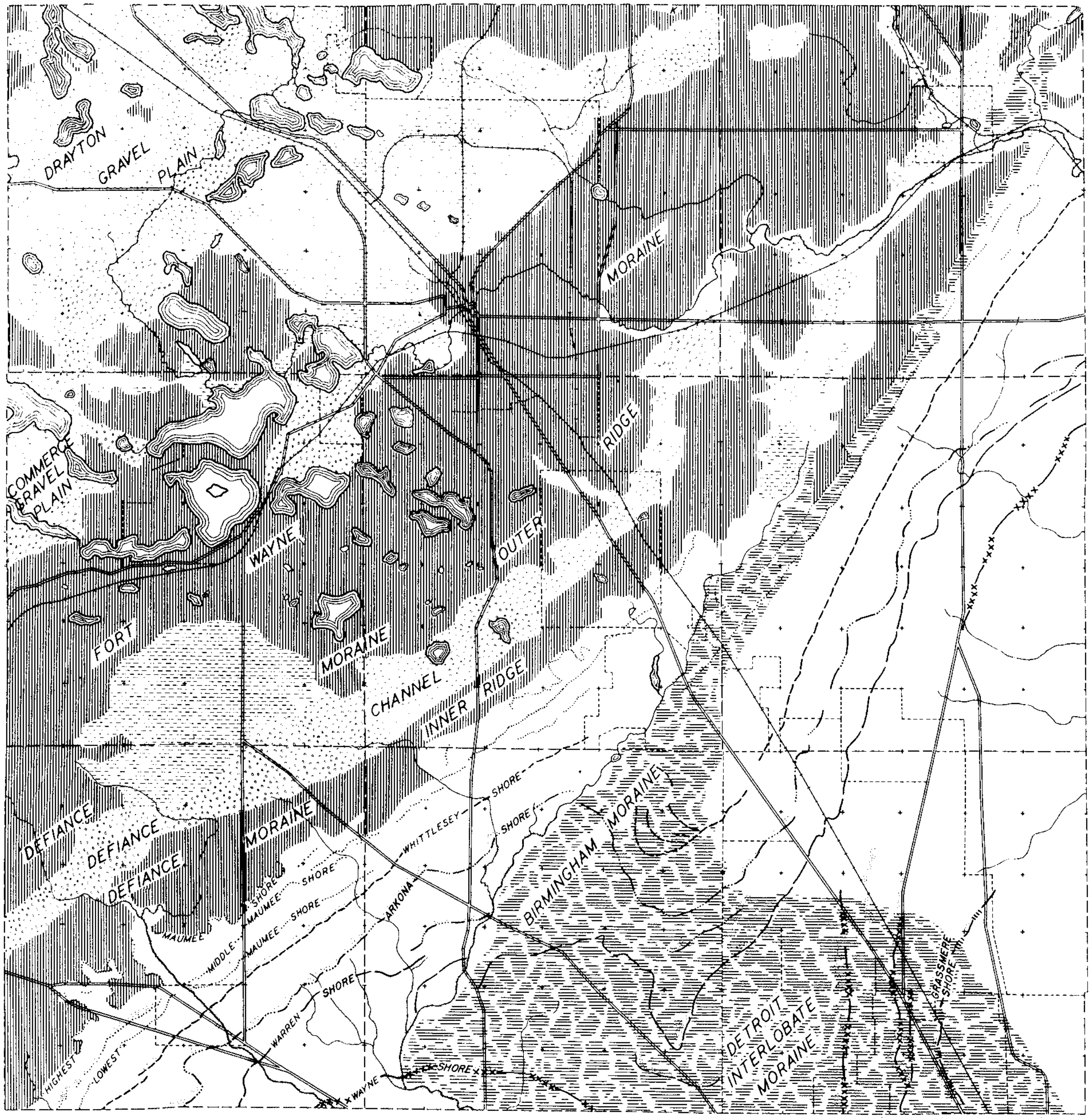
The glacial features of the Southern Peninsula were developed during the Wisconsin stage and are related to three ice lobes which coalesced to form a continental ice sheet at the time of maximum ice extent, but which were more or less distinct during the advance and retreat of the Wisconsin glacier. 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.




Geology compiled from maps and reports of S. G. Bergquist, Frank Leverett, and Helen M. Martin

## EXPLANATION

**QUATERNARY**

*Recent*

ALLUVIUM AND TERRACE DEPOSITS

Silt and gravel deposited by the present streams on their narrow flood plains. Yield small water supplies. Induced infiltration from rivers possible in local areas yielding moderate to large supplies.

*Pleistocene, Wisconsin stage*

WATER-LAID, LAND-LAID RECESSIONAL MORAINE DEPOSITS

Till, generally stony or sandy clay, with interbedded sand or gravel layers in places. Deposited as hills or ridges at the edges of the glacier. Water-laid deposits have been reworked in part. Yield water supplies for domestic use. Moderate supplies of water may be developed from interbedded sand and gravel.

GROUND MORAINE

Admixtures of clay, sand, and gravel. Locally, thin buried beds of sand and gravel. Yield water supplies for domestic use.

OUTWASH

Deposits of highly permeable sand and gravel of variable thickness. Yield small to large water supplies.

K KAME

Permeable sand and gravel deposited as hills and ridges at the edges of the glacier. Where saturated yield large supplies of water, but commonly lie above water table.

LAKE-BED DEPOSITS

Beach, terrace and delta sands yield small to moderate supplies of water. Lake clay deposits may yield small water supplies from interbedded sand and gravel.

BEACH RIDGES

Sand ridges associated with shorelines of the glacial lakes.

SHORELINES OF THE GLACIAL LAKES

MAUMEE

WHITTLESEY

ARKONA

WARREN

WAYNE

GRASSMERE

N

SCALE

0 2 Miles

PLATE I. MAP OF THE SURFACE GEOLOGY OF SOUTHEASTERN OAKLAND COUNTY, MICHIGAN

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.

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 formation, 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 meltwaters 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.

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

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).

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.

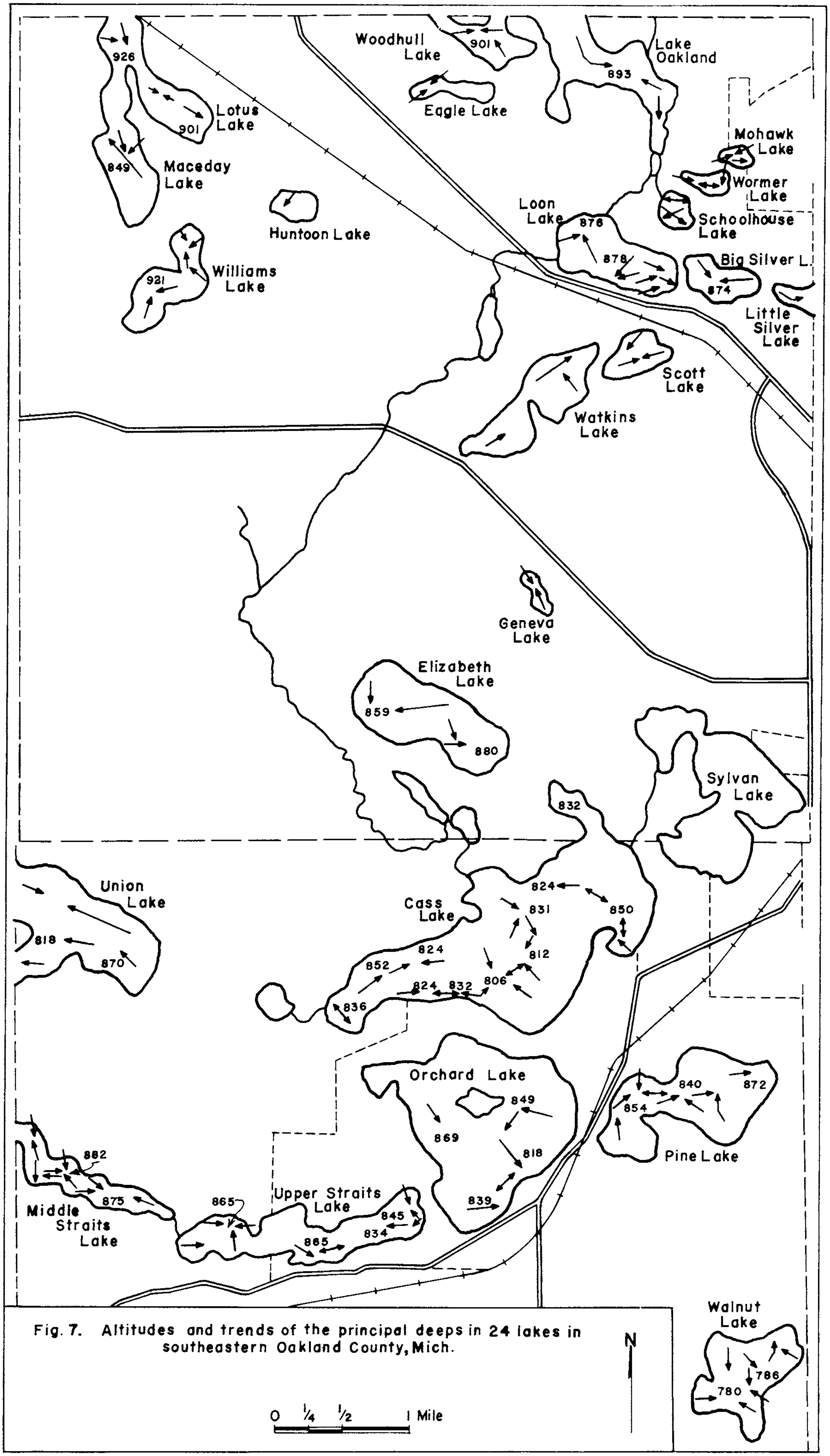



Fig. 7. Altitudes and trends of the principal deeps in 24 lakes in southeastern Oakland County, Mich.

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 meltwater 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.

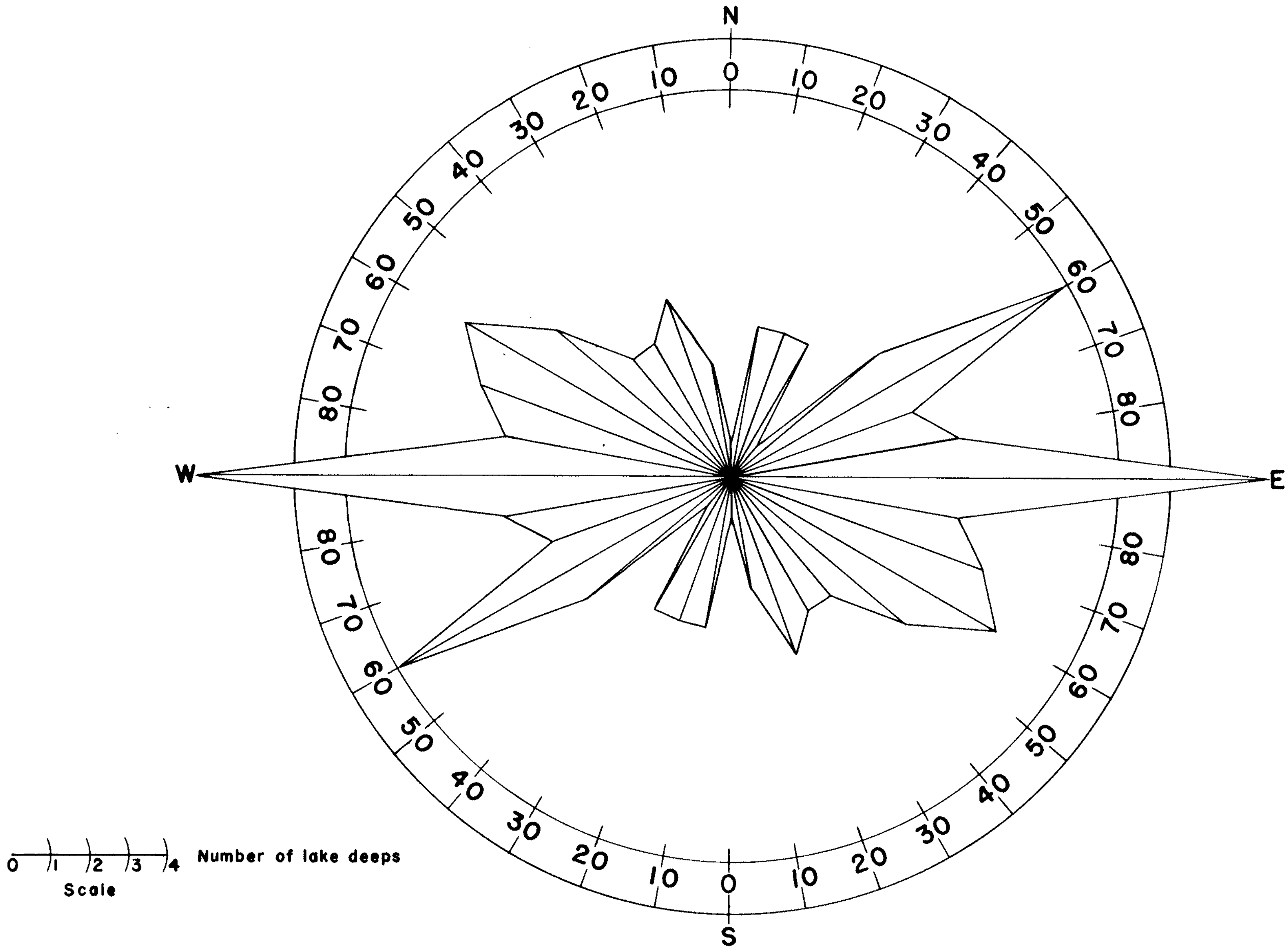



Figure 8. Diagram showing the number of occurrences and direction of lake deeps in 24 lakes in southeastern Oakland County, Mich.

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 post-glacial 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. 1935, pp. 1173-1191). 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

### Till

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.

Outwash

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. Ground-water 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 surface. 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

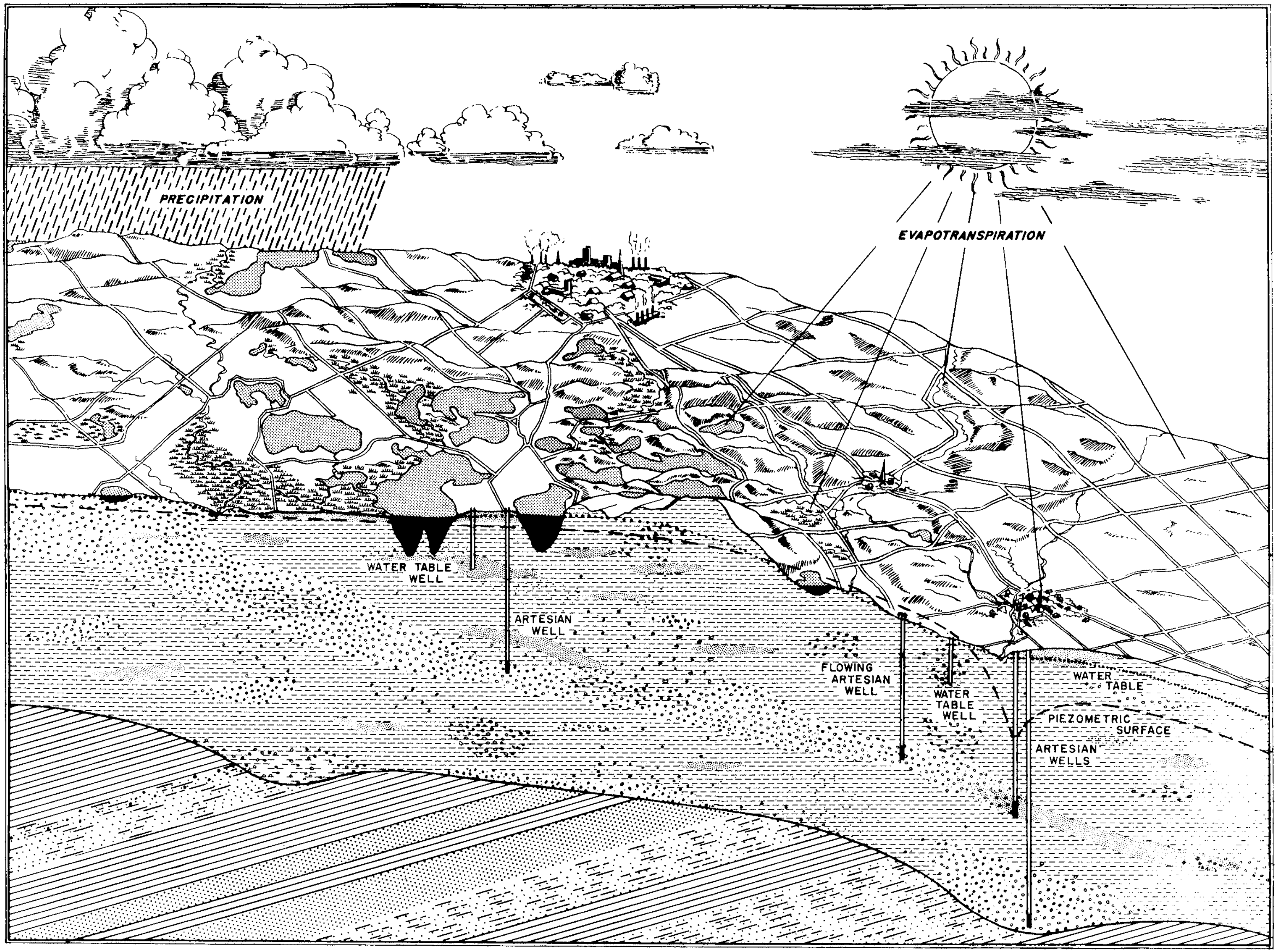



PLATE 2. THE HYDROLOGIC CYCLE ADAPTED TO OAKLAND COUNTY, MICHIGAN.

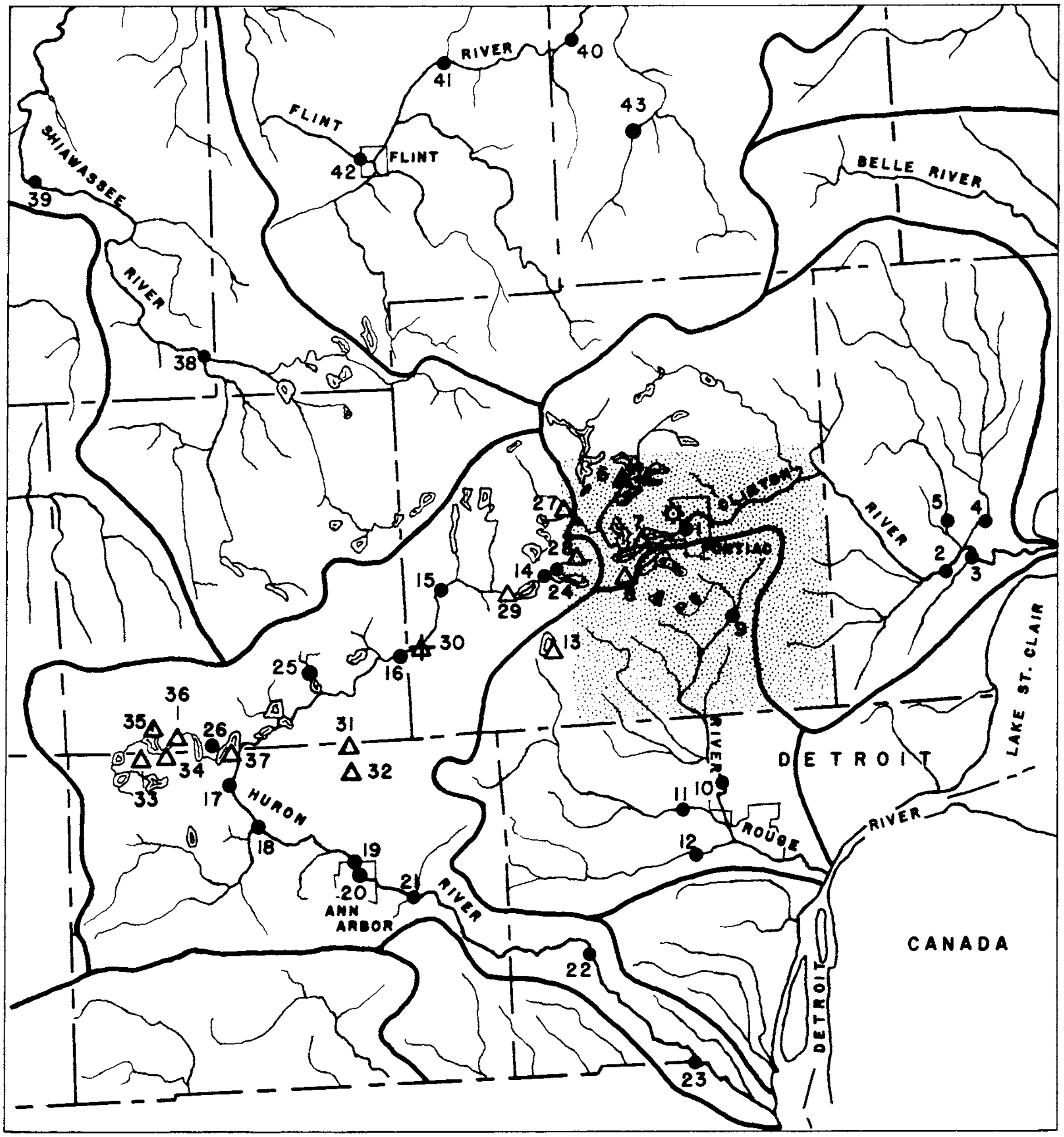
surface to the water table are sufficiently short, evaporation will continue depletion until the water level in the underground reservoir is lowered beyond the effective reach of these evaporating systems. In graphic form the hydrologic cycle is illustrated by plate 2, with adaptation to a generalized geologic section through the area of this report.

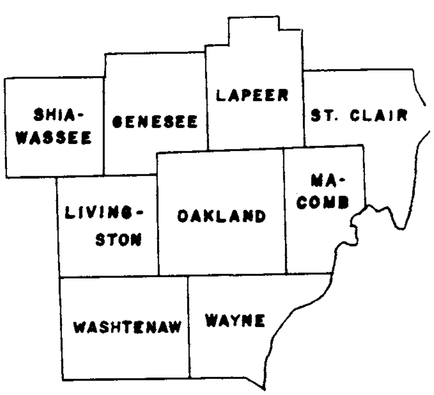
Within the ground-water reservoir, water moves very slowly owing to the great friction in percolating through the maze of minute interstices between the rock particles. Generally, rates of ground-water movement may range from a few feet per year to as much as several feet per day. The water may travel 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




EXPLANATION

Area of report

● River gage

△ Lake gage - non-recording

Lake gage - recording

U.S. Weather Bureau station

For key to numbers see figure 10

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

winter when air temperatures are considerably lower than the annual average, ground water could be used as a heating medium, as in some areas, 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).

### Clinton River

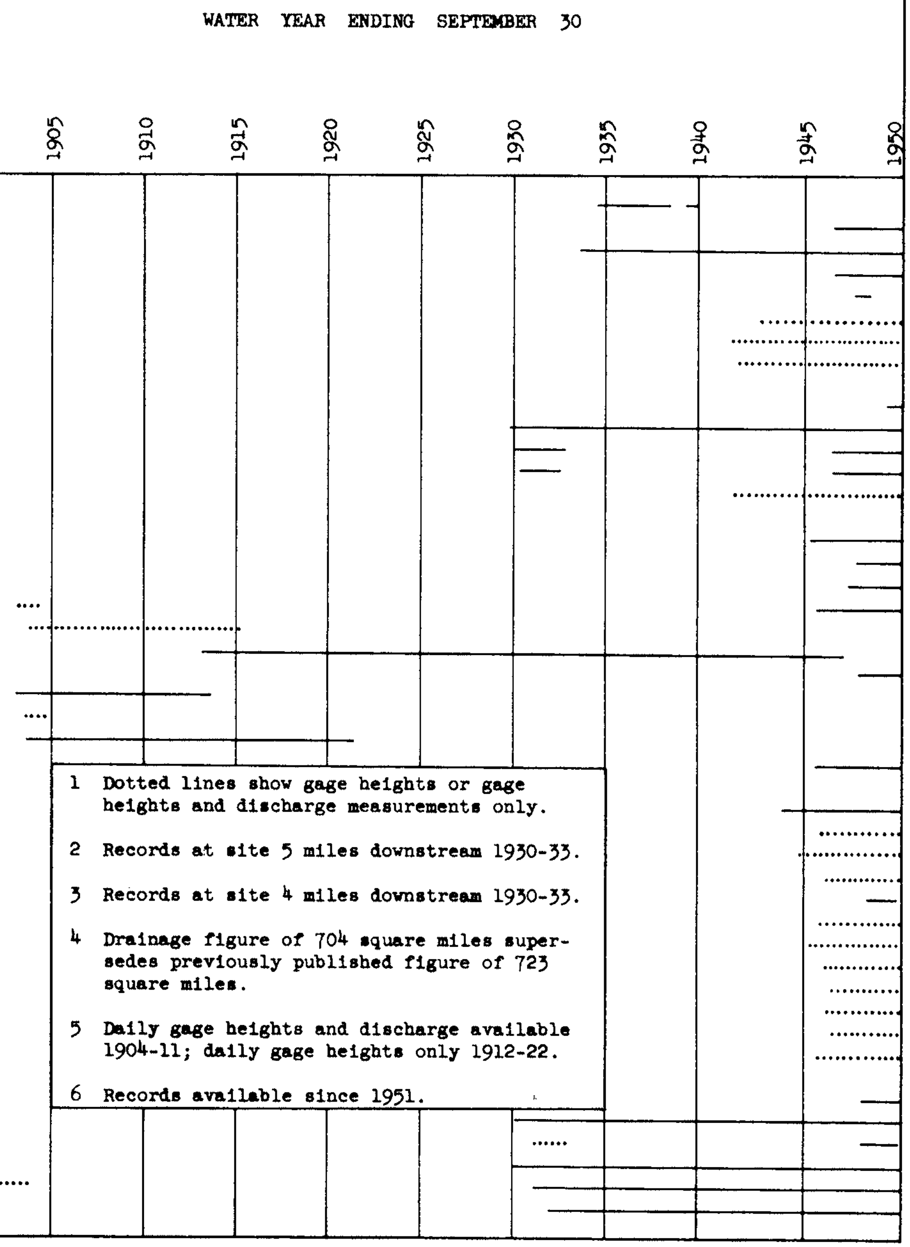
The Clinton River rises in Upper Bushman Lake in Independence Township, about 8 miles northwest of Pontiac. It enters the area of this report near Waterford and winds southward through a chain of lakes to Cass Lake. Beyond Cass Lake it flows northeast through Pontiac and Rochester and leaves the area 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.

| INDEX NO. ON FIG. 9 | GAGING STATION | DRAINAGE AREA IN SQUARE MILES |
|---|---|---|
| 1 | Clinton River at Pontiac, Mich. | 123 |
| 2 | " " near Fraser, Mich. | 454 |
| 3 | " " at Mt. Clemens, Mich. | 733 |
| 4 | N. Branch Clinton River near Mt. Clemens, Mich. | 185 |
| 5 | M. Branch " " " " " " | 51 |
| 6 | Loon Lake at Drayton Plains, Mich.[1] | |
| 7 | Cass Lake at Keego Harbor, Mich. | |
| 8 | Orchard Lake near Orchard Lake, Mich. | |
| 9 | River Rouge at Birmingham, Mich. | 33 |
| 10 | " " " Detroit, Mich. | 193 |
| 11 | M. River Rouge near Garden City, Mich.[2] | 89 |
| 12 | L. " " at Inkster, Mich.[3] | 90 |
| 13 | Walled Lake near Walled Lake, Mich. | |
| 14 | Huron River at Commerce, Mich. | 51 |
| 15 | " " " Milford, Mich. | 125 |
| 16 | " " near New Hudson, Mich. | 143 |
| 17 | " " " Dexter, (at Dover) Mich. | 506 |
| 18 | " " at Dexter, Mich. | 663 |
| 19 | " " " Barton, " | 704[4] |
| 20 | " " " Ann Arbor, Mich. | 711 |
| 21 | " " " Geddes, Mich. | 737 |
| 22 | " " " French Landing, Mich. | 813 |
| 23 | " " " Flat Rock, Mich.[5] | 851 |
| 24 | Hayes Creek at Commerce, Mich. | 7.5 |
| 25 | Ore Creek near Brighton, Mich.[6] | 30 |
| 26 | Portage Creek near Pinckney, Mich. | 79 |
| 27 | Pontiac Lake near Drayton Plains, Mich. | |
| 28 | Union Lake near Commerce, Mich. | |
| 29 | Proud " " " " | |
| 30 | Kent " " New Hudson, Mich. | |
| 31 | Whitmore Lake at Whitmore Lake, Mich. | |
| 32 | Horseshoe Lake near Whitmore Lake, Mich. | |
| 33 | Bruin Lake near Gregory, Mich. | |
| 34 | Blind " " " " | |
| 35 | Patterson Lake near Pinckney, Mich. | |
| 36 | Hiland Lake near Pinckney, Mich. | |
| 37 | Portage " " " " | |
| 38 | Shiawassee River (Head of Saginaw River) at Byron, Mich. | 368 |
| 39 | " " at Owosso, Mich. | 538 |
| 40 | Flint River at Columbiaville, Mich. | 486 |
| 41 | " " " Genesee, Mich. | 593 |
| 42 | " " " Flint, Mich. | 927 |
| 43 | Farmers Creek near Lapeer, Mich. | 57 |




1 Dotted lines show gage heights or gage heights and discharge measurements only.

2 Records at site 5 miles downstream 1930-33.

3 Records at site 4 miles downstream 1930-33.

4 Drainage figure of 704 square miles supersedes previously published figure of 723 square miles.

5 Daily gage heights and discharge available 1904-11; daily gage heights only 1912-22.

6 Records available since 1951.

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

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.

## 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.

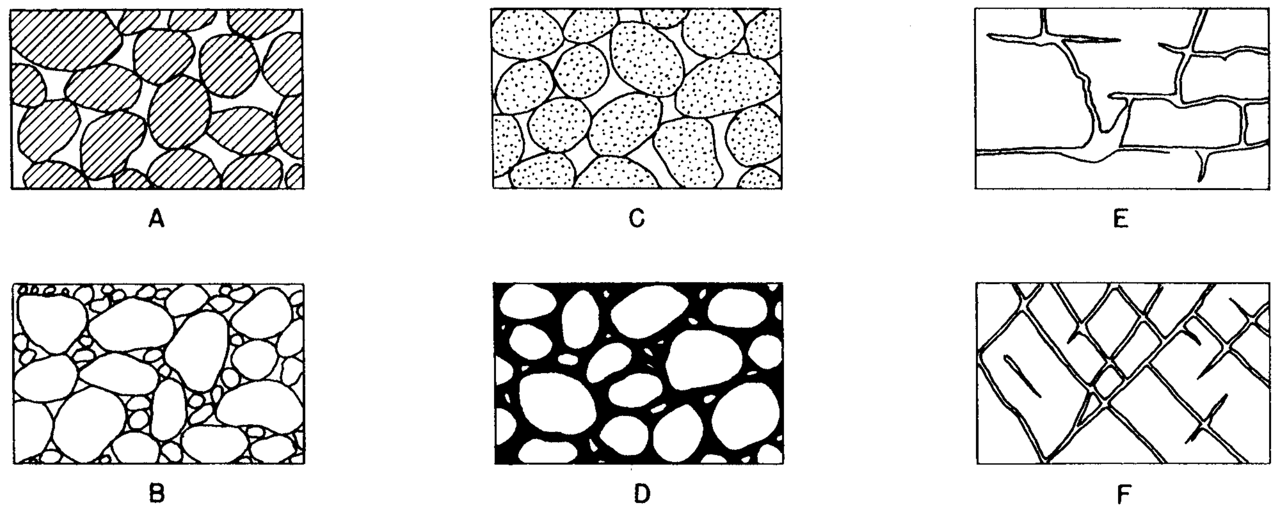



Figure 11. Diagram showing several types of rock interstices and the relation of rock texture to porosity. A, Well-sorted sedimentary deposit having high porosity; B, poorly sorted sedimentary deposit having low porosity; C, well-sorted sedimentary deposit consisting of pebbles that are themselves porous, 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)

## 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.

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 flowing, 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 impedence 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

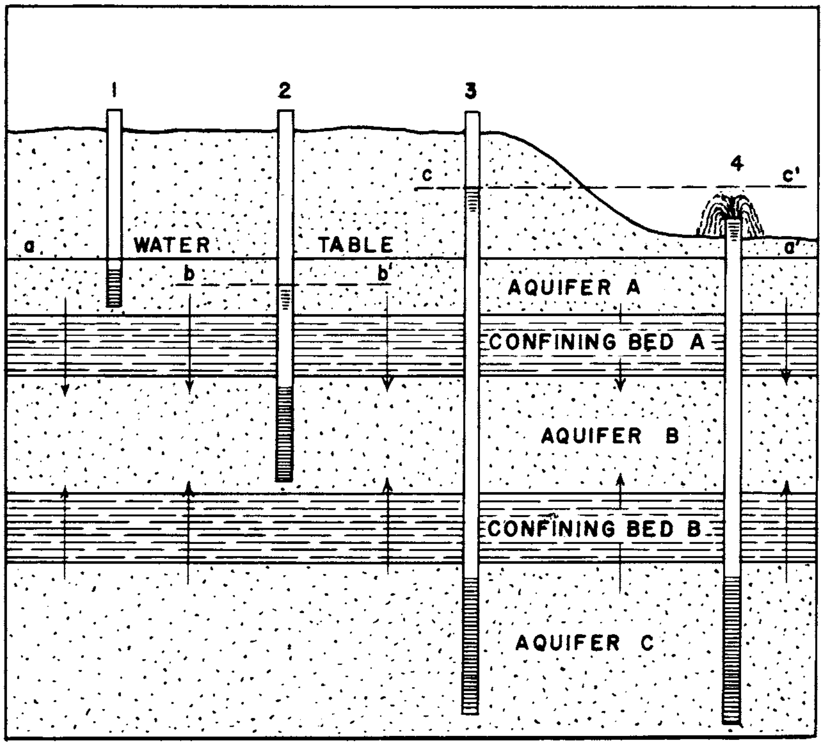



Figure 12. Section showing hydrogeologic conditions for water-table and artesian aquifers. a–a' is the water table in aquifer A and well 1 is a water table well. b–b' is the piezometric surface in aquifer B and well 2 is an artesian well. c–c' is the piezometric surface in aquifer C and wells 3 and 4 are artesian wells. Well 4 is in an area of artesian flow. The arrows indicate the direction of cross-bed leakage.

to a degree that includes more than the specific yield which pertains only to the material drained. The storage coefficient includes also the small 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.

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

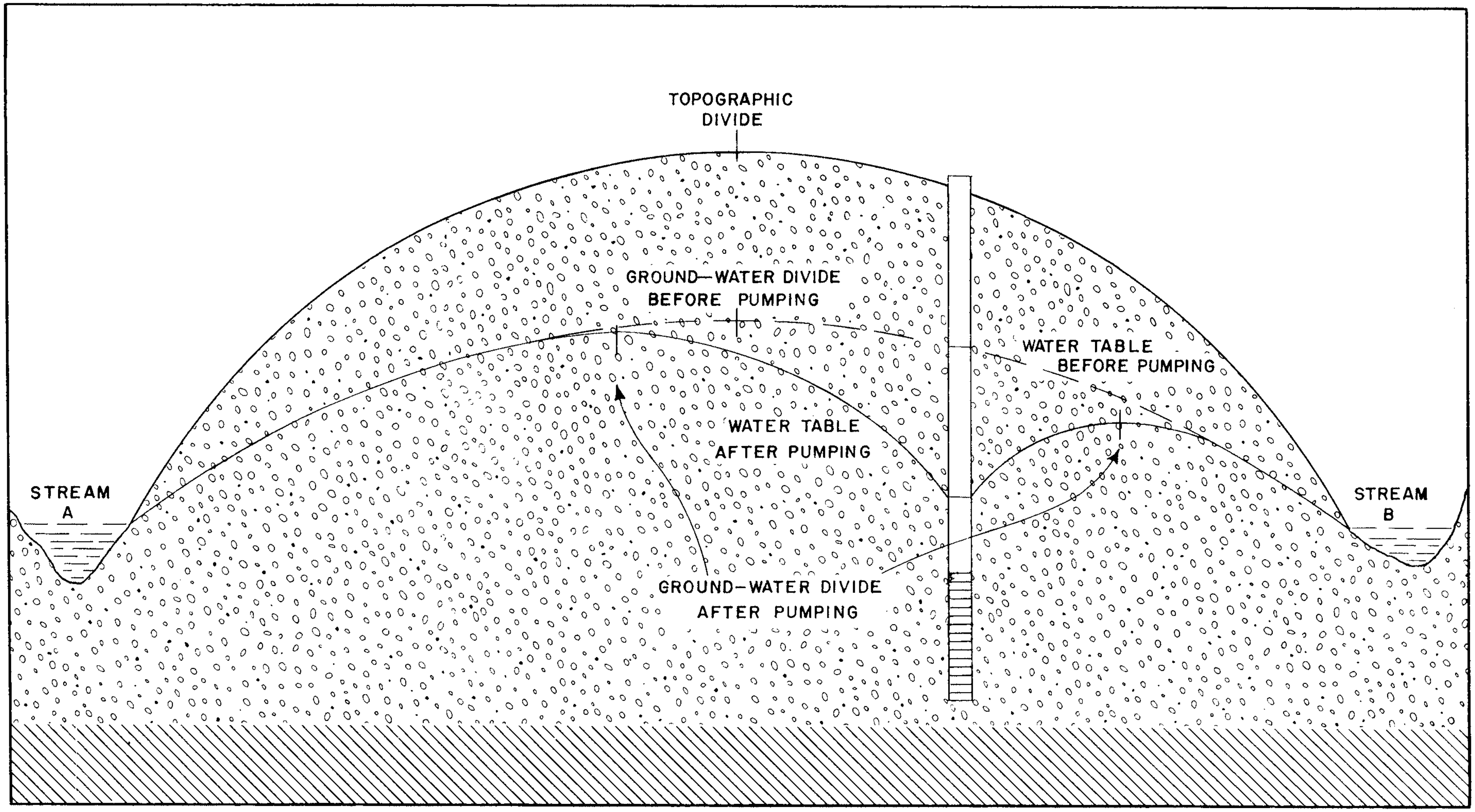



Figure 13. Generalized section showing the shift in the drainage divide as a result of pumping.

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.

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 pump water from greatly increased depths. This type of pumping equipment was once widely used, but

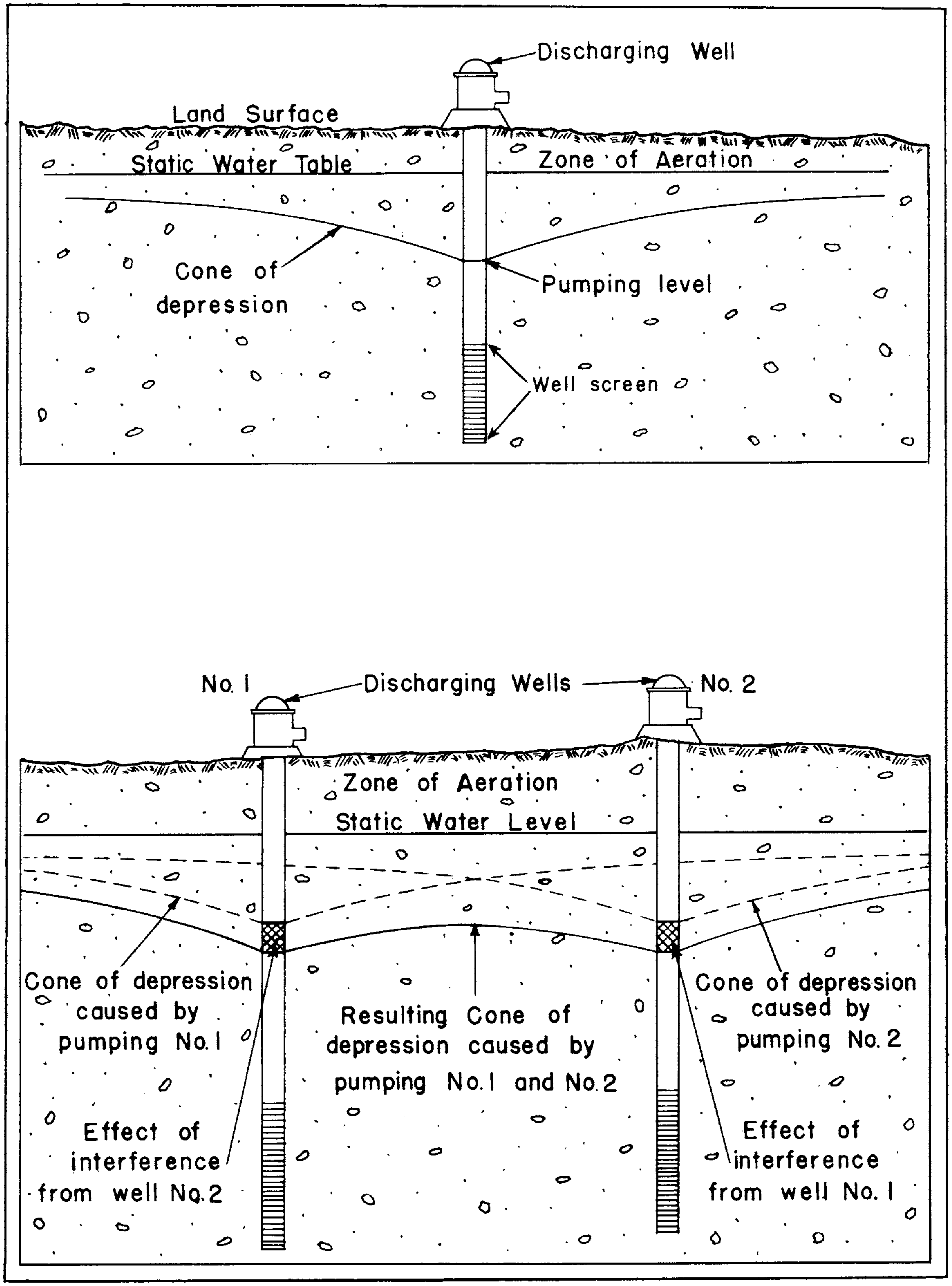



Figure 14. Mutual interference between wells

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.

Pumping test methods

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.

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

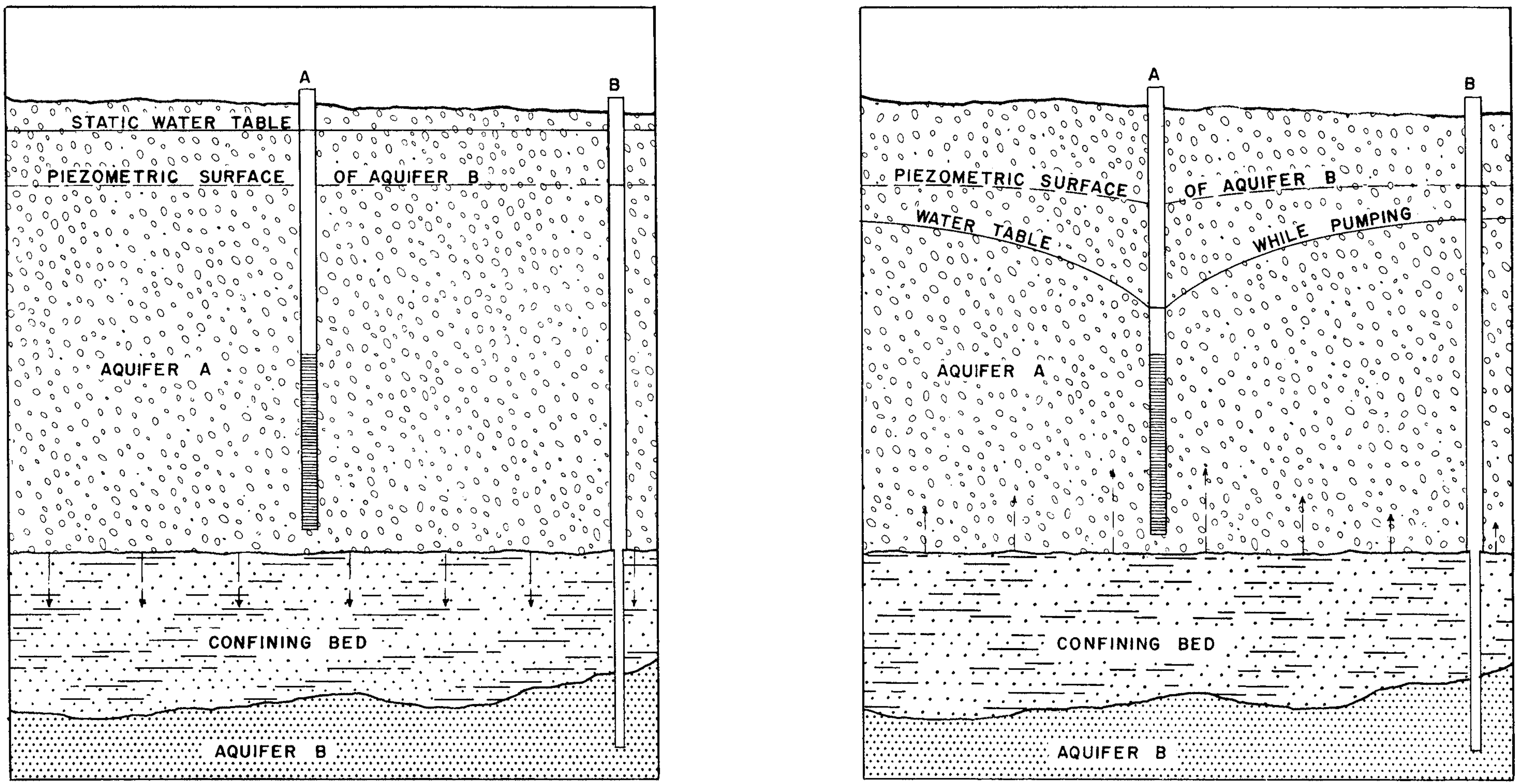



Figure 15. Interformational leakage reversed by pumping.

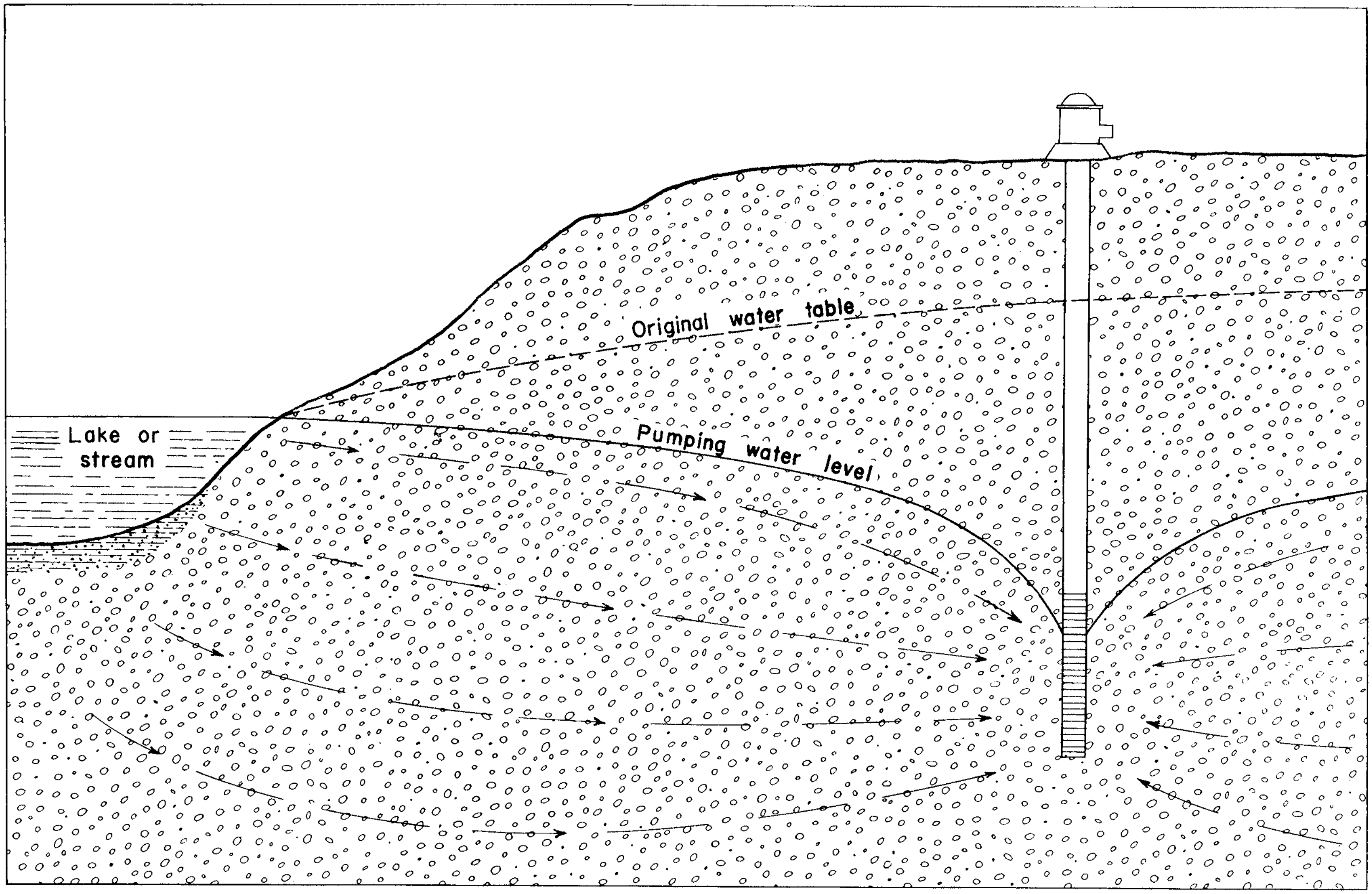



Figure 16. Generalized diagram showing how water can be induced to flow from a source of water to a well.

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.

## 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 4-inch 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 convential 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.

### 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).