STATE OF MICHIGAN
DEPARTMENT OF CONSERVATION
GEOLOGICAL SURVEY DIVISION

PROGRESS REPORT NUMBER 23
Ground-Water Hydrology and Glacial Geology of the Kalamazoo Area, Michigan.

by
Morris Deutsch, K. E. Vanlier, and P. R. Giroux

Prepared cooperatively by the United States Department of the Interior Geological Survey

1960

Contents

Figures

ABSTRACT

The Kalamazoo report area includes about 150 square miles of Kalamazoo County, Mich. The area is principally one of industry and commerce, although agriculture also is of considerable importance. It has a moderate and humid climate and lies within the Lake Michigan “snow belt”. Precipitation averages about 35 inches per year. Snowfall averages about 55 inches.

The surface features of the area were formed during and since the glacial epoch and are classified as outwash plain, morainal highlands, and glaciated channels or drainageways. The area is formed largely on the remnants of an extensive outwash plain, which is breached by the Kalamazoo River in the northeastern part and is dissected elsewhere by several small tributaries to the river. Most of the land drained by these tributaries lies within the report area. A small portion of the southern part drains to the St. Joseph River.

The Coldwater shale, which underlies the glacial deposits throughout the area, and the deeper bedrock formations are not tapped for water by wells and they have little or no potential for future development.

Deposits of glacial drift, which are the source of water to all the wells in the area, have considerable potential for future development. These deposits range in thickness from about 40 feet along the Kalamazoo River to 350 feet where valleys were eroded in the bedrock surface. Permeable outwash and channel deposits are the sources of water for wells of large capacity. The moraines are formed dominantly by till of lower permeability which generally yields small supplies of water, but included sand and gravel beds of higher permeability yield larger supplies locally.

The aquifers of the Kalamazoo area are recharged by infiltration of rainfall and snowmelt and by infiltration of surface waters induced by pumping of wells near the surface sources. Water pumped from most of the municipal well fields is replenished in part by such induced infiltration. Many of the industrial wells along the Kalamazoo River and Portage Creek are recharged in part from these streams. Locally, however, recharge from the streams is impeded, as their bottoms have become partly sealed by silt and solid waste matter.

Water levels fluctuate with seasonal and annual changes in precipitation and in response to pumping. Pumpage by the city of Kalamazoo increased from about 300 million gallons in 1880 to 4.6 billion gallons in 1957. Despite the fact that billions of gallons are pumped annually from well fields in the Axtell Creek area, water levels in this vicinity have declined only a few feet, as the discharge from the fields is approximately compensated by recharge from precipitation and surface water. Pumpage of ground water by industry in 1948 was estimated at about 14 billion gallons, but the use of ground water for industrial purposes has since declined.

Aquifer tests indicate that the coefficient of transmissibility of aquifers in the area ranges from as little as 18,000 to as high as 300,000 gpd (gallons per day) per foot, and that ground water occurs under water-table and artesian conditions.

The ground water is of the calcium magnesium bicarbonate type. It is generally hard to very hard and commonly contains objectionable amounts of iron. Locally, the water contains appreciable amounts of sulfate. Study of the chemical analyses of waters from the area show that all of the tributaries to the Kalamazoo River are fed primarily by ground-water discharge.

INTRODUCTION

The investigation upon which this report is based was started in 1946 by the U. S. Geological Survey in cooperation with the Geological Survey Division of the Michigan Department of Conservation and the city of Kalamazoo. It forms a part of the statewide cooperative investigation of the availability and quality of ground-water resources to meet municipal, domestic, agricultural, and industrial needs. The work in the Kalamazoo area, in addition to the usual collection and compilation of data pertaining to the source, occurrence, availability, chemical quality, and use of ground water, included a series of aquifer tests, and also a program of test drilling, financed by the city of Kalamazoo, to determine the thickness and extent of the fresh-water aquifers underlying the city and contiguous areas. Using the information concerning the geology and hydrology of the area obtained during the study, and new techniques of well development, maintenance, and induced recharge, the city’s Utilities Department has since expanded its well and pumping facilities and has developed one of the largest ground-water supply systems in Michigan.

The present report is designed to make the data collected during the investigation and interpretations there from readily available to the public. The section of the text entitled "Recharge", which is concerned largely with induced recharge of water from surface streams to the aquifers, may be of considerable interest and potential value to industry and to other cities in Michigan and elsewhere having similar geologic and hydrologic settings. In addition, data collected in the interval since the study was completed, and an evaluation of the effects of the increased use of ground water during the past 10 years, are included herein.

Cooperative ground-water investigations by the U. S. Geological Survey in Michigan are directed jointly by P. E. LaMoreaux, Chief of the Survey’s Ground Water Branch, Washington, D. C., and W. L. Daoust, State

Geologist, Michigan Department of Conservation, Lansing, Mich., and are under the direct supervision of Morris Deutsch, District Geologist, who succeeded J. G. Ferris of the Federal Survey.

Historical Sketch of Municipal Ground-Water Developments

In 1843 the village of Kalamazoo adopted an ordinance covering the establishment of a public water-supply and fire-protection system (Kalamazoo City Utilities, 1954). In 1851, water surplus to the needs of the Michigan Central Railroad was made available to the village for a public supply. Later, Arcadia Creek was used as a source of supply for the village. The first waterworks plant was built in 1869 (Leverett, 1906a) and a large well 22 feet in diameter was dug to a depth of 32 feet. In 1872 a second source of supply was installed, consisting of a dug well 20 feet in diameter, 30 feet deep, and surrounded by 13 tubular wells 6 inches in diameter and ranging in depth from 80 to 120 feet. The 6-inch wells flowed 2 or 3 feet above the land surface, but the flow was discharged to the dug well below the surface. These facilities were installed at the site of the present Central Pumping Station on Burdick Street.

In 1914 the Schippers Station (No. 5) at the intersection of Schippers Lane and Lincoln Avenue (now East Michigan Ave.) was added to the system. A station (No. 3) was installed on Balch Street in 1917, another (No. 4) on Maple Street in 1924, and a third (No. 2) on Born Court the following year.

In 1932 Station "B", adjacent to the Central Pumping Station, and Station "C" on Stockbridge Avenue were built to replace the old shallow dug wells as sources of supply. Station "D" was added in 1941 and Stations C-1 and C-2 in 1945. Water from these stations is pumped at low pressure to the nearby Central Pumping Station, where it is repumped into the distribution system.

The Crosstown Station along Axtell Creek (No. 7) was added to the system in 1944. Another station (No. 8) was installed on the south side of East Kilgore Road in Portage Township in 1949. This marked the first time that Kalamazoo had obtained a water supply from facilities beyond the city limits. A second station (No. 9) in Portage Township, on West Kilgore Road, was put into operation in 1955.

To keep pace with the rapid areal growth of the city in recent years, new well stations have been installed near Kendall Avenue (No. 11), U. S. Highway 12 (No. 12), East Kilgore Road along Davis Creek (No. 13), and at Spring Valley (No. 14). Stations 15, 16, and 17 are well fields formerly operated by Millwood Community, which was annexed to the city in 1957. Construction of Stations 18 and 19 was started by the city of Kalamazoo in 1957. Figures 14 and 15 show the approximate locations of the municipal well fields.

Beyond the area served by the city, most residences obtain water supplies from privately owned wells. In at least one case, however, a newer suburban housing development is served by a public-supply system installed by the developer, and deeded to Portage Township for operation and maintenance.

Previous Investigations

The reports of a number of investigations of the geology and water resources of Michigan made since 1895 include data or maps pertaining to the Kalamazoo area. Various phases of the geology of the Southern Peninsula were described by Lane (1895), Leverett (1912, 1917), and Leverett and Taylor (1915). Martin (1955) compiled a map of the surface formations of the Southern Peninsula of Michigan, and reported informally on the glacial history of Kalamazoo County (1957).

Reports of investigations of the water resources of the Southern Peninsula which contain data on the Kalamazoo area were made by Lane (1899) and Leverett (1906a, b), J. G. Ferris of the Geological Survey in 1949 investigated the ground-water hydrology and the relations of the level of the Kalamazoo River to ground-water supplies available to users along the reach of the river in and near the city of Kalamazoo, and much of the information from his unpublished study is included in this report.

Well-Numbering System

The well-numbering system used in this report indicates the location of the wells within the rectangular subdivisions of the public lands, with reference to the Michigan meridian and base line. The first two segments of a well number designate the township and range; the third segment designates both the section and the serial number assigned to each well within the section. Thus, well 1S 12W 25-1 is well number 1 in sec. 25, T. 1 S., R. 12 W. (Alamo Township). Hence, it is necessary to plot only serial numbers on maps showing sections, as the complete number of the well is evident by its location. The locations of most wells described in this report are given to the nearest 10-acre tract within the section (table 1). Numbers formerly assigned to wells for which information has previously been published are also included in table 1.

Acknowledgments

Special thanks are given to the numerous government and industrial officials, well drillers, contractors, engineering firms, businesses, and private individuals who provided assistance and pertinent information which made this report possible. Lack of space prohibits a complete listing of contributors of information for this study. Major contributions of data, however, were made by the following persons or organizations.

Messrs. Albert Sabo, Manager, A. De Does, hydraulic engineer, Paul Sabo, well driller, and Richard Wetmore, Water Superintendent, all of the Kalamazoo Utilities Department; the Layne-Northern Drilling Co.; Mr. A. E.

Woolam, Kalamazoo representative of the Ohio Drilling Co.; the C. S. Raymer Drilling Co.; Messrs. Walker H. Sisson, Engineering Division, Upjohn Co.; Charles M. Waddle and Dwight Lemon, Kalamazoo Vegetable Parchment Co.; and J. C. Newman, well driller; and officials of the Sutherland Paper Co., Allied Paper Co., Hawthorne Paper Co., Bryant Paper Co. (now St, Regis Paper Co.), Kalamazoo Paper Co.; and Raymond Concrete Pile Co.

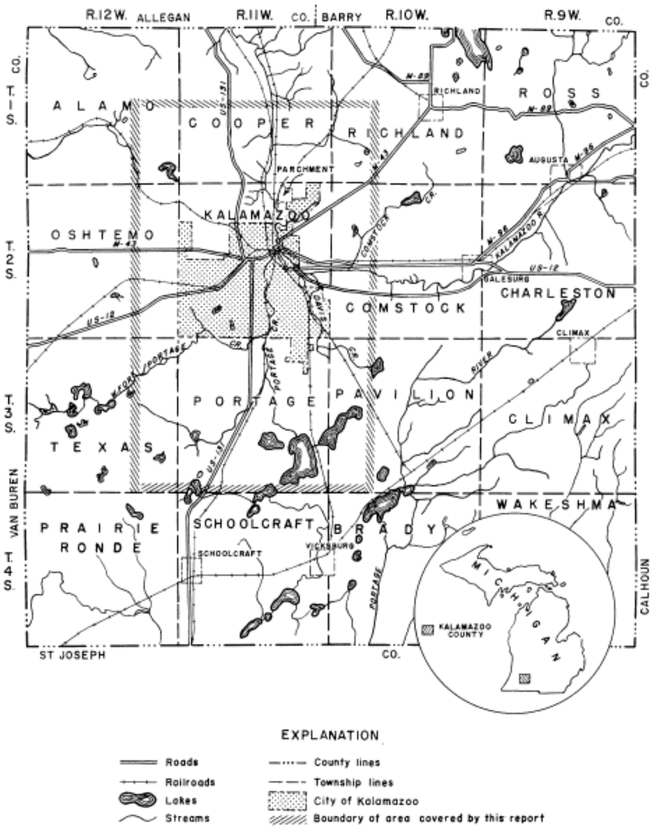

Figure 1. Index map showing location of the Kalamazoo area, Michigan.

GEOGRAPHY

Location and Extent of the Kalamazoo Area

The area covered by this report is rectangle consisting of about 150 square miles in Kalamazoo County, which is in the southwestern part of the Southern Peninsula of Michigan (fig. 1). The area includes the cities of Kalamazoo and Parchment, all of Kalamazoo and Portage Townships plus contiguous parts of Alamo, Cooper, Richland, Oshtemo, Comstock, Texas, and Pavilion Townships, and the villages of Oshtemo, Comstock, and Portage (fig. 2).

Kalamazoo and Parchment in the north-central part of the report area include most of the land formerly occupied by Kalamazoo Township (T. 2 S., R. 11 W.). The Kalamazoo River flows into the area at Comstock, turns sharply north at Kalamazoo, and flows out of the area at Cooper.

Population and Economic Development

The population of the city of Kalamazoo according to the 1950 census was 57,704, and that of the Kalamazoo metropolitan area (all of Kalamazoo County) was 126,707. Parchment at that time had a population of 1,179. According to the latest estimate of the Michigan Health Department, the population of Kalamazoo had grown to 75,020 by 1957, and the county's population to 153,410. The W. E. Upjohn Institute for Community Research has estimated that the population of the county will grow to 208,000 by 1970 and to 234,000 by 1975 (Taylor, 1956). During the interval from 1920 to 1950 the population of the city of Kalamazoo increased by about 10,000, while that of Kalamazoo Township increased from about 5,000 to 28,000. Since 1950, however, the city's population and areal extent have increased through annexation of much of the township.

Kalamazoo is connected to other cities by U. S. Highways 12 and 131 and State Highways M-43, 89, and 96. It is served by the Grand Trunk Western, New York Central, and Pennsylvania Railroads, by 7 bus lines and 32 Michigan or interstate truck lines, and by Lake Central and North Central Airlines.

The industry of the area is very diversified and in 1953 employed more than 24,000 persons. Among the most important products manufactured are paper and allied products, pharmaceuticals, chemicals, transportation equipment, various types of machinery, and fabricated metal products (Bennett and Jordan, 1950). Mineral industries in the county produce sand and gravel, marl, and a small amount of petroleum.

The agricultural land in the region around Kalamazoo yields a variety of specialized and general farm products. Celery and blueberries are the principal agricultural exports. The county is also one of the Nation's leading producers of cherries and grapes.

Physiography and Relief

The Kalamazoo area lies in a region glaciated by a succession of at least four major continental ice sheets. The main topographic features of the area were formed during the recession of the last of the ice sheets. The physiographic features of the area may be classified into three major types: dissected outwash plain, morainal highlands, and glaciated channels or drainageways (fig. 5).

Most of the area is composed of the remnants of an extensive outwash plain which is breached by the Kalamazoo River and is dissected by several small tributaries to the river. This plain is not readily recognized as such because of the great amount of erosion that has occurred in glacial and postglacial time. Some of the uplands in the outwash plain have flat surfaces, and it is apparent locally that these flat-topped highlands are part of this plain. Remnants of the outwash plain lie at altitudes as much as 960 feet above sea level.

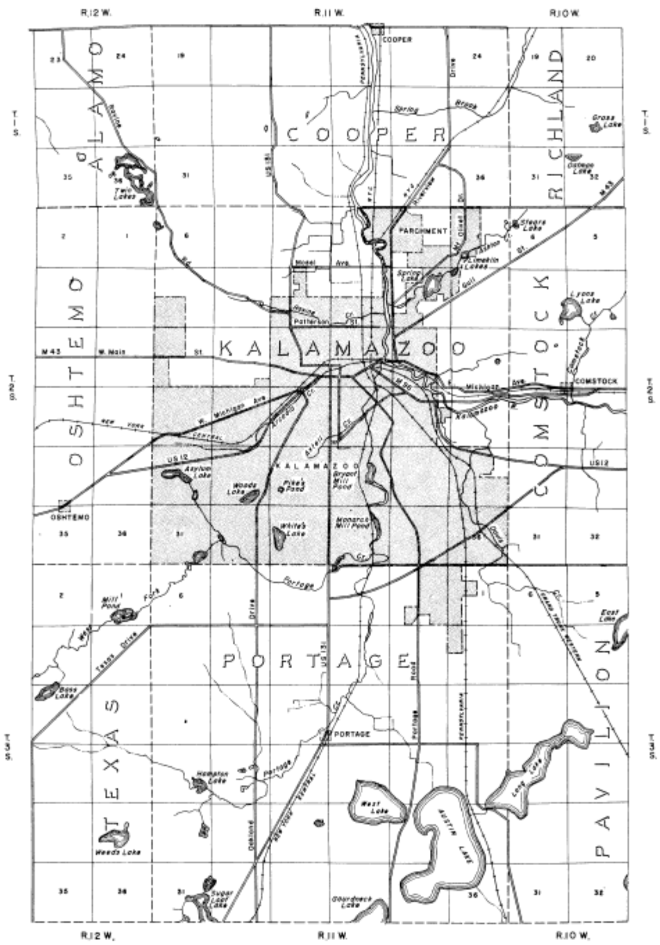

Figure 2. Location map of the Kalamazoo area.

The most readily distinguished physiographic feature is the Outer Kalamazoo moraine, which crosses the northwestern part of the report area. A segment of the Inner Kalamazoo moraine is present in the extreme northwestern part of the report area, in Alamo Township. The moraines have a characteristic "knob-and-kettle" topography in contrast to the flat surface of the undissected remnants of the outwash plain. Some of the knobs reach altitudes greater than 1,000 feet, although in some areas the morainal deposits are lower than adjacent outwash deposits. Several small hills of morainal origin and some rolling till plains occur in the southeastern part of the report area. These features, which are of small areal extent and hydrologic significance, have only slightly different topographic expression from the surrounding outwash plain.

Broad bottom lands along the Kalamazoo River mark the drainage-ways or channels of the river during the glacial epoch, when its flow greatly exceeded that of the modern river. The bottom lands are formed on sand and gravel deposited in the channel of the glacial river. These lands are at elevations of less than 800 feet and are 80 to 100 feet below remnants of the adjacent outwash plain. The level of the Kalamazoo River, which is incised into these bottom lands for its entire reach within the report area, declines from about 760 feet above mean sea level at Comstock to about 740 feet at Cooper.

Drainage and Streamflow

With the exception of a small portion of the southern part, which lies in the St. Joseph River drainage basin (fig. 10), the area covered by this report lies within the drainage basin of the Kalamazoo River. Above Comstock, the river drains an area of 1,010 square miles (Wells and others, 1958). The mean flow of the river at the Comstock gaging station for the period 1932-57 was 851 cfs (cubic feet per second). The minimum annual flow of the river recorded by this station was 577 cfs in 1934; however, records of similar streams indicate that the mean annual flow of the Kalamazoo in 1931 was about 400 cfs.

The altitude of the zero datum on the U. S. Geological Survey gage at Comstock is 759-12 feet above mean sea level. The Corps of Engineers (1958) designates a stage of 763.62 feet as critical flood stage. This stage is equivalent to a discharge of 3,100 cfs. According to the Michigan Water Resources Commission (1957), the river at the Kalamazoo Board of Water and Light gage in downtown Kalamazoo will overflow its banks at an altitude of 758.8 feet. Since 1946, flows in excess of 3,100 cfs have been observed 10 times, a maximum discharge of 6,910 cfs having been recorded during the flood of April 1947.

Several creeks are tributary to the Kalamazoo River within the report area. The largest of these is Portage Creek, which during the period 1947-57 had a mean flow of 57.5 cfs at the gaging station located on the boundary between secs. 22 and 27, T. 2 S., R. 11 W. Above this station, the creek drains an area of 48 square miles. The West Fork of Portage Creek flows into the main creek above the gaging station, but the confluence of Axtell Creek with the main creek is below the station. Comstock, Davis, Schippers, and Arcadia Creeks and Spring Brook are the largest of other tributaries to the Kalamazoo River within the report area. Flow of water in a few of the tributaries ceases intermittently because of the heavy pumping of ground water in nearby well fields.

Climate

Weather data for the Kalamazoo area show that the highest temperature ever recorded was 109°F, on July 13, 1936, and the lowest was -25°F, on February 10, 1885. Temperatures reach the 100°F mark in about 1 summer out of 3. Days on which temperatures reach 90°F, or above, average 25 per year. At the other extreme, temperatures fall to zero or below on an average of 4 times during the winter. The average dates of the last freezing temperature in the spring and the first in the fall are May 9 and October 9. Lake Michigan greatly affects the weather at Kalamazoo, as the prevailing westerly winds are warmed in the winter and cooled in the summer while passing over the lake.

The average annual precipitation in the area is about 35 inches (fig. 3). Precipitation received during the growing season (April-September) averages 57 percent of the annual total. The rainfall is heaviest in May, which has an average of about 3.8 inches. The driest month of the year is February, in which the average is about 2 inches.

Snowfall averages about 55 inches, and 7 months of the average year have measurable amounts. January has the most snow, averaging 14.3 inches. Kalamazoo is on the eastern edge of the so-called snow belt, which is induced by moisture and warmth picked up by the prevailing westerlies while crossing Lake Michigan. Consequently, the average annual snowfall at Kalamazoo is 10 to 15 inches greater than in the central and eastern sections of southern Michigan.

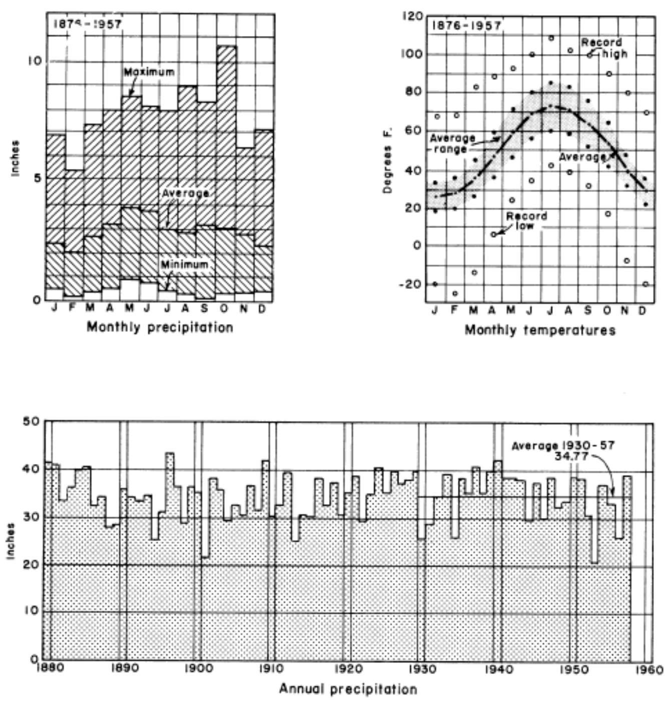

Figure 3. Precipitation and temperature records at Kalamazoo.

GEOLOGY

Summary of Geologic History

The bedrock formations that underlie the Kalamazoo area were formed by the consolidation of sediments deposited in seas which covered most of Michigan during the Paleozoic era. More than 10,000 feet of Paleozoic sedimentary rocks are present in the center of the Michigan basin.

The long interval of geologic time from the close of the Paleozoic era to the beginning of glaciation was primarily one of erosion. During this period, the land surface in and around the Kalamazoo area was reduced to relatively low relief. The major streams flowed from the southeast to the northwest (fig. 4), the direction of flow being controlled by the structure of the bedrock formations, which in this area strike northwest. (Strike is the direction of a horizontal line in the plane of the inclined strata and is perpendicular to the dip.) These streams are believed to have been actively downcutting into the sedimentary rocks at the start of the glacial epoch.

The period in the geologic history of the Kalamazoo area most significant to ground water is the Pleistocene or glacial epoch. In the Pleistocene epoch, ice migrated into the Great Lakes region from the north. The glaciers carried great amounts of rock materials picked up from the surface over which the ice passed. These materials, which were deposited as the ice sheets melted away, make up the only important fresh-water aquifers in the Kalamazoo area.

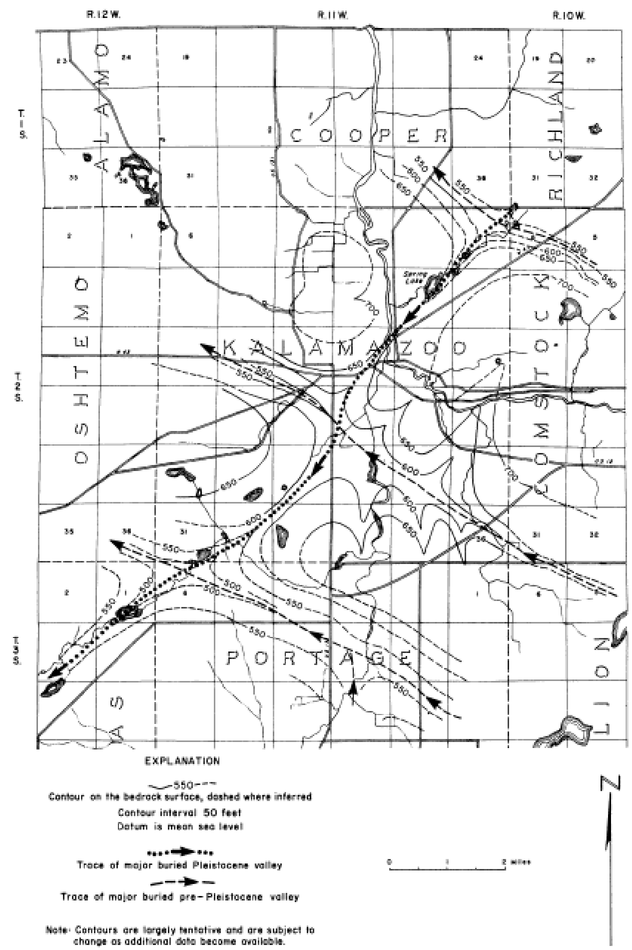

Figure 4. Map showing generalized contours on the surface of the Coldwater shale in part of the Kalamazoo area.

During Wisconsin time Kalamazoo County was first covered, at least in part, by a lobe of ice emanating from the Saginaw Bay area. Areas in the southeastern part of the county contain glacial deposits associated with the Saginaw lobe. The rest of the county, including the area covered by this report, was later covered by ice of the Lake Michigan lobe, which advanced from the Lake Michigan basin to the northwest. The movement of ice into the area from the Lake Michigan basin probably followed in part along the valleys in the pre-Pleistocene bedrock surface.

The ice front became stabilized at intervals along several fronts, and subsequent retreats of the fronts caused by melting left two moraines in the eastern part of the county. The ice front then retreated to a new position, marked by the Outer Kalamazoo moraine, which extends from northeastern Cooper Township through Texas Township. Melt water streams, which flowed from the ice standing on the Outer Kalamazoo moraine, spread outwash deposits of sand and gravel in front of the moraine. The melt water streams flowed eastward from the moraine into the glacial Kalamazoo River which at that time drained to the south.

Blocks of ice became detached from the melting glacier through the center of the county and were buried by sand and gravel outwash. Pits, formed when the ice remnants melted, now contain most of the lakes in Kalamazoo County. Melt water draining from the glaciers ponded against the ice front and formed glacial Lake Kalamazoo, which covered parts of the present Kalamazoo, Cooper, Comstock, Pavilion, and Portage Townships (Martin, 1957). Most of the sediments deposited in this lake were subsequently removed during downcutting of the Kalamazoo Valley.

The ice front then retreated a short distance to a position marked by the Inner Kalamazoo moraine. Melt waters from the ice at this front deposited outwash between the Inner and Outer Kalamazoo moraines. The melt waters drained to the east through several gaps in the Outer Kalamazoo moraine, one of which is in the vicinity of Crooked Lake in the central part of Texas Township.

After the ice retreated from the county, the Kalamazoo River abandoned its southern outlet and flowed northward to a lower outlet in southeastern Allegan County. Melt waters from the Saginaw lobe and the waters of Lake Kalamazoo also drained through this new valley to the vicinity of Otsego in Allegan County, where they emptied into the Gun River, a southward-flowing tributary of the St. Joseph River. The Kalamazoo River at that time cut 80 to 100 feet into the former outwash and lake plains, removed large quantities of sediment, and greatly widened the old valleys.

After the close of the Pleistocene epoch the volume of water discharged through the Kalamazoo River valley was greatly reduced, and hence the present-day Kalamazoo River occupies only a very small portion of the valley of the ancestral river.

Bedrock Structure

The Paleozoic sediments of the Michigan basin were deposited in nearly horizontal layers, but gradual subsidence and compaction of the beds, which was contemporaneous with deposition and greatest in the center of the basin, produced a bowl-shaped structure. The formations crop out in roughly concentric bands, the youngest beds being at the surface in the central part of the structure and the oldest at the surface around the perimeter. The Kalamazoo area is in the southwestern part of the basin, where the Coldwater shale of Mississippian age forms the bedrock surface. This formation is 500 feet or more thick in the Kalamazoo area, dips generally northeastward toward the center of the basin, and strikes northwest. The Marshall formation, which directly overlies the Coldwater shale in the central part of the basin, extends into the northeast corner of Kalamazoo County; but elsewhere in the county, including the area covered by this report, it has been eroded away. Rocks older than the Coldwater shale crop out in the extreme southwest corner of the State and in northwestern Indiana.

Bedrock Topography

The bedrock topography as shown on figure 4 has been inferred from the records of water wells that reach bedrock and oil wells and oil test wells in and adjacent to the Kalamazoo area. As shown by Terwilliger (1958), the southwestern part of Michigan in preglacial time was drained through valleys that trended northwestward, generally parallel to the strike of the underlying bedrock formations. At least three major bedrock valleys of preglacial origin are believed to cross the report area. Data from wells indicate that another valley, probably of Pleistocene age, transects the three older valleys. This Pleistocene channel probably was cut when the advancing glaciers blocked the normal northwestward flow of the streams. Sediments filling these valleys compose the thickest deposits of glacial drift in the Kalamazoo area. Wells in the Axtell Creek area (fig. 15) tap thick, permeable drift deposits at the intersection of a major pre-Pleistocene valley and the Pleistocene valley.

Generally, the basal part of the glacial-drift mantle is composed of dark-blue clay, most of which was derived from the Coldwater shale and redeposited by glacial ice. The shale is similar lithologically to the glacial-clay deposits, and it is difficult for drillers to distinguish between them in wells. Thus, the contact between the glacial drift and the Coldwater shale has not been accurately delineated in the logs of many wells. It appears that test drilling, which would more accurately define the bedrock valleys, would aid in the location of ground-water sources similar to that supplying the Axtell Creek area fields.

GROUND WATER

A rock formation, part of a formation, or group of formations that yields water in usable quantities is called an "aquifer". The imaginary surface consisting of all points to which water will rise in wells tapping an aquifer is called the "piezometric surface". Aquifers are classified as water-table or artesian. In a water-table aquifer, ground water is unconfined; its surface within the aquifer is termed the "water table" and may be considered the piezometric surface of that aquifer. The zone of saturation is that part of the formation in which openings are filled with water under hydrostatic pressure. In an artesian aquifer, ground water is confined under pressure between relatively impermeable strata (strata through which water does not move readily). Under natural conditions, the water in a well that is finished in an artesian aquifer and tightly cased through the overlying confining bed will rise above the bottom of that bed, and therefore the piezometric surface is above the top of the aquifer. An artesian aquifer is full of water at all times, even when water is being removed from it. In topographically low areas wells tapping artesian aquifers may flow at the surface.

The capacity of a material to transmit water under pressure is called "permeability". The ability of an aquifer to yield water, however, relates not only to its permeability but also to its extent and thickness and to the amount of recharge available to it. The permeability of the glacial drift, which is the chief aquifer in the Kalamazoo area, is determined by the character (size and shape) of the open spaces between the drift particles. The character of the open spaces depends primarily on the mode of deposition of the various types of drift.

The coefficient of permeability (P) expressed in meinzers, is the rate of flow of water in gallons per day through a cross-sectional, area of 1 square foot under a hydraulic gradient of 100 percent at a temperature of 60°F. The hydraulic characteristics of an aquifer are commonly expressed in terms of the coefficients of transmissibility and storage. The coefficient of transmissibility (T) is defined as the number of gallons of water per day, at the prevailing temperature, that will move through a vertical strip of the aquifer 1 foot wide and of a height equal to the thickness of the aquifer, under a hydraulic gradient of 100 percent, or 1 foot per foot. The transmissibility of an aquifer equals the average field coefficient of permeability (the coefficient measured at the prevailing temperature rather than at 60°F) times the thickness of the aquifer. The coefficient of storage (S) of an aquifer is defined as the volume of water the aquifer releases from or takes into storage per unit surface area per unit change in the component of head normal to that surface. The hydraulic characteristics of the glacial-drift aquifers in various parts of the Kalamazoo area are described below in the section entitled "Aquifer Tests".

The yield or the specific capacity of a well is a function of the efficiency of the well, the transmissibility and areal extent of the aquifer, and the availability of recharge. Specific capacity is defined as the yield per unit of drawdown and is usually expressed as the yield, in gallons per minute, for each foot of drawdown in water level caused by pumping of the well. Table 3 lists the specific capacities of a number of wells in the Kalamazoo area.

Ground Water in Consolidated Rocks

The glacial drift in the Kalamazoo area is underlain by a thick sequence of shale, limestone, dolomite, sandstone, and other consolidated sedimentary rocks. The total thickness of the consolidated sediments has not been determined. None of these rock formations are known to supply fresh water to wells in the Kalamazoo area.

The Coldwater shale of Mississippian age, which is the uppermost bedrock formation under the Kalamazoo area, is composed primarily of dark-blue and relatively impermeable shale. Locally it contains layers of sandstone which may be water-bearing. The presence of two layers of water-bearing sandstone, one of which is 15 feet thick, is reported in the log of well 2S 11W 11-9 (table 2), but sandstone has not been reported in logs of other water wells in the area.

Ground Water in Glacial Drift

Deposits of unconsolidated glacial drift constitute the only important fresh-water aquifers in the Kalamazoo area. The general term "glacial drift" embraces all types of sediments deposited during the glacial epoch by ice, melt-water streams, glacial lakes, and wind.

The glacial drift, which covers the entire Kalamazoo area, consists primarily of morainal, outwash, and channel deposits (fig. 5). The morainal deposits consist of till and were deposited directly from the glacial ice, water playing a minimum part in deposition. Outwash deposits are formed of materials deposited by melt-water streams issuing from the glacial ice. The channel deposits are similar in origin to the outwash deposits, except that in late glacial and postglacial time the waters of the Kalamazoo River system extensively eroded and reworked these deposits and subsequently covered them with finer grained sediments. Layers of silt and clay deposited in glacial lakes and lenses of windblown sand also are present in the drift, but they are not present over significant areas of the surface and therefore are not shown on figure 5.

Figure 5 shows the nature of the glacial materials at or near the land surface and can be used as a general aid in prospecting for ground-water supplies. The aquifers best capable of supplying wells of high capacity are in areas mapped as outwash or channel deposits where the glacial drift is thick or where permeable beds of sand and gravel are hydraulically connected with surface streams or lakes.

Figure 6 shows the general thickness of the glacial drift in part of the area covered by this report. The drift ranges in thickness from about 50 feet at places along the Kalamazoo River to more than 300 feet where it fills the pre-Pleistocene valleys in the bedrock surface. Sufficient data were not available for construction of a drift-thickness (isopachous) map for the entire report area. Figure 7 shows schematically the thickness and general composition of the glacial drift along several cross sections through the city of Kalamazoo, from the north well field of the Kalamazoo Vegetable Parchment Co. to the north edge of Portage Township.

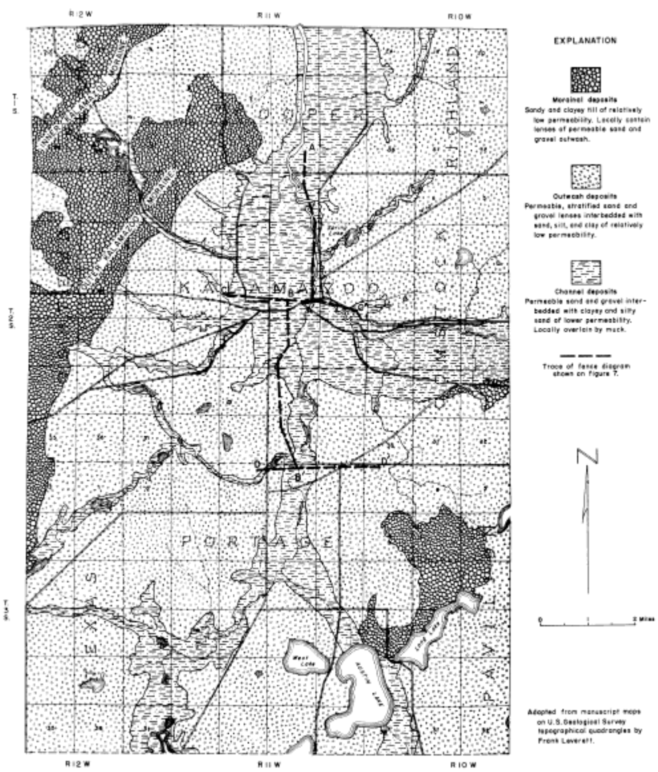

Figure 5. Surface geology of the Kalamazoo area.

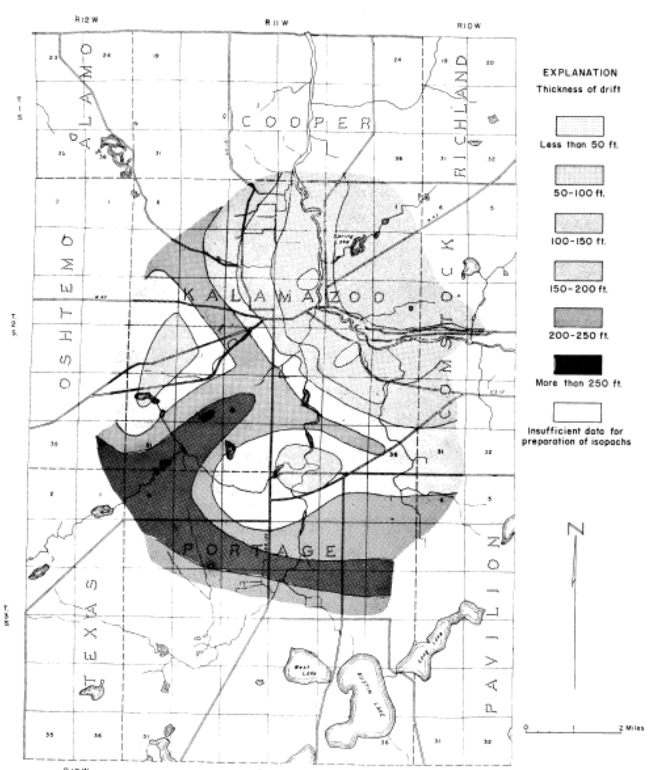

Figure 6. Generalized isopach map showing thickness of the glacial drift in part of the Kalamazoo area.

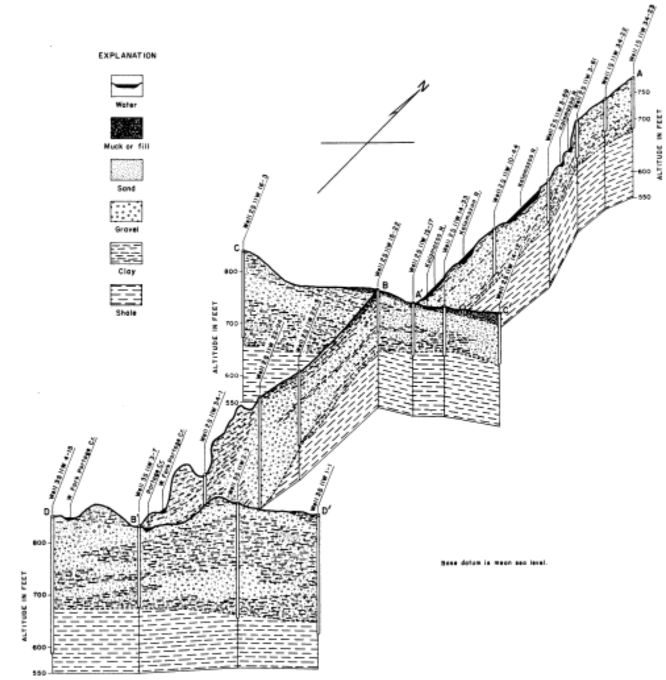

Figure 7. Schematic fence diagram sections through the glacial drift along lines shown on figure 5.

Morainal Deposits

The Outer and Inner Kalamazoo moraines are ridges of glacial till deposited along relatively static fronts of the Lake Michigan lobe of the Wisconsin glacier. The morainal tills generally are an unstratified and poorly sorted mixture of rock debris consisting of particles that range in size from clay to boulders. The tills of the Outer and Inner Kalamazoo moraines within the report area are generally sandy but contain sufficient amounts of clay and silt to reduce the permeability.

The morainal deposits generally will yield water adequate for domestic needs. Locally, however, they include beds of permeable sand or gravel outwash which will yield moderate to large supplies of water. Test hole 2S 11W 6-1, drilled to a depth of 167 feet (table 1), yielded 400 gpm. The source of most of this water is a bed of coarse gravel and boulders at a depth of 134 to 147 feet. The till above and below this bed is presumed to be of low permeability and to have contributed little to the yield of the well. The productivity of this well demonstrates the feasibility of obtaining water, at least locally, from permeable zones in the deposits of the Outer Kalamazoo moraine. Data are lacking, however, concerning the distribution, extent, and thickness of permeable materials that may be buried by or interbedded in the morainal tills.

Till was deposited also as ground moraine during retreat of the ice front in a period of rapid melting. The surface formed by such deposition is a rolling plain of low relief, and is referred to as a "till plain". Till plains are present in western Pavilion Township and extend into eastern Portage Township (fig. 5). The water-yielding characteristics of the ground-moraine deposits are not known, but supplies adequate for domestic use are pumped from shallow driven wells in this area. Data are not available as to whether these surficial till deposits are underlain by permeable sand and gravel out-wash deposits.

The bedrock surface in most of the Kalamazoo area is mantled directly by basal till composed predominantly of blue clay, although stream-deposited sand and gravel may lie on the shale surface along the bottoms of preglacial valleys. The basal till Was derived largely from the Coldwater shale, over which the ice advanced, and hence is similar to the shale in hydrologic and lithologic characteristics. These till deposits are not a source of ground water,

Outwash Deposits

The outwash deposits in the Kalamazoo area are composed of relatively well sorted and stratified sand and gravel deposits, but some of the outwash is rather poorly sorted and difficult to distinguish from adjacent till. The sand and gravel outwash deposits are interbedded with numerous lenses of clay, silt, and fine sand.

The variation in grain size of the outwash particles is indicated in table 4, which lists the effective openings of screens used in different wells in the Kalamazoo area. The successful use of slotted casings in several wells indicates that much of the outwash is composed largely of coarse-grained material. Many lenses of highly permeable outwash are present at varying depths within the report area as indicated by the many depths of screen or slot settings, and a single well commonly penetrates several good water-bearing zones. Many of these lenses are thin and discontinuous and hence, even in the rather restricted area of a well field, it is difficult to correlate individual lenses of permeable outwash material between wells. In some areas the outwash consists primarily of fine-grained sediments of relatively low permeability.

Outwash deposits compose the most important water-bearing zones within the glacial-drift aquifers of the Kalamazoo area. The aggregate thickness of these deposits, which are at the surface in much of the area (fig. 5), is as much as 300 feet where they have filled the pre-Pleistocene valleys in the bedrock surface. Wells 2S 11W 28-1 and 2S 10W 5-3 penetrated 294 and 330 feet of glacial drift, respectively, most of which is composed of layers of sand and gravel outwash.

Many wells tapping the outwash deposits have specific capacities of 25 gpm, or more, per foot of drawdown (table 3). The major well fields operated by the city of Kalamazoo, including those in the Axtell and Portage Creek areas which tap these deposits, have yielded large quantities of water throughout the years (see "Pumpage, Municipal" below). The outwash deposits are the source of water to most of the large capacity public-supply wells in and near Kalamazoo, but in some areas they may not be a source of large or even moderate supplies.

Channel Deposits

The material mapped as channel deposits on figure 5 consists mainly of well-sorted sand and gravel beds which are similar in composition and hydrologic characteristics to the outwash deposits. The channel deposits, however, are of more recent origin than the outwash deposits, and locally they are interbedded with lake-deposited silt and clay and are mantled by silt deposits of the modern Kalamazoo River. In some areas the channel deposits are mantled also by muck. The channel deposits are differentiated from the adjacent outwash deposits primarily by their lower topographic position.

The channel deposits are present in the drainageways developed after the Kalamazoo River changed its course from the south to a lower outlet at the north, in Allegan County. This change resulted in down-cutting of the outwash plain by 80 to 100 feet. Hence the channel deposits represent outwash that was reworked by the Kalamazoo River and its tributaries plus additional sediments deposited in the new drainage-ways.

The sand and gravel channel deposits along the Kalamazoo River range in thickness from about 50 to more than 100 feet. The log of well 2S 11W 24-3 at the National Gypsum Co. reports shale at a depth of 38 feet, but logs of other nearby wells report clay or hardpan at that depth (table 2).

The channel deposits are very important aquifers in the Kalamazoo area, inasmuch as they are tapped for water supply by the various paper companies located along the Kalamazoo River. The sand and gravel beds included within the channel deposits are rather permeable and have yielded large quantities of ground water for many years, despite the fact that their aggregate thickness is much less than that of the outwash deposits. These beds are connected hydraulically to the Kalamazoo Rivers which serves as a source of recharge to the streamside aquifers and thus maintains relatively stable water levels (see "Recharge" below).

Recharge

The initial source of all fresh ground water in the Kalamazoo area is precipitation, which averages about 35 inches annually (fig. 3). The percentage of precipitation that ultimately percolates to the various aquifers has not been determined, but there is no doubt that a large percentage of the annual precipitation over the area is evaporated, is transpired by vegetation, or runs off directly to surface streams.

Areas where unsaturated permeable materials are at or near the surface are favorable for infiltration of precipitation to the underlying aquifers. Precipitation on already-saturated sediments or on areas underlain by materials of relatively low permeability, such as clayey till or lake deposits, will not result in appreciable recharge. Much of the surface runoff is available for recharge to the ground-water reservoirs through induced infiltration to well fields in the area.

Under normal, conditions in the Kalamazoo area, ground water discharges to the Kalamazoo River and its tributaries, which are hence classified as effluent streams. Where the streams are incised into permeable materials in the aquifer, water flows from the stream into the aquifer if the water level in the aquifer is lowered to a depth beneath the stream surface by pumping or any other influence. That reach of the stream is then classified as influent and is a source of recharge to the aquifer potentially equal to the flow of the stream. Pumping of wells in such an area will induce migration of water from the stream toward the wells.

Water levels in wells along or near the Kalamazoo River are influenced by changes in stage (gage height) of the river (fig. 8) in such a way as to demonstrate that the river and aquifer are connected hydraulically. The water level in observation well 23 11W 10-11, which is about 300 feet from the Kalamazoo River, rose about 14 feet in response to precipitation that caused a 7-foot rise in stage of the river in March and April 1947. The water level in well 2S 11W 26-3, about 3,700 feet from the river, rose about 4 feet during the same period. A rise or fall in river stage ultimately results in corresponding changes of water level in the aquifer, although there is a lag in time before the entire effect is felt. The amount of rise in water levels in these wells which can be attributed directly to rise in river stage, and not to direct recharge from precipitation, however, cannot be determined on the basis of presently available data.

Most of the well fields of the city of Kalamazoo are adjacent to creeks tributary to the Kalamazoo River. The City Utilities Department is engaged in a continuing program of inducing recharge to some of the municipal well-field aquifers from these streams by construction of recharge ponds, lakes, and channels, and by streambed improvement. The recharge operations increase the yield of the well fields because surface storage capacity (available recharge) is increased, and hydraulic connection with the aquifers is created or improved. Growth of cones of depression and lowering of water levels are practically halted as recharge in quantities equal to pumpage moves into the aquifers under increased hydraulic gradients. The quantity of surface water that can be recharged to the aquifer varies directly with the transmissibility of the aquifer, the permeability and area of the bottom of the surface source, the hydraulic gradient, and, of course, with the amount of surface water available.

For example, Axtell Creek has been deepened and widened to create three large ponds in the area of the important complex of well fields shown on figure 15. Silt and organic materials are periodically removed from the bottoms of these ponds and adjacent reaches of the creek so that optimum infiltration capacity can be maintained. Despite the fact that billions of gallons of water are pumped annually from numerous high-capacity wells in this area the relatively small drawdown of the ground-water level (fig. 18) is marked evidence of the success of this project. The amount of water pumped from the area is governed by the quantity of recharge available from precipitation and by the water carried into the area by Axtell Creek. The effects of pumping on Axtell Creek are illustrated by base flow measurements of the creek made on November 20, 1947 at the Maple Street bridge near Station 4 (drainage area, 0.77 square miles) and near the confluence of Axtell and Portage Creeks (drainage area, 1.47 square miles). The data showed an actual loss in flow from 0.876 to 0.650 cfs in this reach (Paulsen, 1950, p. 286). In terms of yield per square mile of drainage area, the flow at the mouth was only 39 percent of that at the Maple Street bridge. During many days in the summer, little or no water from Axtell Creek discharges to Portage Creek. The city endeavors to limit-pumping to amounts equal to the available recharge, so as to avoid dewatering of the upper portion of the aquifer, which would cause increased pumping lifts.

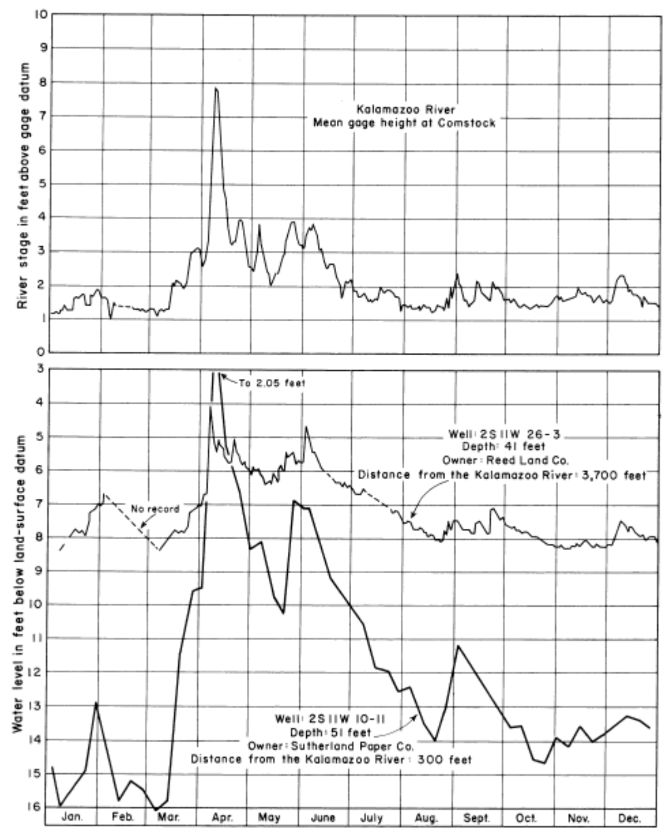

Figure 8. Graphs showing the relation between the mean gage height of the Kalamazoo River and water levels in wells 2S 11W 10-11 and 26-3 during 1947.

A similar program is being carried out at the West Kilgore Road well field (Station 9). Here, a recharge channel has been dredged within the field. Part of the flow of the West Fork of Portage Creek is diverted to the recharge channel via a ditch arid culvert. The waters in the creek and the channel are available for induced recharge to the aquifer by pumping. Figure 9 illustrates the principles involved in this case of induced infiltration and the general direction of movement of water from the stream and recharge channel through the aquifer and into the well. It does not, however, show movement of water to the well from sources other than the stream and recharge channel, such as precipitation on the area and on adjacent uplands.

The new Spring Valley well field (Station 14, fig. 14) constructed by the City Utilities Department has demonstrated supplemental benefits that can be derived from sound hydrologic research when, combined with integrated urban planning. To provide water for the rapidly expanding population in the northeastern part of the city, a new well field was constructed in the vicinity of a series of small lakes, the so-called Limekiln Lakes in secs. 1, 11, and 12, T. 2 N., R. 11 W. The outwash materials in this area are only moderately permeable, because they contain a relatively large percentage of fine sand and silt. The Parks and Utilities Departments collaborated in dredging and expanding the lowest of the small lakes, providing a large source of recharge to the aquifer. The large area of recharge compensates for the moderate permeability of the aquifer. An elevated storage tank was constructed so that this facility could be used independently to provide water in the area without the necessity of importing water from distant pumping stations located at considerably lower altitudes. A scenic park was developed around the new lake, which was renamed Spring Lake (fig. 2).

The Upjohn Co., which pumps 5 to 9 million gallons of ground water daily, constructed two artificial-recharge ponds of 10,000 and 40,000 square feet, into which clean, but warm, process water is pumped (Sisson, 1955). Enough chloride is added to maintain a residual to prevent bacterial growth. A natural pond covering 90 acres also is used for recharging. Sisson calculated that the artificial ponds recharge 9 percent, and the natural pond 16 percent, of the well water pumped by the company.

Figure 8 demonstrates that hydraulic connection exists between the Kalamazoo River and the channel deposits that make up the aquifers along the reach of the river through the Kalamazoo area. The river thus provides recharge to the aquifer, which is tapped by numerous high-capacity industrial wells. Potentially, the river is a source of recharge greatly in excess of foreseeable industrial demands. However, recharge to the stream-side well fields is impeded by the partial sealing of the river bottom by natural sedimentation and by settling of solids from industrial effluents. Measures designed to promote recharge from the river are necessary to utilize more fully the water-resource potential along the Kalamazoo River. Efforts made by several industries to scrape or remove impermeable materials from the river bottom in order to increase the recharge locally have met with varying degrees of success. Measures are also being taken by the industrial concerns in the area to reduce the volume of solids discharged to the river.

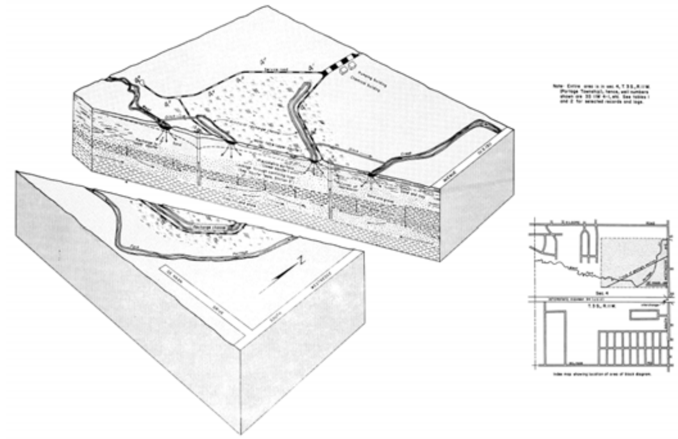

Figure 9. Schematic block diagram showing direction of movement of water from creek and recharge channel induced by pumping of Kalamazoo station 9.

Movement and Discharge

The movement of water underground is similar to that of surface streams, as the water moves by gravity from high levels to low levels in response to differences in hydraulic head. Ground water, however, moves slowly through the drift aquifers because of the resistance to flow in the small openings through which it passes. Sisson (1955) calculated that water recharged to the aquifer in sec. 14, T. 3 S., R. 11 W., traveled at a velocity of 1 3/4 feet per day. Velocities of ground-water movement vary considerably, however, and may range from a few feet per year to as much as several feet per day. Water may travel considerable distances in the ground, from areas of recharge at the surface to areas downgradient where it may be pumped from wells, or may, under natural conditions, once more reach the surface and join the flow of streams, appear as a seep or spring, enter a lake, or escape directly to the atmosphere by evaporation or transpiration.

In the Kalamazoo area, except for the southern parts of Texas, Portage, and Pavilion Townships, which lie in the drainage basin of the St. Joseph River, the general direction of ground-water movement is toward the Kalamazoo River. Figure 10 shows the general configuration of the ground-water surface and the direction of flow in the Kalamazoo area. Movement of ground water is in the direction of the hydraulic gradient at right angles to the contours. The hydraulic gradient conforms generally to the topographic gradient. It should be clearly understood that the contours shown on figure 10 are generalized, as the actual pattern of flow in any aquifer is complex. In addition, the contours are interpolated from all available hydrologic data and represent a combination of the configurations of the water tables and piezometric surfaces in numerous water-bearing lenses within the glacial drift. Where two or more water-bearing zones in a given area are under different artesian pressures, water will percolate or "leak" from the aquifer having the higher head to the one having lower head.

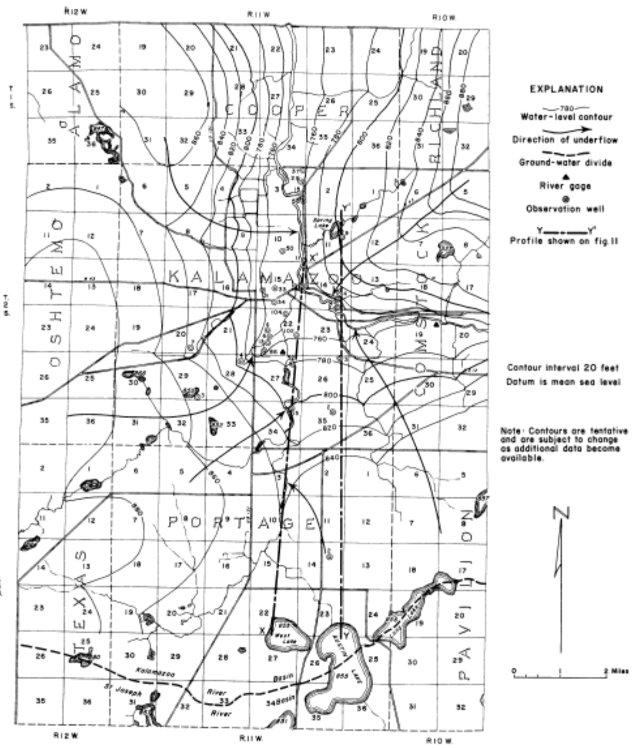

Figure 10. Generalized hydrologic map of the Kalamazoo area showing direction of ground-water movement.

Along the flank of the Outer Kalamazoo moraine, on the west side of Kalamazoo, the piezometric surface is above the land surface, indicating that the water in the underlying aquifers is under sufficient artesian pressure to flow.

Figure 10 is insufficiently detailed to show depressions in the piezometric surface caused by pumping in numerous well fields in the area. Figure 11, however, shows the effects of pumping on the water-level profiles along two north-south sections. Section X-X' shows that ground water flows northward to the Kalamazoo River from Austin Lake, which is on the ground-water divide between the Kalamazoo and St. Joseph River drainage basins. The section roughly parallels Portage Creek, and the ground-water level is a few feet above the level of Portage Creek in Portage and southern Kalamazoo Townships. In this area, except for the cone of depression created by well 3S 11W 14-40 and other wells of the Upjohn Co., the stream is effluent, as ground water is discharged to it. Where the aquifer is heavily pumped in the city of Kalamazoo, the water level is below the level of the stream, and in this reach the stream is influent, recharging the aquifer. The level of Portage Creek does not coincide with the land-surface profile shown on the section, inasmuch as the creek is about 1 to 1 1/2 miles west of the line of the section. This section also illustrates the recharge potential, of the Kalamazoo River for aquifers that adjoin the river.

Section Y-Y' on figure 11 more closely parallels Portage Creek but crosses the creek several times. Where the water-level profile is above the land surface, wells drilled into the artesian aquifers will flow. Wells at the East Kilgore station (Station 8), which is located along side of Portage Creek in the north part of sec. 3, T. 3 S., R. 11 W., flow when they are not being pumped. Flows from artesian aquifers in the Kalamazoo area are generally small, and pumping is required to satisfy demands for most purposes. Along most of the reach of Portage Creek in the city of Kalamazoo, pumping has lowered ground-water levels, changing the creek to an influent stream.

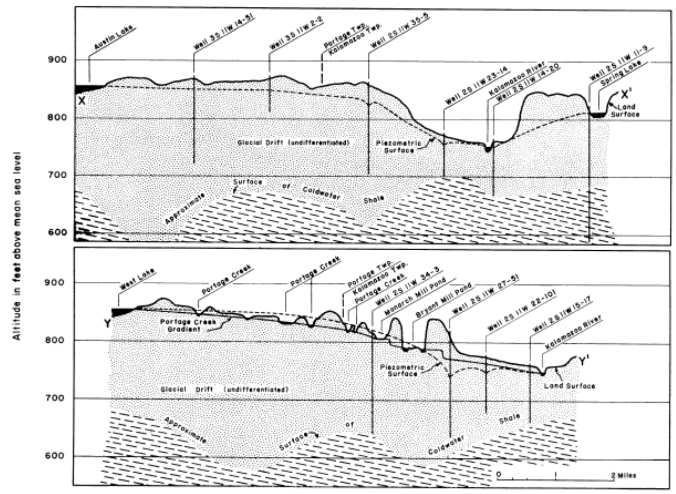

Figure 11. Profiles of the piezometric surface, Portage Creek, and the surface of the Coldwater shale along lines shown on figure 10.

Figure 10 shows also that the general movement of ground water in the Kalamazoo area is in the direction of flow of the various tributary streams, although the movement is deflected toward the tributaries where they drain the aquifers. Where municipal and industrial pumping operations have created cones of depression that intersect surface-water bodies, the direction of movement of ground water, and water recharged from the surface, is diverted toward the wells.

Under natural conditions, most of the discharge of ground water is to the Kalamazoo River and its tributaries. Although it is known that some of the surface-water runoff is intercepted by pumping of ground water, the quantity intercepted from most of the streams cannot be determined on the basis of presently available data. It is known, however, that during periods of heavy pumping all the flow of Schippers Creek, and much of that of Axtell Creek, is recharged to the ground. Most of the water pumped from wells is ultimately returned to the surface streams through sewers and drains. Also, some ground water is discharged directly to the atmosphere by evapotranspiration.

Pumpage

Municipal

Annual pumpage by the city of Kalamazoo from 1880 through 1957 is shown on figure 12, During this 78-year period, a total of about 118 billion gallons was withdrawn from the glacial-drift aquifers underlying the city and contiguous areas. Total pumpage in 1880 was about 300 million gallons, or about one-fifteenth of the municipal pumpage in 1957. By 1890, pumpage had increased to 790 million gallons, but subsequently, annual pumpage gradually declined until 1902, when only 400 million gallons was pumped. Most of this decline may be attributed to the gradual installation of water meters beginning in 1894 (Norman, 1949).

Annual pumpage increased to a new high of about 2.2 billion gallons in 1930, but declined during the following five years to 1.5 billion gallons in 1935. The decline in pumping can be attributed to the economic depression of that period. By the end of World War II the city of Kalamazoo was pumping about 3.2 billion gallons a year. The volume of pumping increased in the postwar years, but fell off in the early 1950's. This decline undoubtedly was due to above-average precipitation in 1950 and 1951, which tended to reduce water demands for lawn watering and certain other uses, and pumping from several of the smaller stations was temporarily discontinued. Deficient precipitation during the subsequent years was a principal cause of sharp increases in pumping, which reached a record high of about 4.6 billion gallons in 1957.

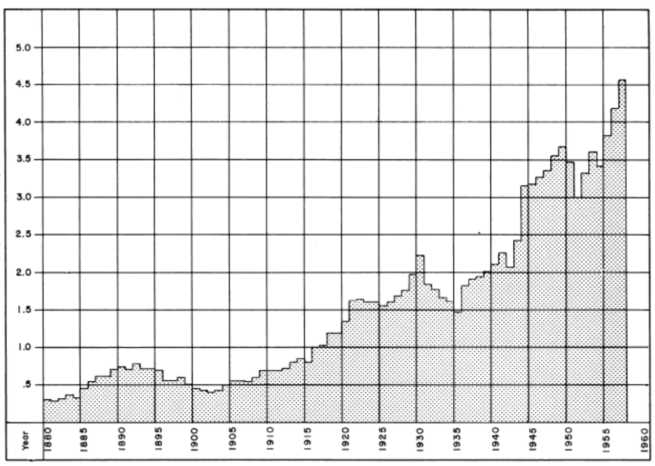

Figure 12. Annual pumpage by city of Kalamazoo, 1880-1957.

Prior to the close of World War II almost all the municipal water was pumped from stations along Axtell Creek near the Central Pumping Station, referred to herein as the Axtell Creek area. During this period, only Stations 4 and 5 supplemented the supply obtained from the Axtell Creek area.

After World War II, however, the city began a program of well-field construction in peripheral areas both inside and beyond the city limits. During the period 1946-57 pumpage of ground water from stations other than those located in the Axtell Creek area ranged from about 40 million gallons per year in 1951 to about 1.27 billion gallons in 1957. The pumpage from the various Kalamazoo city well fields for the period 1946-57 is given on figure 13. Figure 14 shows the approximate distribution and magnitude of pumpage from the Axtell Creek area stations and all other municipal well fields in 1957. The stations are at about the centers of the circular pumpage diagrams. Figure 15 shows the approximate location of pumping stations within the Axtell Creek area and the pumpage by each in 1957.

The city of Kalamazoo furnishes water to various industries, commercial firms, and institutions, as well as to the general public. The Kalamazoo State Hospital maintains its own well field and pumping facilities, Portage Township maintains a public supply at the Southfield Subdivision. Elsewhere, beyond the city of Kalamazoo's distribution facilities, public and domestic water needs are supplied by individual wells or well fields.

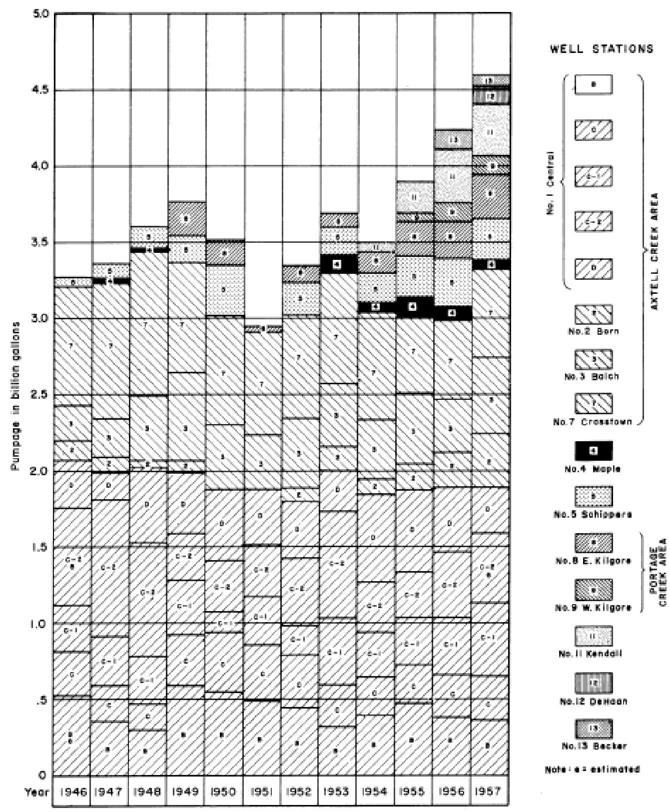

Figure 13. Annual municipal pumpage by stations, 1946-57.

Industrial

A canvass of the larger industrial water users in and near Kalamazoo was made in 1948 in order to estimate the volume of ground water pumped from nonmunicipal wells. Detailed records of pumpage were not available, but it was estimated that the withdrawal of ground water for industrial use in 1948 was about 14 billion gallons. No data on industrial pumpage have been collected since 1948. It is believed, however, that industrial pumping of ground water has declined slightly, and that industrial use of surface water has increase. The paper manufacturers, most of whom are located along the Kalamazoo River and Portage Creek, account for most of the pumpage of ground water for industrial use. The Kalamazoo Vegetable Parchment Co. supplies the city of Parchment with water, in addition to supplying its own needs. The Upjohn Co. in Portage Township, which pumps 5 to 9 million gallons daily, is the only other industrial concern that uses large quantities of ground water; numerous other industrial and commercial firms in the area pump much smaller quantities of ground water for various uses.

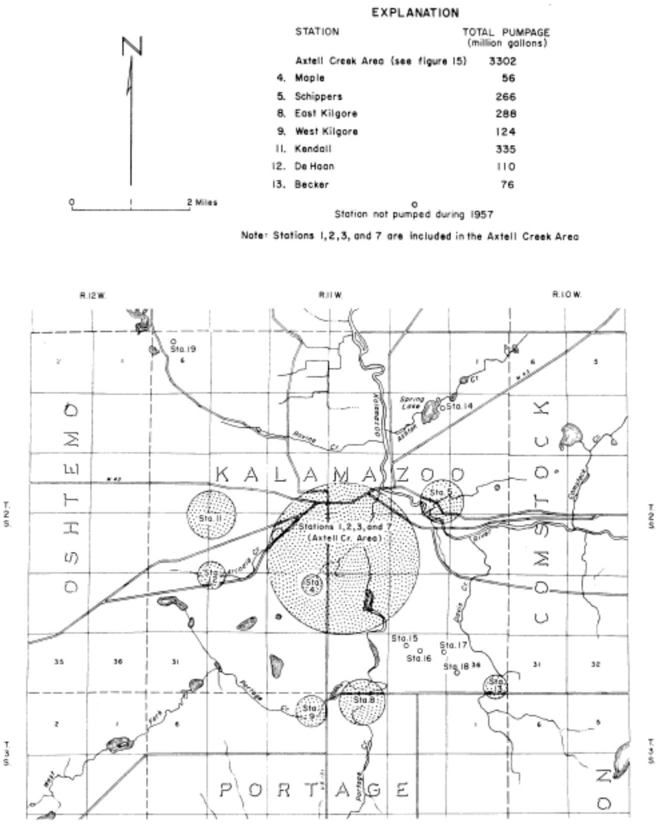

Figure 14. Distribution and magnitude of municipal ground-water pumpage by the city of Kalamazoo, 1957.

Water Levels

Water levels fluctuate in response to climatic and other natural influences and to pumping and other manmade changes in the hydrologic regimen. Giroux (1958) has analyzed fluctuations of ground-water level in the Kalamazoo area for the year 1957 and has tabulated the range in fluctuation in 15 observation wells in which measurements were made during the period 1946-57. Tabulations of many water-level measurements made in the Kalamazoo area since 1939 are contained in the annual series of U. S. Geological water-supply papers entitled "Water Levels and Artesian Pressures in Observation Wells in the United States" (for 1956 and subsequent years, "Ground-Water Levels in the United States"). The length of the published record for each well and the number of the water-supply paper for each year are shown on figure 16.

Natural Influences

Ground-water levels in the area fluctuate with seasonal changes in the rate of natural recharge to and discharge from the ground-water reservoirs. During the spring, water levels normally rise in response to the infiltration of rain and melting snow. Warmer temperatures that prevail during the growing season result in an increase in evapotranspiration and a reduction in the opportunity for recharge. Thus, unless total precipitation is abnormally high during the growing season, water levels decline. In the fall, when cold weather ends the growing season, precipitation may result in rises of water level after depleted soil moisture is restored. However, the usual summer decline in stage may continue if precipitation in the fall is deficient or if an early general freeze impedes infiltration. Recharge to the ground-water reservoir in the winter is reduced if most of the precipitation is in the form of snow and subfreezing temperatures persist.

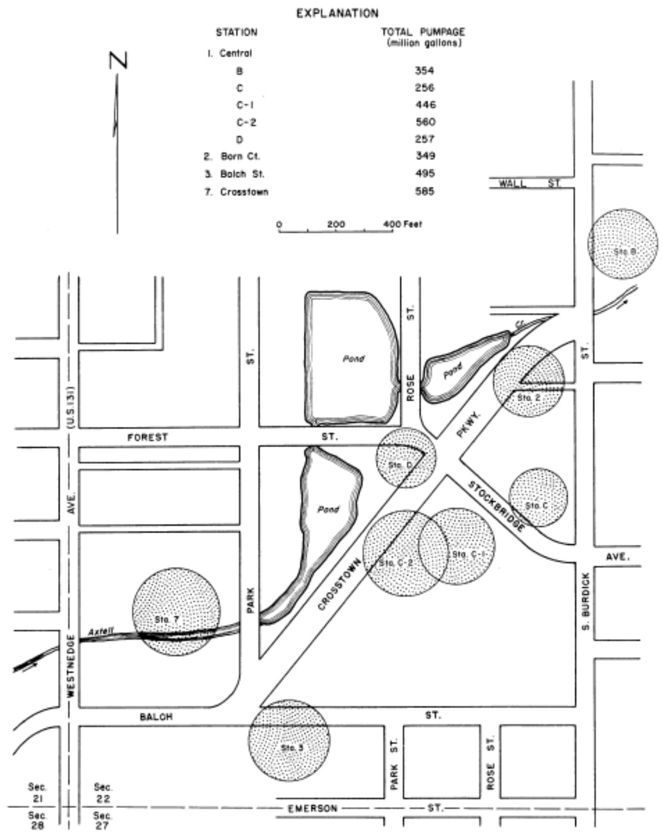

Figure 15. Distribution and magnitude of municipal ground-water pumpage in the Axtell Creek area, 1957.

Fluctuations of water levels, primarily in response to natural influences, are illustrated by the hydrographs of wells 2S 11W 20-7, 26-3, and 29-3 (fig. 17). The hydrographs show that the water levels in these wells in and near the city of Kalamazoo have remained relatively steady, barring seasonal fluctuations, during the period 1946-57. The water levels in these wells were somewhat higher during the period 1946-52 than in 1953-57. The relatively high water levels which were observed in 1950, 1951, and the early part of 1952 resulted from above average precipitation during that period. The lower levels during the latter period of record resulted from deficiencies of precipitation during the second half of 1952, and in 1953, 1955, and 1956 (figs. 3 and 18). Precipitation continued to be deficient until the fall of 1957, and the water level fell to a record low in well 20-7 at the Western Michigan University golf course, and to a near-record low in well 29-3 at Wood's Lake. Subsequently, levels rose in response to more than 11 inches of precipitation during the last quarter of 1957.

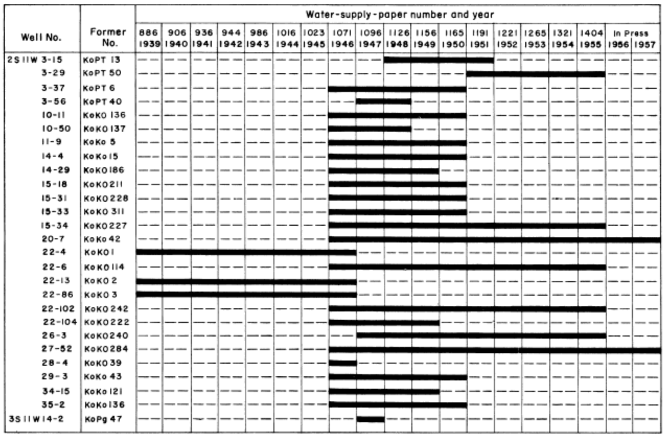

Figure 16. Chart showing length of water-level records for observation wells in the Kalamazoo area published in U.S. Geological Survey water-supply papers, 1939-57.

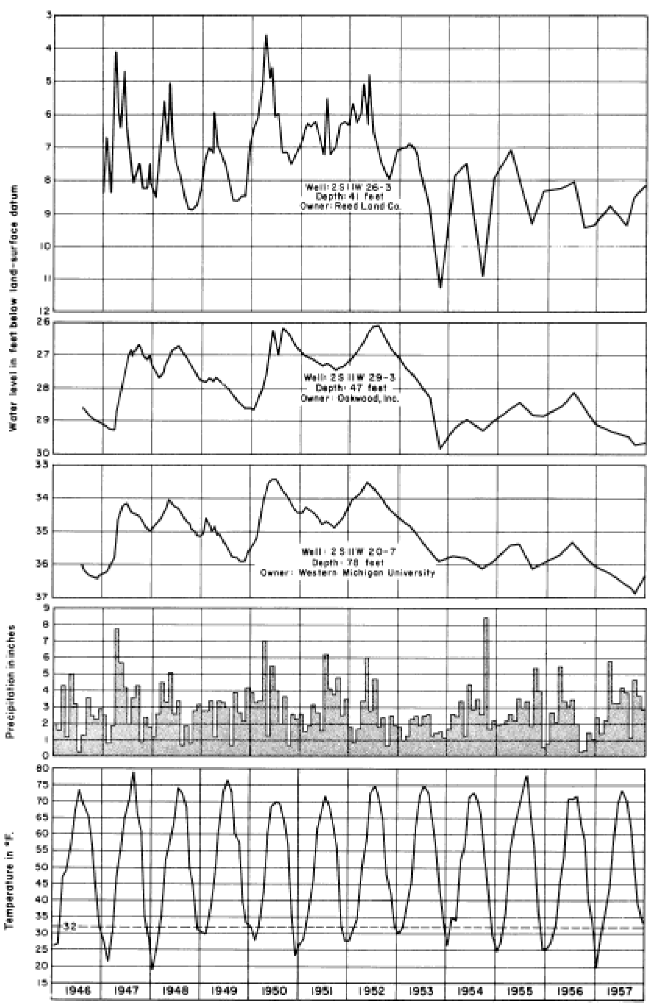

Figure 17. Hydrographs of observation wells, monthly totals of precipitation, and monthly mean temperatures at Kalamazoo, 1946-57.

Pumping Influences

Generally, ground water is a renewable natural resource because it is intermittently or continually being replaced directly or indirectly by precipitation. If an aquifer is to be developed by means of wells so that a long-term yield can be obtained, then the average rate of recharge must balance the rate of discharge. An approximate dynamic equilibrium between recharge and discharge exists in any aquifer in its natural state (before it is tapped by wells). When water is withdrawn from an aquifer by a well, a temporary change in the total discharge from the aquifer results. The pumping of the well causes a cone-shaped depression in the piezometric surface around the well. With continued discharge, the cone of depression expands until the resultant lowering of water level causes a decrease in discharge from the aquifer or an increase in recharge to the aquifer, or a combination of the two, which tends to restore the aquifer to a state of equilibrium. If the discharge from a well or group of wells exceeds the total available recharge, the water level will continue to decline so long as the discharge continues. Where a number of wells are pumped, a composite cone of depression is formed, which may extend over a large area. Water levels in other wells within this cone of depression also are lowered, even if the wells are not pumped.

A lowering of the water level, therefore, is a necessary result of the development of an aquifer. Historical data (Leverett, 1906a) reveal that artesian pressures in the aquifer in the vicinity of the Central Pumping Station at Burdick Street were sufficient to cause water to flow above the land surface. The development of the aquifer at this station has lowered the piezometric surface below the land surface. The graphs on figure 18 indicate that recharge by normal precipitation and by induced infiltration from surface sources is adequate to support pumpage of about 3 to 3.5 billion gallons annually without a further appreciable lowering of the water level. The declining trend, in water levels from 1952 to 1957 apparently resulted from deficiencies of precipitation during this period, as pumping In the area has remained relatively constant (fig. 13). It is probable that normal precipitation for a period of several years, a slight decrease in pumpage, or a slight increase in artificially induced recharge would halt the declining trend in water levels. It is apparent from the data shown on figures 12, 13, and 18 that the glacial-drift aquifer in this area is a very productive source of water, inasmuch as billions of gallons of ground water have been pumped In this vicinity for the past 90 years, with relatively little drawdown of water levels.

Wells 2S 11W 15-18, 15-31, 15-33, and 15-34 (fig.19) are in the business district of Kalamazoo, and they all tap the channel deposits along the Kalamazoo River. The glacial drift In this area ranges in thickness from about 75 to 150 feet (fig. 6, table 2). Water levels in these wells fluctuate in response to pumping and to seasonal climatic changes which Influence the rate of recharge to the aquifer.

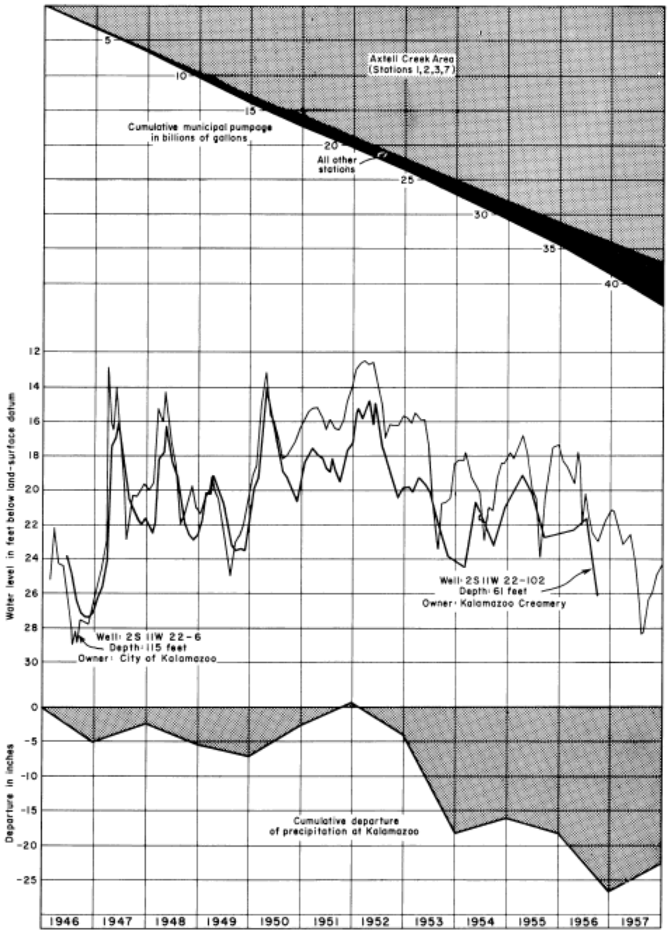

Figure 18. Cumulative municipal pumpage, hydrographs of wells 2S 11W 22-6 and 22-102, and cumulative departure of precipitation, 1946-57.

The total range In water-level fluctuations in these wells is comparatively small, and the lowest level recorded was about 27 feet below the land surface, in well 2S 11W 15-34. In 1953, however, the frequency of measurements in the wells was reduced from monthly to quarterly, and the range in fluctuations recorded since then is probably not as great as the actual range. Water levels in wells in this area generally will not decline to stages below that of the Kalamazoo River except in localized cones of depression caused by pumping. Ground water is naturally discharged to the Kalamazoo River as the ground-water level is generally above river stage. Arcadia Creek, Portage Creek, and the Kalamazoo River are potential sources of recharge, but they do not replenish the aquifer in the downtown area, as recharge from precipitation and underflow is adequate to meet present demands. A number of wells in the business district recharge the aquifer with disposed air-conditioning water.

Figure 20 shows hydrographs of observation wells located in industrial well fields where nearby surface streams are a potential source of recharge by induced infiltration. The hydrographs of the wells at the Kalamazoo Vegetable Parchment Co. plant at Parchment show a maximum range in water-level fluctuations of about 6 feet. Hydrographs of wells 2S 11W 3-56, 3-15, and 3-29 are combined to cover the period 1947-56 and are reduced to a common datum in feet above sea level. The fact that water levels in these wells do not decline below river stage in a heavily pumped aquifer indicates that the river becomes a source of recharge when the cone of depression caused by pumping intersects it.

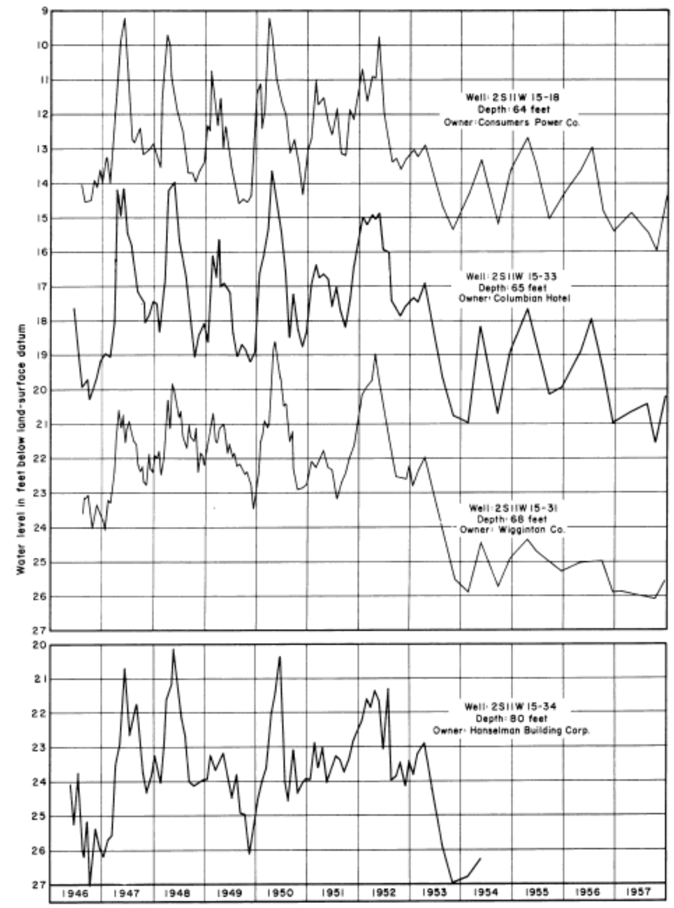

Figure 19. Hydrographs of observation wells in the Kalamazoo business district, 1946-57.

The water level in observation well 2S 11W 10-11, at the Sutherland Paper Co. plant on the north side of Kalamazoo, ranged from 2 to 20 feet below the land surface. The cone of depression around the pumped wells in this field extends to the Kalamazoo River, and thus the river is a source of recharge. Heavy pumping in this field causes drawdowns of water level which in some wells are to stages below the screens (see tables 3 and 4). The relatively large pumping drawdowns in wells in this field, some of which are very close to the edge of the Kalamazoo River, to levels substantially below the river stage indicate that sedimentation and precipitation of solids from industrial effluents have substantially reduced recharge to the aquifer along this reach of the river.

Water levels in observation well 2S 11W 27-52, alongside Portage Creek in the well field of the Bryant Paper Co. (now St. Regis Paper Co.), have ranged for the most part between 35 and 50 feet below the land surface, or about at the level of Portage Creek. The low water levels recorded in 1946 probably were caused by heavy pumping during and immediately after World War II.

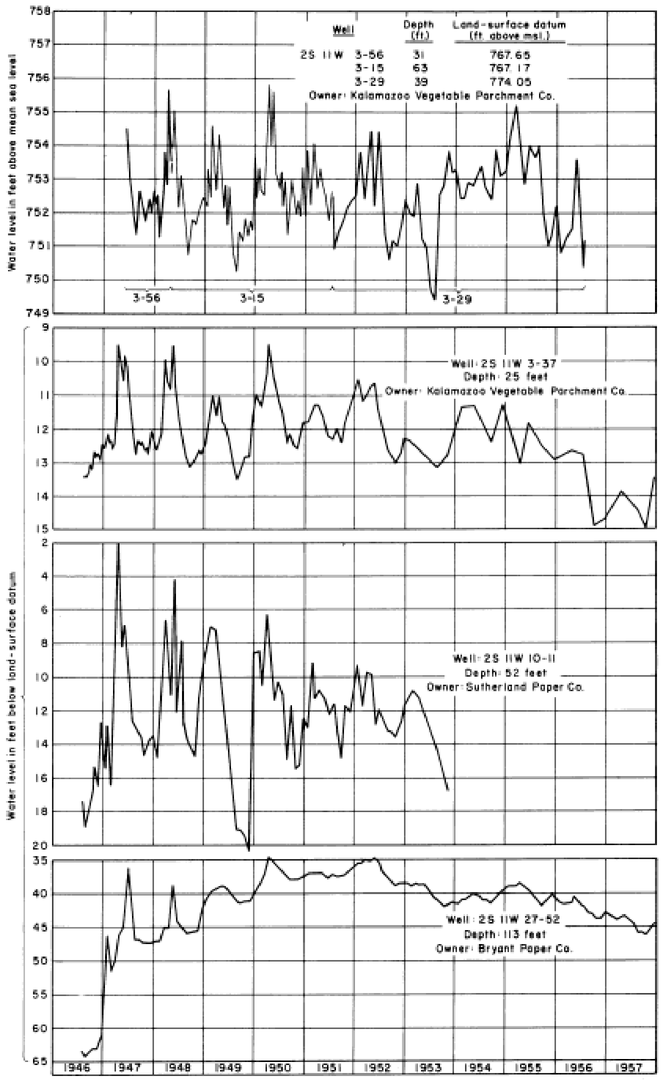

Figure 20. Hydrographs of observation wells in industrial well fields adjacent to the Kalamazoo River or Portage Creek, 1946-1957.

Aquifer Tests

The most effective method for determining the amount of water that can be obtained from an aquifer is by analysis of records of water levels and pumpage. Such data, which are presented above, were supplemented by a number of aquifer (pumping) tests made during the period 1944-57 to determine the hydraulic characteristics of the channel and outwash deposits in the area.

By methods devised by Theis (1935) and others, the coefficients of transmissibility (T) and storage (S) of an aquifer can be determined. Aquifer tests usually consist of pumping one well at a given rate and measuring the resultant change in water levels in nearby observation wells. The observed changes are then compared with the type curve of Theis' non-equilibrium equation.

The Theis equation, which may be used to predict water-level changes from anticipated pumping rates, is as follows:

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

Where

T = coefficient of transmissibility, in gallons per day per foot

Q = rate of pumping, in gallons per minute

s = drawdown or recovery of water level, in feet
W(u) = well function of u

or

$$W(u) = \int_u^{\infty} \frac{e^{-u}}{u}\, du$$

and

$$u = \frac{1.87\ r^2\ S}{T\ t}$$

r = distance from pumped well, in feet

t - time since pumping started or stopped, in days

S = coefficient of storage

The formula is based on the assumption that the aquifer is infinite in extent, that it is homogeneous and isotropic (transmits water in all directions with equal facility), that its coefficients of transmissibility and storage are constant, that water is under artesian conditions, and that the water is released from storage instantaneously with the decline in head. The assumptions on which the formula is based must be met, or appropriate adjustments must be made in the formula. The presence of boundaries of the aquifer, leakage through the confining beds, and lowering of the water level below the upper confining bed are among the conditions that nullify the basic assumptions of the formula and therefore require adjustment.

The aquifers in the Kalamazoo area depart considerably from the ideal aquifer of the Theis equation. They are limited in areal extent, vary in permeability both vertically and horizontally, locally are hydraulically connected to surface waters which form recharge boundaries, and generally leak considerable water through the confining layers. Thus, the coefficients of transmissibility and storage can only be approximated from the tests conducted in the area. Whether surface water recharges the aquifer when a well is pumped may commonly be determined by use of a method devised by Ferris (1948). In the Kalamazoo area, however, use of this method is complicated by the fact that the aquifers are generally recharged indirectly through leaky confining layers (fig. 9).

Sutherland Paper Co. (July 16, 1944)

A test was made in the Sutherland Paper Co. well field along the Kalamazoo River in sec. 10, T. 2 S., R. 11 W. The aquifer at this site is composed of about 60 feet of sand and gravel, but it includes layers of clay and sandy clay. The surface of the Coldwater shale at this site ranges from about 55 to 90 feet below the land surface.

Well 2S 11W 10-46, which is screened from 57 to 82 feet (table 4) was pumped at a rate of 232 gpm for several days. The pump was then stopped and the recovery of water levels was measured in 12 observation wells.

Analysis of the test data indicates that T is in the range of 18,000 to 24,000 gpd per foot. The aquifer is under semiartesian conditions, in that there is a wide range in vertical permeability in the aquifer. The test indicates that the Kalamazoo River is a source of recharge. Movement of water from the river to the screened portion of the aquifer is impeded, however, by several clay lenses within the drift section. Although more recent test data for this site are not available, yields reportedly have declined since the date of the test, presumably because of diminishing recharge from the Kalamazoo River.

Station C-1 (February 12, 1947)

The aquifer at Station C-1, near Axtell Creek, is composed of about 160 feet of sand and gravel and a few layers of silt. Well 2S 11W 22-51 (C-1-4), which is screened from 154 to 174 feet, was pumped for this test at a rate of 350 gpm. Drawdown of water levels was measured in three observation wells.

The aquifer at this site shows semiartesian conditions as a result of wide variations in vertical permeability. The test indicates that the aquifer is recharged by Axtell Creek. The coefficient of transmissibility cannot be determined precisely from the test data, but a figure in excess of 100,000 gpd per foot is indicated.

Station 3 (February 28, 1947)

The aquifer at Station 3 consists of more than 200 feet of sand and gravel (see log of well 2S 11W 22-94, table 2). Station 3 is in the Axtell Creek area (fig. 15).

Well 2S 11W 22-91 was pumped at a rate of 400 gpm. The drawdown of water levels was measured in five observation wells.

The coefficient of transmissibility of the aquifer at this site as calculated from the test is about 300,000 gpd per foot and the coefficient of storage about 0.17. A coefficient of storage of this magnitude is typical of water-table conditions. Axtell Creek is probably a source of recharge to the aquifer, although the test was not long enough to provide data adequate to prove this.

Upjohn Co. (June 24, 1947)

The glacial drift at the Upjohn Co. test site is about 300 feet thick, and the upper part of the drift section consists of layers of sand and gravel. The pumped well of this test (3S 11W 14-1) is 120 feet deep and screened from 85 to 95 feet and from 100 to 115 feet. The well was pumped at a rate of 280 gpm for 24 hours. Water levels in 1 deep well that was screened at the same depths and in 8 shallow wells that penetrated a short distance below the water table were measured during the test. The greatest drawdown in any of the observation wells was recorded in the deep well, which is farther from the pumped well than any of the eight shallow wells. The test revealed that the aquifer is under semiartesian conditions, in that there is a great difference In vertical permeability. The indicated transmissibility of the part of the aquifer tapped by the pumped well is 65,000 gpd per foot. However, the transmissibility of the entire aquifer probably is considerably greater.

Station 8 (July 23, 1948)

The wells at Station 8 tap about 50 feet of sand and gravel which is overlain by about 75 feet of clayey drift (table 2, logs 3S 11W 3-2, 3-7, 3-8, and 3-10.) About 20 feet of permeable sand and gravel channel deposits lie at the surface but are not used as a source of supply. The wells at this station are drilled along a line adjacent to Portage Creek, which trends roughly north-south.

The pumped well of the test (3S 11W 3-3) was flowing at a rate of 300 gpm prior to the start of pumping. During the test the well was pumped at a rate of 650 gpm, and the drawdown was measured in nine observation wells. The transmissibility was calculated as 42,000 gpd per foot. The fact that the wells at this station flow when they are not being pumped, and that a typically artesian coefficient of storage of 2.4×10^{-4} was determined by the test, demonstrates that the clayey drift in this area forms an efficient confining layer.

Station 9 (October 14, 1949)

The wells at Station 9 penetrate about 160 feet of glacial drift consisting of layers of sandy and gravelly clay and about 100 feet of permeable sand and gravel. The West Fork of Portage Greek flows through the station. The pumped well of this test (3S 11W 4-3) and the other production wells at this station are completed in about 40 feet of sand and gravel which is present from about 120 to 160 feet. This aquifer is overlain by materials that contain a considerable amount of clay and silt and form a very leaky artesian cap (fig. 9).

The pumped well yielded 300 gpm during the test. The drawdown was measured in four observation wells, and recovery was measured after pumping was stopped.

The transmissibility at this site was calculated as 110,000 gpd per foot. The aquifer is semiartesian, as the upper zone is of lower permeability but does not form an efficient confining layer. The test proved that the

West Fork of Portage Creek is a source of recharge to the aquifer. The relatively high transmissibility of the aquifer and the availability of abundant recharge combine to make this site a productive source of ground water.

Kalamazoo Vegetable Parchment Co. (June 26, 1950)

The aquifer at the test site consists of a layer of coarse-gravel channel deposits at a depth of 23 to 48 feet. A layer of clayey material 7 feet thick forms an artesian cap over the aquifer. The aquifer is underlain by about 35 feet of clay till, which mantles the Coldwater shale.

The pumped well (1S 11W 34-7) yielded 470 gpm. Water levels in 12 observation wells were measured during the test. The transmissibility was determined to be about 230,000 gpd per foot. Divided by 25, the thickness of the aquifer in feet, this gives an average permeability of 9,200 gpd per square foot, the highest determined in the report area. The coefficient of storage is 2.7×10^{-4} which indicates that the layer of clay above the aquifer forms an efficient artesian cap.

The data from the test show that the Kalamazoo River, which is about 300 feet southwest of the pumped well, is a source of recharge to the aquifer. This is demonstrated also by the fact that water-level, fluctuations in the aquifer closely correlate with fluctuations in river stage. The test data and correlation of river stage and ground-water level indicate that the artesian cap is breached along the river.

Cahill Farms, Inc. (October 21, 1957)

The aquifer that underlies the site of the Southland Subdivision, in Portage Township, is composed primarily of medium and coarse sand and some fine gravel. Well 3S 11W 9-2, which is screened from 139 to 185 feet, was pumped at a rate of 770 gpm, and one observation well was measured during the test. The aquifer is semiartesian, in that a layer of sandy clay between depths of 32 to 43 feet (table 2) forms a very leaky artesian cap over the part of the aquifer in which the well is screened. The coefficient of transmissibility of the part of the aquifer tapped by the well is about 130,000 gpd per foot. The part of the aquifer above 32 feet also contributes water to the well through vertical leakage. The effects of the vertical leakage were clearly illustrated during the test f when the water level in the observation well rose in response to rainfall.

CHEMICAL QUALITY OF THE WATER

Water percolating through soil and rocks dissolves some of the material with which it comes in contact. The amount and character of the dissolved mineral matter in ground water depend on the chemical and physical composition of the rocks through which the water moves, the duration of the contact, and other factors such as temperature, pressure, and amount of mixing, if any, with highly mineralized connate water (water entrapped at the time the sediment was deposited).

Water in the glacial drift is predominantly of the calcium magnesium bicarbonate type. The calcium, magnesium, and bicarbonate ions are derived largely from particles of limestone and sandstone which are major constituents of the glacial drift. Some of the water pumped from the drift, however, is of the calcium sulfate type. The Coldwater shale and the basal till, which was derived mainly from the shale, are the principal sources of the calcium sulfate in the water of the Kalamazoo area.

Concentrations of sulfate are commonly greatest in water from wells completed in sand and gravel that are in contact with shale or basal till. The lowering of water levels by pumping tends to induce upward migration of the calcium sulfate water into the glacial-drift aquifers. In Holland, Mich., where drift aquifers overlying the Coldwater shale were used as a source of supply, the concentration of sulfate in water from the municipal well fields increased with decline in water levels (Deutsch and others, 1959). Well 2S 11W 10-40, drilled to a depth of 50 feet, is completed a few feet above the basal till and shale and yielded water containing 225 ppm of sulfate (table 5). The highest sulfate concentration observed was in a sample taken from well 2S 11W 25-9, which also is completed in the drift near the surface of the Goldwater shale. It is believed that both the samples were taken at times when water levels were lowered by pumping. The Michigan Department of Health (1948) classifies water containing 250 ppm or more of sulfate as objectionable. Most of the ground water in the area, however, contains only relatively minor amounts of sulfate.

Nearly all the ground water in the Kalamazoo area is hard or very hard. Hardness is caused almost entirely by calcium and magnesium in the water. The hardness of ground-water samples collected in the area ranged from 185 ppm in well 2S 11W 32-1 to 580 ppm in well 2S 11W 10-40. Water is classified with respect to hardness by the Michigan Department of Health as follows:

Class	Hardness (parts per million)
Very soft	……………………………less than 50
Soft	…………………………………..50-100
Moderately hard	…………………………………100-200
Hard	…………………………………200-300
Very hard	…………………………more than 300

(Hardness may be computed also in grains per gallon. One grain per gallon equals 17.1 ppm.)

The presence of appreciable quantities of iron in the form of bog ore was noted in the Kalamazoo area as early as 1840 (Douglass, 1928). Iron in the glacial drift and the bog ore are sources of objectionable quantities of iron present in ground water in parts of the Kalamazoo area. The iron content ranges from 0 to 7.5 ppm. Iron content exceeding about 0.2 will cause staining, and more than 0.3 ppm of iron, or iron and manganese together is considered objectionable in this regard (Michigan Department of Health, 1948). The city of Kalamazoo adds a sequestering agent to water high in iron content in order to prevent precipitation and staining.

The chemical quality of surface water in the area shows a definite relation to the quality of ground water yielded by wells near these streams (fig. 21). The similarity in chemical composition of surface- and ground-water samples indicates that the streams are fed largely by effluent seepage. Austin Lake, which is on the ground-water divide between the St. Joseph and Kalamazoo River drainage basins, is fed mainly by precipitation and is lower in mineral content than the ground-water-fed streams. The surface water of the area is generally somewhat lower in mineral content than the ground water. Additional information is needed regarding the effects of surface-water recharge on the quality of ground water.

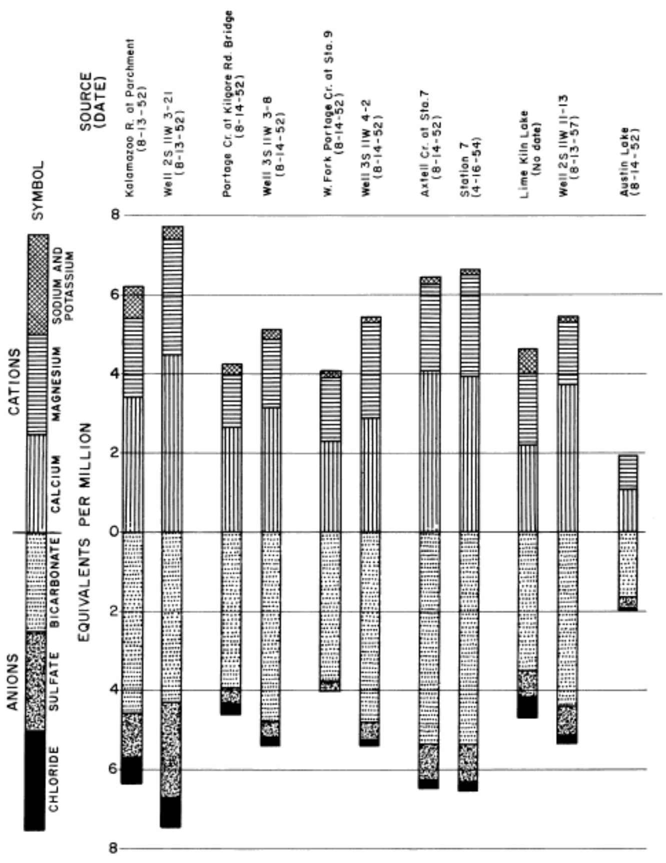

Figure 21. Diagrams showing the relation in chemical composition of ground water and surface water from nearby sources.

Ground-water temperatures range from about 50° to 58°F. This rather wide range reflects the influence of surface water recharged to the aquifers from nearby sources. The temperature of water from wells distant from surface sources commonly varies only 1° or 2°F throughout the year.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE STUDIES

The glacial-drift aquifers within the Kalamazoo area are adequate for present municipal and suburban demands and also for considerable additional development. With proper use and husbandry of the resource guided by continuing scientific development and research, ground-crater supplies in the area will be adequate to satisfy future requirements greatly exceeding present demands. An accurate quantitative appraisal of the total resource, however, cannot be made on the basis of presently available information.

Data from the Axtell Creek area indicate that under normal climatic conditions the present high water levels (and low pumping lifts) can be maintained if the total annual pumpage is restricted to the present rate of about 3 to 3.5 billion gallons per year, and if the surface recharge ponds are maintained at present efficiency. Construction of artificial-recharge facilities comparable to those already in operation probably would result in considerably increased yields at other pumping stations without significant lowering of water levels. Continuous observations of water levels should be made in and near major well, fields to determine the amount of drawdown caused by pumping. This information would reveal if pumping is exceeding recharge, if recharge facilities are declining in efficiency, and if the cones of depression in the well fields are expanding.

The city's program of construction of well fields, at widely spaced sites where surface water can be utilized as a supplementary source of recharge to the aquifer, has met with considerable success, especially at the stations where surface storage capacity has been artificially increased. Continuation of this program will most likely result in the location of new sites where additional large supplies of water may be obtained.

Although the Kalamazoo River is a potential source of recharge to ground water far in excess of foreseeable demands by industry, areas where geologic conditions are most favorable for recharge have not been delineated. Also, at present the extent to which recharge is impeded by natural and artificial, sealing of the river bottom is not known. Methods of effectively maintaining hydraulic connection between the river and the streamside aquifers and of inducing recharge should be investigated.

Quantitative appraisals of the effective recharge from surface sources to the aquifers at various well fields, and of the effect of sedimentation on the amount of recharge, should be made. A complementary study of the effects of recharging operations on water quality would also be desirable. The Kalamazoo area would provide an ideal field laboratory where such a study could be made. Results of such studies are of considerable potential value not only to water users in the Kalamazoo area but also to numerous communities in similar hydrologic settings elsewhere.

Test drilling and detailed geologic studies would be desirable, to enable determining more accurately the location, thickness, and extent of permeable sand and gravel deposits within the buried valleys in the bedrock surface, both In the vicinity of existing high-capacity well fields and in the vicinity of new ones constructed in the future.

REFERENCES CITED

Bennett, S. V., and Jordan, J. E., 1950, Resources for industry in Kalamazoo: W. E. Upjohn Inst. Community Research (Kalamazoo), mimeo. rept., 32 p.

Corps of Engineers, 1958, Flood emergency plan and disaster operating procedures, pt. 1: U. S. Dept. Army, Corps Engineers, Detroit Dist, rept.

Deutsch, Morris, Burt, E. M., and Vanlier, K. E., 1959, Summary of ground-water investigations in the Holland area, Michigan: Michigan Geol. Survey Prog. Rept. 20.

Douglass, C. C., 1928, Report of January 12, 1840 to the State Geologist in Fuller, G. N., ed., Geological reports of Douglass Houghton: Michigan Hist. Comm., p. 416-438.

Ferris, J. G., 1948, Ground-water hydraulics as a geophysical aide: Michigan Geol. Survey Tech. Rept. 1.

Giroux, P. R., 1958, Summary of ground-water conditions in Michigan, 1957: Michigan Geol. Survey Water-Supply Rept. 20

Kalamazoo City Utilities, 1954, The annual report for the year 1954: Kalamazoo Dept. City Light and Water Utilities Ann. Rept.

Lane, A. C., 1895, The geology of Lower Michigan, with reference to deep borings (edited from notes of C. E. Wright): Michigan Geol. Survey v. 5, pt. 2.

Lane, A. C., 1899, Lower Michigan mineral waters, a study into the connection between their chemical composition and mode of occurrence: U, S, Geol, Survey Water-Supply Paper 31.

Leverett, Frank, 1906a, Water supplies of Kalamazoo County, in Leverett and others, Flowing wells and municipal water supplies in the southern portion of the Southern Peninsula of Michigan: U, S, Geol, Survey Water-Supply Paper 182, p. 127-130.

Leverett, Frank, 1906b, Geological conditions of municipal and institutional water supplies in Michigan: Michigan Acad. Sci. Ann. Rept., v. 87 p. 99-136.

Leverett, Frank, 1912, Surface geology and agricultural conditions of the Southern Peninsula of Michigan: Michigan Geol. Survey Pub. 9.

Leverett, Frank, 1917, Surface geology and agricultural conditions in Michigan: Michigan Geol. Survey Pub. 25, pt. 2, chap. 2.

Leverett, Frank, and Taylor, F. B., 1915, The Pleistocene of Indiana and Michigan and the history of the Great Lakes: U. S. Geol. Survey Mon. 53.

Martin, H. M., compiler, 1955, Map of the surface formations of the Southern Peninsula of Michigan: Michigan Geol. Survey Pub. 49.

_________ 1957, Outline of the geologic history of Kalamazoo County: Michigan Geol. Survey dupl. rept.

Michigan Department of Health, 1948, Chemical analyses and their Interpretations -- Public water supplies in Michigan: Michigan Dept. Health Eng. Bull. 4.

Michigan Water Resources Commission, 1957, Flood conditions in the Kalamazoo area: Michigan Water Resources Comm. dupl. rept.

Norman, E. E., 1949, The annual report for the year 1949: Kalamazoo Dept. City Light and Water Utilities Ann. Rept.

Paulsen, C. G., and others, 1950, Surface water water supply of the United States, 1948, Part 4, St. Lawrence River Basin: U. S. Geol. Survey Water-Supply Paper 1114.

Sisson, W. H., 1955, Recharge operations at Kalamazoo (Mich.): Am. Waterworks Assoc. Jour., v. 47, no. 9, p. 914-922.

Taylor, H. C., 1956, The population of Kalamazoo County, Michigan -- Estimates as of July 19 1956 and forecasts to 1975: W. E. Upjohn Inst. Community Research (Kalamazoo) dupl. rept., 22 p., Sept.

Terwilliger, F. W., compiler, 1958, Map of the bedrock topography of southwestern Michigan: Michigan Geol. Survey ms. Map, unpub.

Theis, C. V., 1935, The relation between lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., p. 519-524, Aug.

Wells, J. V. B., and others, 1958, Surface water supply of the United States, 1956, Part 4, St. Lawrence River Basin: U. S. Geol. Survey Water-Supply Paper 1437

DEPARTMENT OF CONSERVATION
Gerald E. Eddy, *Director*

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