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Water Resources in a Rapidly Growing Region — Oakland County, Michigan

Open File Report 2005-1269

U.S. Department of the Interior
U.S. Geological Survey

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By Stephen S. Aichele

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^2 pt)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
gallon per minute (gal/min)	0.06309	liter per second (L/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
gallon per day per square mile [(gal/d)/mi^2]	0.001461	cubic meter per day per square kilometer [(m^3/d)/km^2]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
million gallons per day per square mile [(Mgal/d)/mi^2]	1,461	cubic meter per day per square kilometer [(m^3/d)/km^2]
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton per year (ton/yr)	0.9072	metric ton per year

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8 × °C)+32

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water Resources in a Rapidly Growing Region - Oakland County, Michigan

By Stephen S. Aichele

Abstract

Oakland County is a suburban county in southeast Michigan. Population and demand for water grew steadily in the county over the 20th century, and these trends are expected to continue in coming decades. Roughly 75 percent of current water demand is met by imported water from the Detroit Water and Sewerage Division (DWSD), but water use from ground-water sources within the county still exceeds 43 million gallons per day. Because much of the population growth is in areas beyond the DWSD system, an additional 20-25 million gallons per day of supply may be necessary to meet future demands. Managing the wastewater produced while also protecting human and ecosystem health also may present challenges.

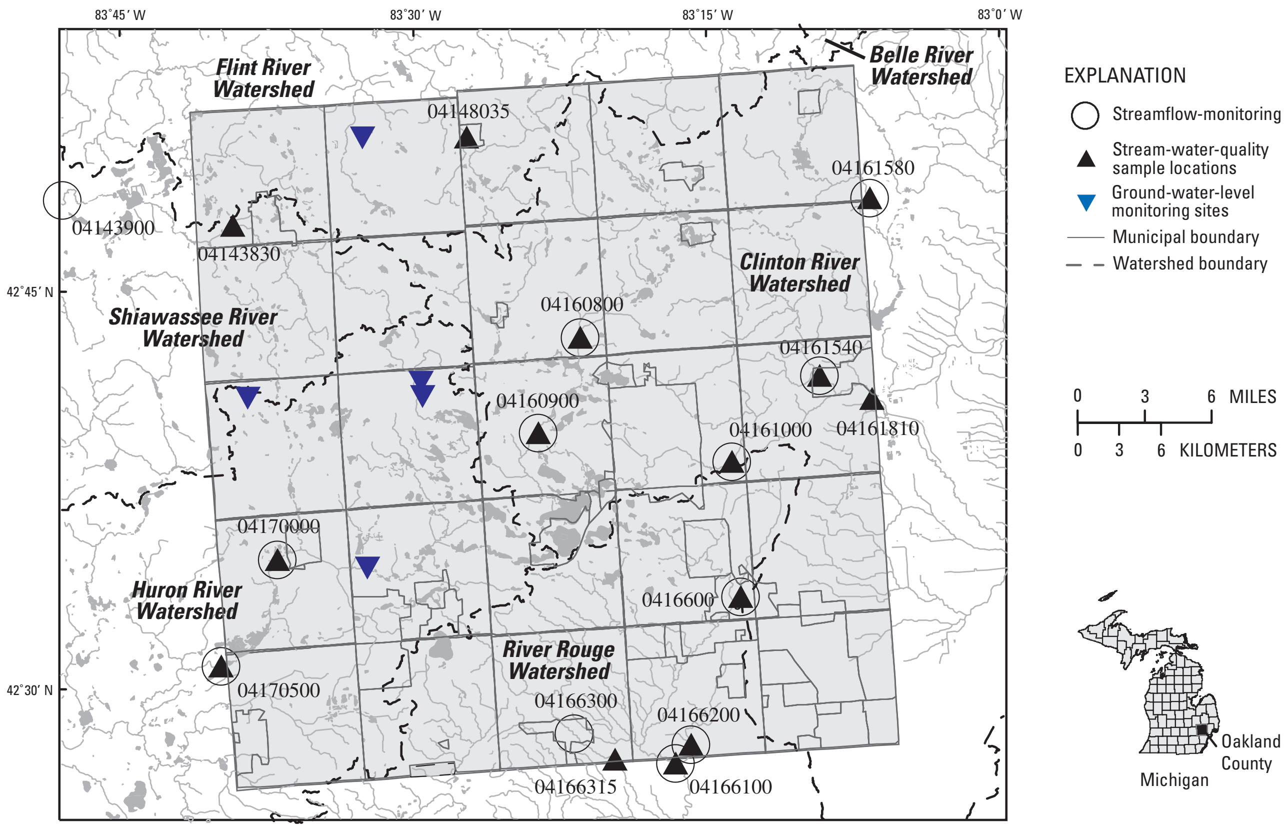
Despite considerable expansion of urban areas, streamflow characteristics at most sites have not been affected. However, at several sites in areas of the county that are both supplied by ground water and sewered, statistically significant downward trends in low-flow stream discharges have been noted between 1970 and 2003. Stream chemistry, compared to a previous study of county water resources prepared in 1972, has generally improved, with marked decreases in concentrations of nitrogen, phosphorus, and sulfate. Chloride concentrations, however, have increased dramatically in river and lake water across the county. Detectable concentrations of personal-care products, flame retardants, and petroleum fuel compounds were identified at all river sites sampled.

Introduction

In 1972, the U.S. Geological Survey (USGS) published Water Supply Paper 2000, "Water for a Rapidly Growing Urban Community— Oakland County, Michigan" (Twenter and Knutilla, 1972). In 2001, Oakland County and the USGS initiated a cooperative project to update the 1972 study in light of changes in the county as well as advances in the field of hydrology. From 2001 through 2003, the USGS monitored stream flow and water quality, ground-water level, and lake-water quality at sites throughout Oakland County (fig. 1). Several recent USGS technical reports document specific aspects of the study: a data report (Aichele and others, 2004), a report describing characteristics of the glacial aquifer (Bissell and Aichele, 2004), a report describing the effects of urban land-cover change on water resources (Aichele, 2005), and a report describing the microbiological quality of rivers and streams in Oakland County (Fogarty and others, 2005).

This report summarizes the results and conclusions in the above-mentioned USGS technical reports and serves as an overall assessment of the current quantity and quality of water resources in Oakland County. It also describes changes in the quantity and quality of water resources in Oakland County during the past 30 years.

In 1972, about 850,000 people lived in Oakland County, and used about 100 million gallons of water per day (Mgal/d). In 2000, about 1.2 million people lived in Oakland County an increase of nearly 50 percent. In



Political boundaries from Oakland County GIS Utility, 2003.
Hydrographic data from USGS 1:100,000 scale Digital Line Graphs.

Figure 1. USGS water-monitoring stations used in this study.

2000, Oakland County's water use totaled 168 Mgal/d, an increase of 68 percent. About 75 percent of water currently used in the county is supplied from the Great Lakes and connecting channels by the Detroit Water and Sewerage Department (DWSD). In 2000, DWSD supplied 785,000 residents with 125 Mgal/d, slightly less than 160 gallons per day (gal/d) per person. Community ground-water supplies in the county delivered 23 Mgal/d to 169,000 Oakland residents, slightly more than 135 gal/d per person. A further 240,000 residents met their water needs with on-site domestic wells, which delivered an estimated 21 Mgal/d, or approximately 86 gal/d per person.

In Oakland County, population and demand for water continue to grow. Over the next 20 years, population is expected to grow by an additional 200,000, requiring an additional 20 Mgal/d. Much of this growth is expected to be in the northern and western parts of the county, where water needs are currently met from ground-water sources. This report, supported by the previously published USGS technical reports, is intended to provide decision makers, water-resources managers and interested citizens in Oakland County with information necessary to meet not only the recreational, esthetic, and water-supply needs of residents but also to meet the ecological demands of lakes, rivers, and wetlands. In addition, this report provides a retrospective look at the effects of population growth in Oakland County on water quality and water availability. This information will be useful in areas with similar hydrogeologic settings that are experiencing rapid population growth and its accompanying demands on water resources.

Water has always been an important part of life in Oakland County, in obvious and in subtle ways. When settlers first began coming to Michigan, Oakland County's many lakes, streams, and wetlands made it a good place for hunting and trapping. Later, agriculture thrived, supported by abundant water and fertile soils. In the early 1900s, many small communities developed waterworks around flowing wells (Leverett and others, 1906). Through the 20th century, water was important to industry, and water continues to be vital to the continued health of Oakland County's residents, environment, and economy (fig. 2). The most obvious and basic need is for drinking water. However, water is also vital for diluting and removing waste, including wastewater and stormwater, from the county. The many lakes and streams in Oakland County are important natural features that have esthetic appeal and attract tourists, vacationers, new homeowners, and businesses to the community. In addition, fish, waterfowl, and other wildlife all depend on the continued availability of clean water.

Water in the ground, on the ground, or in the air is all part of a single resource (Winter and others, 1998). Water used from the environment for one purpose, such as drinking water or industrial cooling, may not be available—or may not be of sufficient quality when returned to the environment—to be used for other purposes, such as sustaining aquatic ecosystems and habitats. For example, water pumped from the ground for household use and released to a sewer system is no longer available for discharge to a local wetland, lake, or river. Resource needs commonly compete; for example, increased ground-water withdrawal for public consumption can compete against the water needed to support aquatic life and habitat in a river, or the need to maintain a specific lake level for recreational use can compete against the quantity of summer streamflow required to dilute wastewater discharge downstream in the same watershed. This report, like the Twenter and Knutilla (1972) report, is intended to provide county and local officials, and interested citizens, with the background information needed for informed decision making.

To manage competing demands on the water resources of Oakland County, a comprehensive assessment of the current state of the resource is required. Some of the natural factors affecting this resource include the climate, physiography, and geology of the county. However, much of the water resource in Oakland County have already been affected in various ways by human activity. This report includes three major sections intended to address these issues. The first section is a summary of data available on the natural and built landscape of Oakland County, including climatology, soils, land cover, and population. The second section is an overview of the hydrologic cycle and how people and water interact in Oakland County. The third section of the report is an assessment of the current status of water resources in Oakland County, drawn from several recently published technical reports. This section describes the current quantity and quality of water resources in the county, including comparison to the information presented in Twenter and Knutilla's 1972 report where appropriate. More detailed information on specific topics can be obtained in the referenced technical reports.

Oakland County — Population and Land

Oakland County comprises 910 mi^2 of land in the southeastern part of Michigan's Lower Peninsula.

Figure 2. Water has many uses in Oakland County.

Southeastern parts of the county are just a few miles from downtown Detroit, but the northwestern parts are approximately 40 miles distant (fig. 3). The county includes 63 cities, villages, and townships, and includes the headwaters of 6 rivers. Although much of Oakland County was either rural or a suburb of Detroit in 1972, several communities have since become centers of economic activity in their own right and have spawned their own suburban communities.

The distribution of commercial development in Oakland County is driven by the transportation network. The primary axis of development is along the Interstate 75 corridor which links Detroit, Pontiac, and Flint. This corridor is crossed by the Interstate 96/696 corridor in the south and the Michigan Route 59 corridor across the central tier of townships. These three corridors have formed the basic framework for development in Oakland County. Overlaid on this framework is a similar distribution of residential development, with the highest densities generally in the southeast, followed by the southwest, the northwest, and the lowest densities in the northeast.

People

The population of Oakland County has grown steadily since about 1900 (fig. 4). Growth has averaged approximately 100,000 new residents per decade throughout the 20th century. From a base of around 50,000 residents and a primarily agricultural economy in 1900, the rise of manufacturing in the county spurred the population to almost 400,000 in 1950. During the 1950's and 1960's, the growth of suburbs in the southern part of the county as well as continued expansion in manufacturing attracted over 30,000 new residents per year to the county and over 20,000 new residents per year in the 1970's. By 1980 the population stood at slightly over one million. Most of these new residents located in suburban communities built in the southeastern corner of the county. Following a brief pause in growth in the early 1980's, the county has continued to add about 10,000 new residents every year. In each wave of growth, expansion has happened in a series of roughly concentric circles radiating from Detroit. With 1.2 million residents, Oakland County has a total popula-

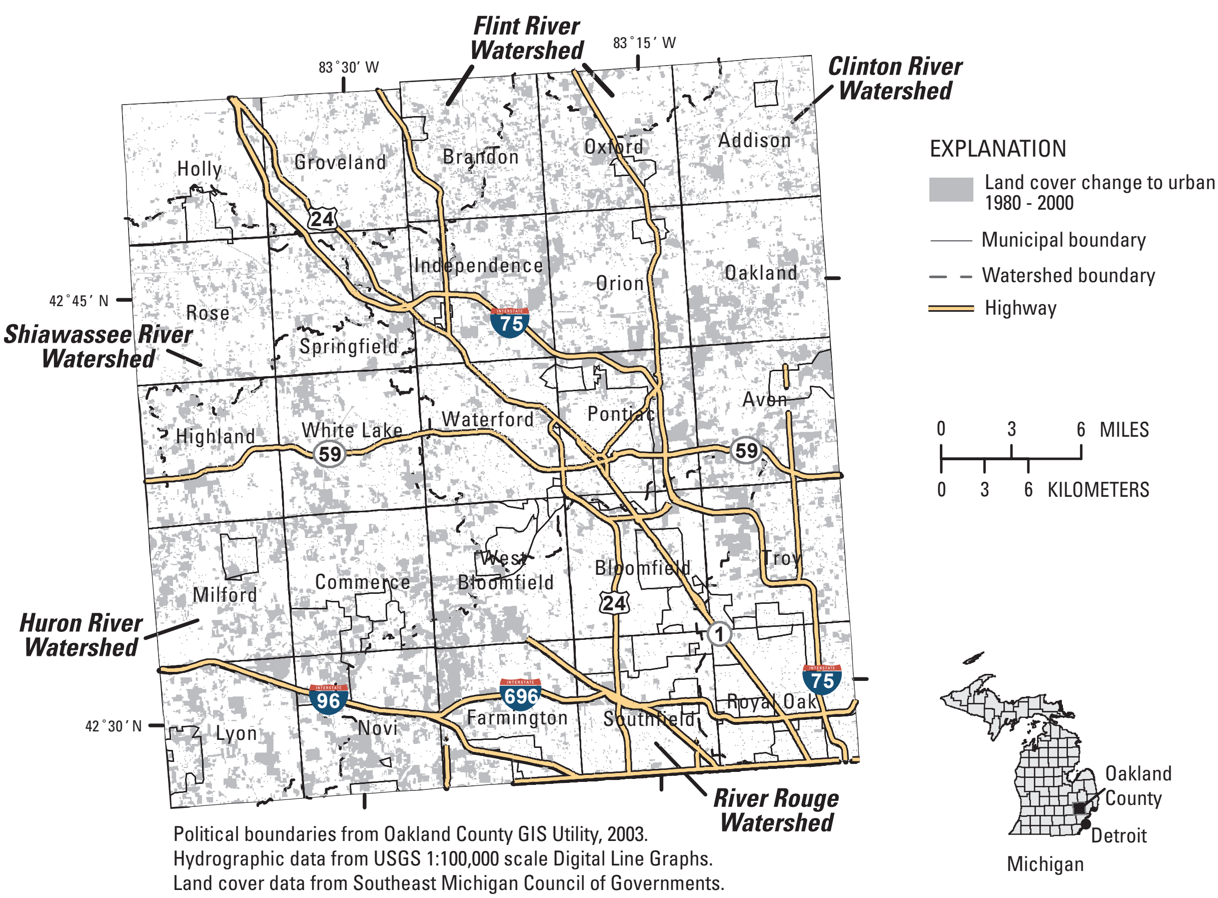


Figure 3. Oakland County is a rapidly urbanizing area in southeastern Michigan, near Detroit.

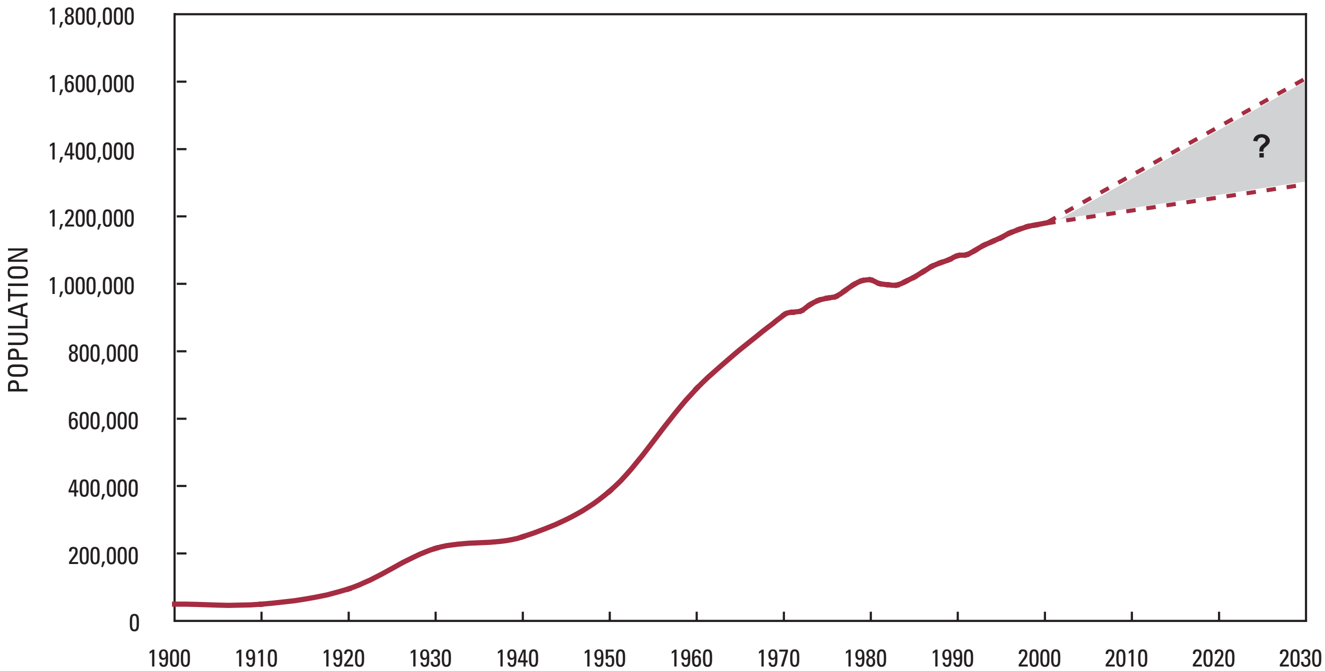


Figure 4. Population growth in Oakland County has averaged approximately 100,000 people per decade throughout the 20th century.

tion greater than 9 of the 50 United States, and is comparable in population to Hawaii or New Hampshire.

Increases in population bring accompanying increases in water demand. Although per-capita water use in Michigan, and in the United States, has decreased slightly over the past decade, the decrease has not occurred as rapidly as the population has increased. In the early decades of the 20th century, when the population of Oakland County was about 50,000 people, water use was estimated to be approximately three Mgal/d, drawn almost entirely from ground-water sources inside the county. Wastewater was largely returned through on-site systems such as cesspools, or discharged to surface water, –with little or no treatment, –in small communities with sewer systems. As the population of the county grew through the century, water continued to be supplied primarily from ground water within the county, hitting a peak of approximately 85 Mgal/d in the early 1960's. With the drought of the early 1960's, Oakland County began buying water from the DWSD, which provided water from Lake Huron, and the St. Clair and Detroit Rivers to the communities south and east of Pontiac. This relieved much of the stress on the aquifer system in the county, as evidenced by the rebound in the hydrograph of a monitoring well near Pontiac (fig. 5)

Residents of Oakland County consumed approximately 167.75 million gallons of water every day in 2000 (Luukkonnen, written communication, 2004). Of that, approximately 42.5 Mgal/d is supplied from the ground-water sources in the county (fig.6). The remainder is piped into the county by the DWSD.

As the population has expanded into the northern and western parts of the county, the number of people relying on ground water for their domestic water supply has increased. Although some new lines have been added to the DWSD supply system in recent years, most of the northern two tiers of townships, as well as Highland, White Lake, Waterford, Milford, and other areas in the county still rely on ground water for their water supply (fig. 7). Public ground-water suppliers delivered approximately 22.87 Mgal/d to 169,000 residents in 2000, and an additional 240,000 residents used private domestic-supply wells.

The installation and expansion of sanitary sewers throughout the county, although generally beneficial in terms of water quality and public health, has had some detrimental effects on water availability. A household using a well and a septic system returns approximately 90 percent of the water pumped from the well back into the ground (Horn, 2000). In contrast, because nearly all wastewater treatment plants discharge to rivers, water pumped from a well and discharged to a sanitary sewer is rapidly transported out of the county in the river system; this routing represents nearly a 100 percent loss of water to the aquifer system. Areas served by sanitary sewers are shown in figure 8. Comparison of figure 7 with figure 8 reveals several areas where community water needs are met from ground water sources, but where water is not necessarily returned to the aquifer.

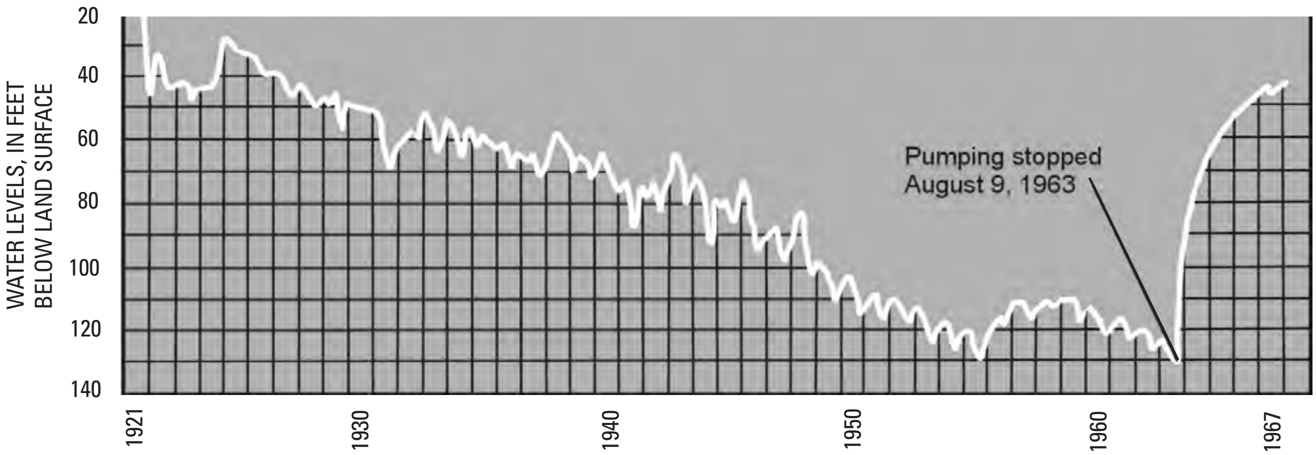


Figure 5. Ground-water levels near Pontiac recovered quickly after pumping ceased in 1963 (after Twenter and Knutilla, 1972).

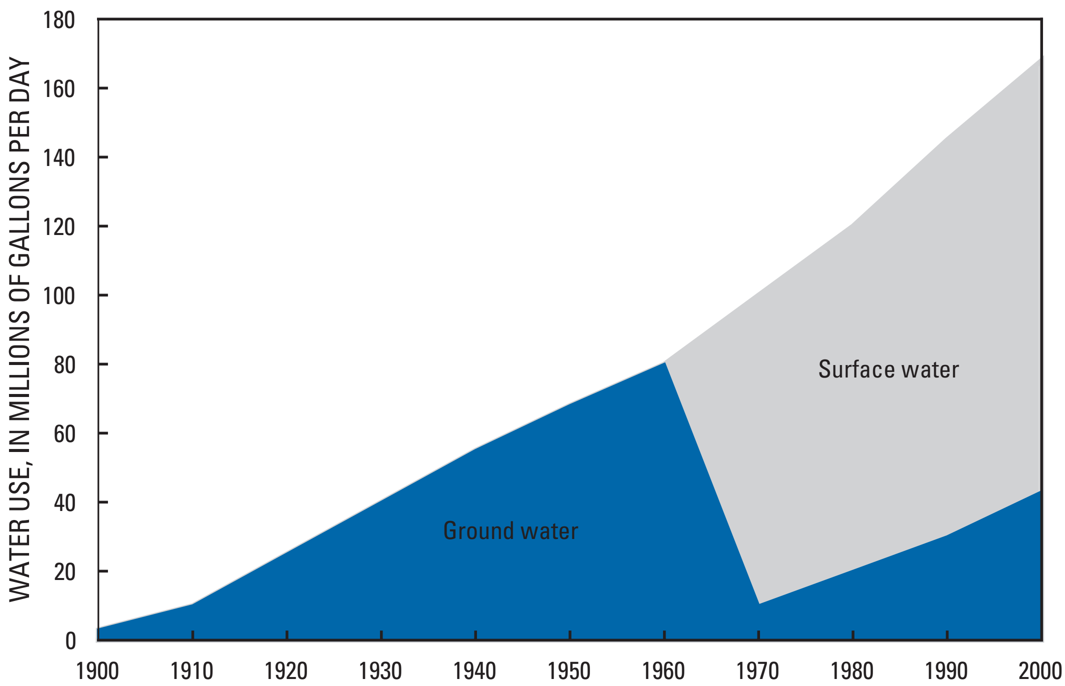


Figure 6. Ground water has been an important source of water in Oakland County, Michigan and despite the use of surface-water supplies, ground-water use is still increasing. (Data from Twenter and Knutilla, 1972; and C.L. Luukkonen, USGS Lansing, Michigan.)

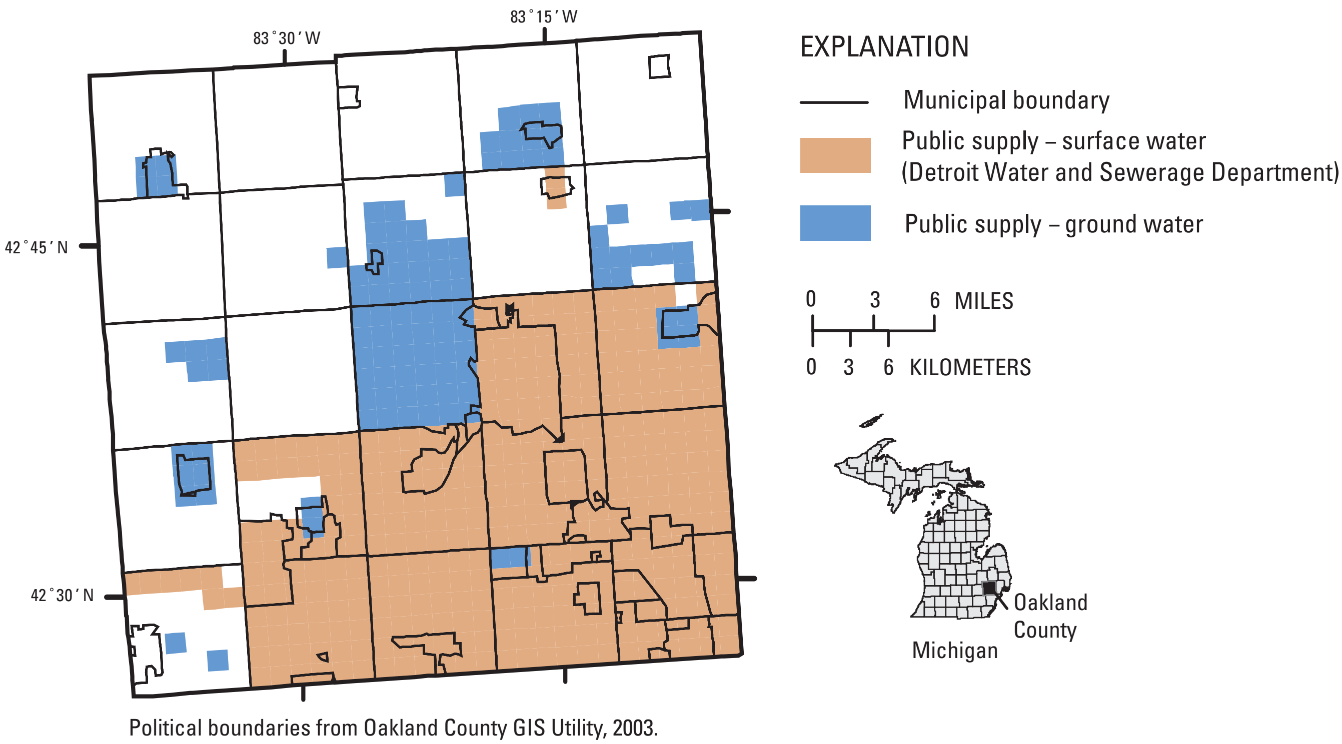


Figure 7. Public-water supplies, from both surface-water and ground-water sources, are available throughout the southern and central parts of Oakland County, Michigan.

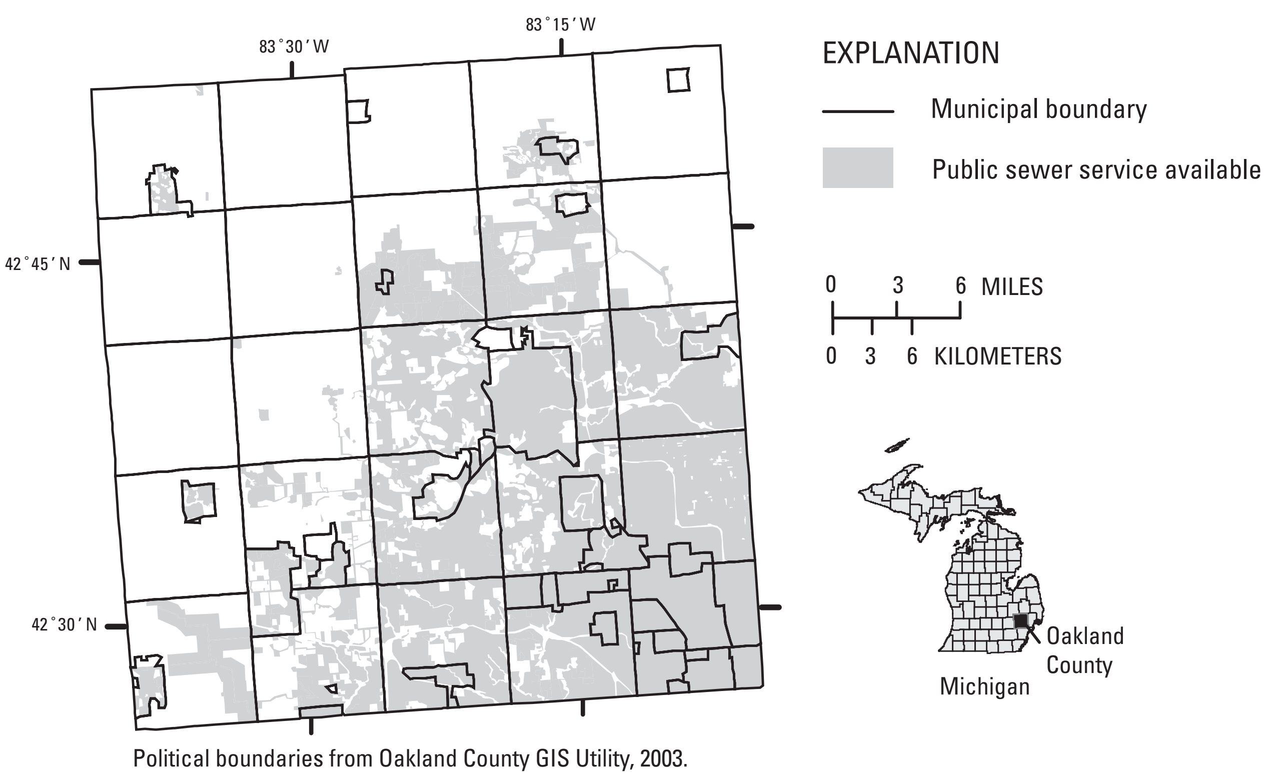


Figure 8. Public sanitary sewer service is available throughout much of southern Oakland County. (Data from Southeast Michigan Council of Governments, 2005)

Physiography and geomorphology

Oakland County can be divided into three broad but physiographically distinct areas, each oriented along an axis from southwest to northeast (fig. 9). In the southeast, glacial lake-plain sediments form a relatively flat landscape with modest relief, generally sloping towards the southeast. Soils tend to be clay rich and poorly drained, with low infiltration capacity. Through the center of the county, a series of till features interspersed among outwash plains forms a landscape of modest relief with many shallow lakes, with occasional hills formed by till deposits. In the northwest, a landscape dominated by glacial till features forms a rolling and irregular surface, characterized by many hills and depressions, generally sloping towards the northwest. Soil conditions throughout this area are highly variable, ranging from very poorly drained lake-clay soils to well-drained soils derived from glacial channel deposits.

Oakland County contains the major parts of the headwaters of five major river systems, and a small part of the headwaters of a sixth (fig. 10). The Clinton River drains the central and eastern parts of the county, flowing eastward toward Lake St. Clair. The Rouge River drains the southern part of the county, flowing to the Detroit River. The Huron River drains the southwestern part of the county to Lake Erie. The Shiawassee and Flint Rivers each drain parts of the northwestern corner of the county to Saginaw Bay, and the Belle River drains a small area of Addison Township to the St. Clair River.

Climate

Oakland County has a climate typical of the upper Midwest, with four distinct seasons characterized by differences in temperature, precipitation, and evaporation. Mean daily temperatures range from a low of 23^{o}F in January to 72.4^{o}F in July. Typical monthly temperature characteristics observed at Pontiac over the period 1970-2000 are listed in table 1 and shown in figure 11 (Peter Kurtz, Michigan Climatological Resources Program, written communication, 2004).

Precipitation typically falls in Oakland County during each month, but more falls during the summer months than during the winter (fig. 12). From 1960 through 1998, annual precipitation averaged 29.6 in. in Pontiac. However, the precipitation could range from less than 20 to more than 40 in. in any specific year. Throughout much of the last four decades, the amount of precipitation in a given year has been increasing (fig. 13).

Over the last century, temperatures have also been increasing. This trend is particularly noticeable in winter

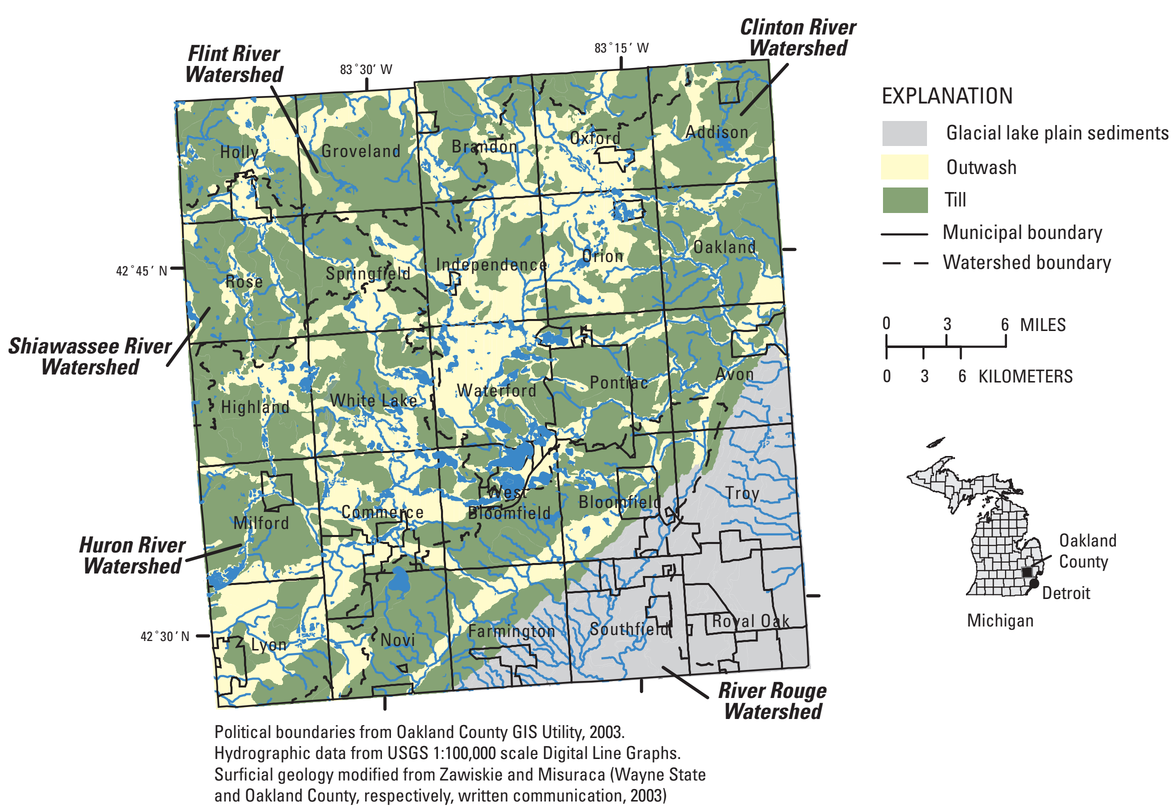
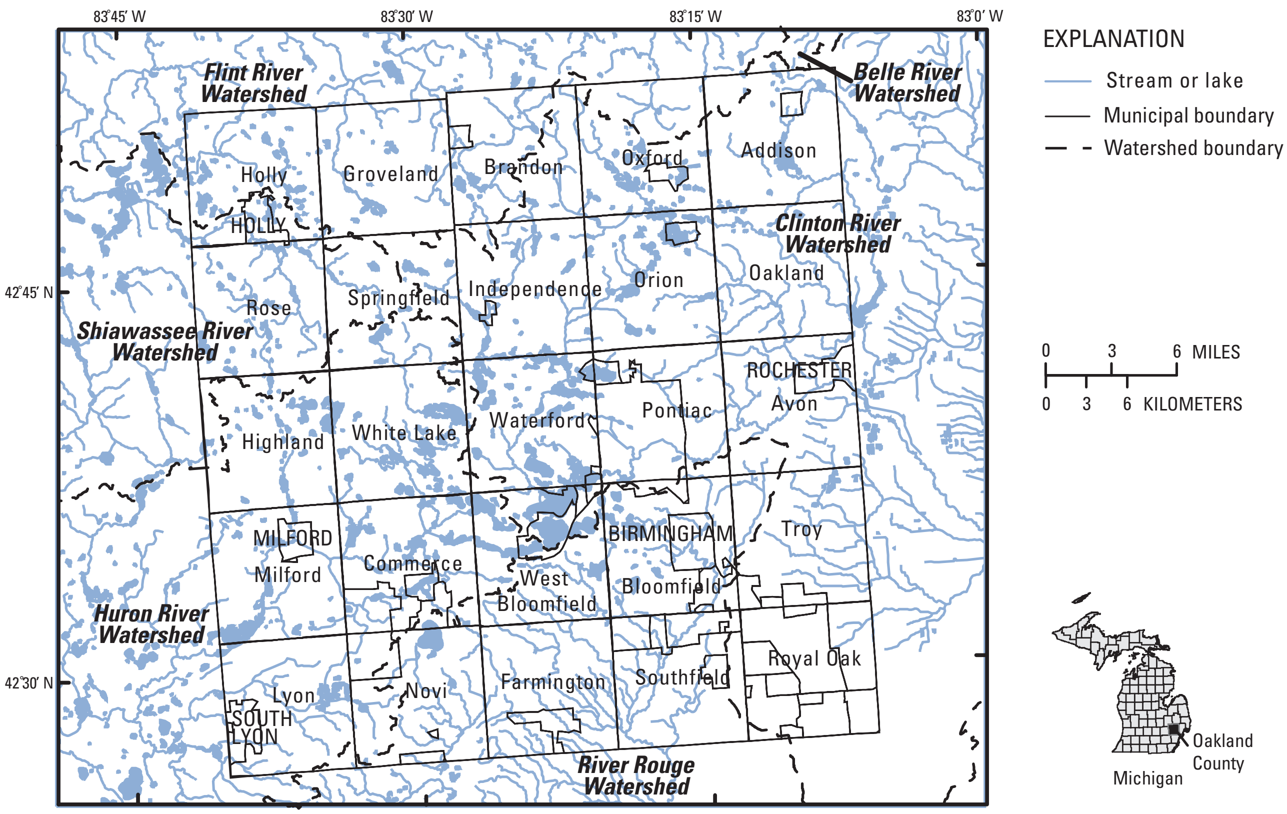


Figure 9. Physiography and surficial geology of Oakland County, Michigan.



Political boundaries from Oakland County GIS Utility, 2003.
Hydrographic data from USGS 1:100,000 scale Digital Line Graphs.

Figure 10. Oakland County, Michigan is located in the headwaters of 6 watersheds.

Table 1. Average monthly temperature characteristics at Pontiac, Michigan 1970-2000.

[Source: Peter Kurtz, Michigan Climatological Resources Program, written commun., 2004]

	Temperatures (in degrees Fahrenheit)		
	Maximum	**Minimum**	**Daily mean**
January	30.0	16.0	23.0
February	33.5	17.4	25.5
March	44.7	25.9	35.3
April	58.0	36.1	47.1
May	70.4	47.4	58.9
June	79.3	56.6	68.0
July	83.4	61.3	72.4
August	81.2	59.9	70.6
September	73.6	52.6	63.1
October	60.6	41.6	51.1
November	46.4	31.8	39.1
December	34.4	21.6	28.0

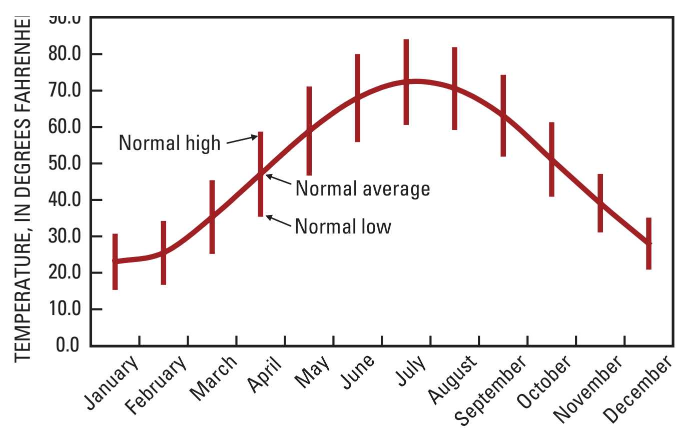


Figure 11. Normal daily temperature characteristics at Pontiac, Michigan, 1970-2000. (Data from Peter Kurtz, Michigan Climatological Resources Program, written communication, 2003.)

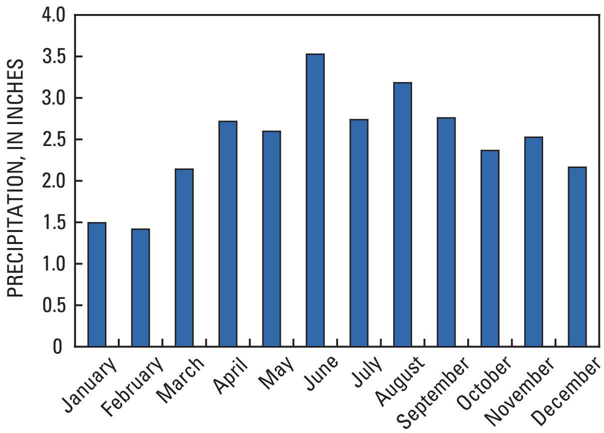


Figure 12. Precipitation, measured at Pontiac, Michigan, is seasonally biased, with more rainfall in the summer months than during the winter. (Data from 1960-1998; Peter Kurtz, Michigan Climatological Resources Program, written communication, 2003.)

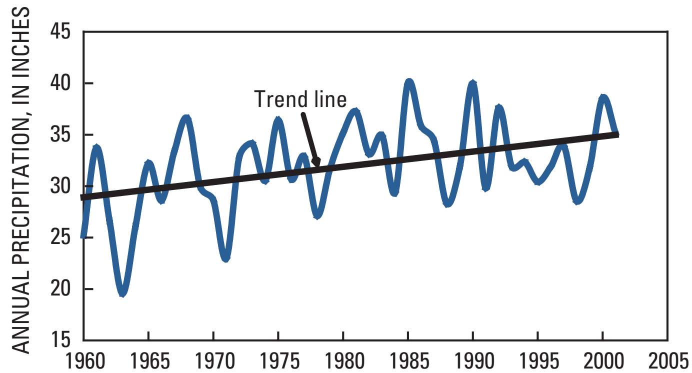


Figure 13. Annual precipitation in southeastern Michigan has been increasing since 1960.

temperatures. One approach to quantifying this trend is to show the number of degree days (based on 32°F) accumulated monthly through a period. The freezing/melting point of water (32°F) is a convenient threshold for water resources because the amount of energy required to evaporate a fixed quantity of water in liquid form is dramatically less than the energy required to evaporate the same quantity of water in solid form. An increase in the number of days above freezing during the winter reduces the amount of water stored in the snow pack. The base-32 degree days are calculated as follows. For each of the 365 days of the year, 32 is subtracted from the high temperature for the day. If the high temperature never reaches 32 degrees, the day has zero degree days. Thus, if the high for a day is 40°F, it has eight base-32 degree days. A graph showing the monthly accumulation of these base-32 degree days is presented in figure 14. Although the accumulations for summer months are relatively steady or even decreasing slightly, the accumulations for winter months have increased considerably during the past decade. In the figure 14, this pattern is shown by relatively consistent summer peaks, but winter troughs that are not as low over time.

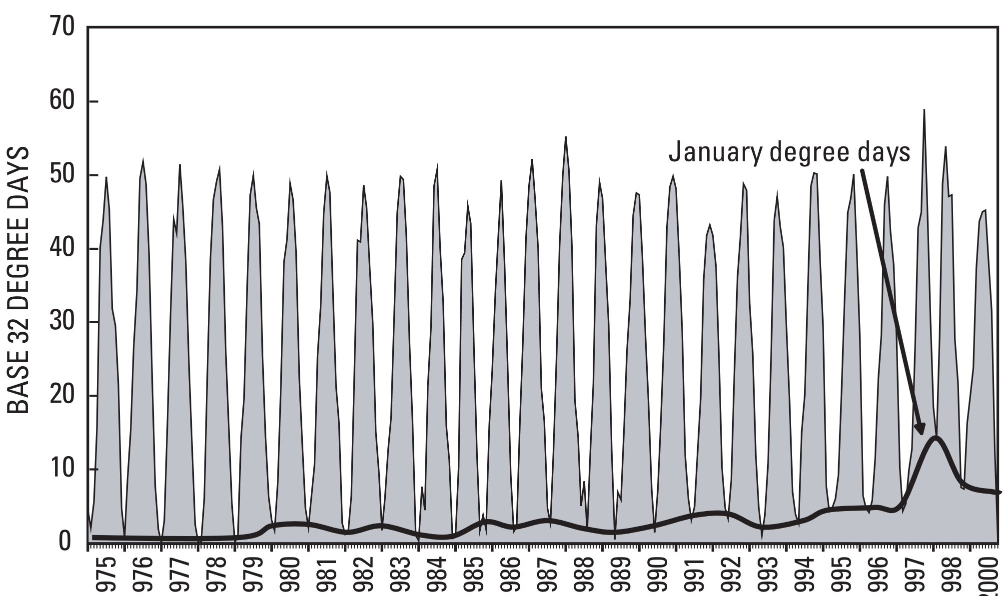


Figure 14. Winter temperatures in Pontiac, Michigan, as measured by base-32 degree days, have been increasing since 1975.

This increase in base-32 degree days is matched by a similar increase in the winter season potential evapotranspiration (PET). Cumulative PET for the period from December 1 through February 28 based on data measured at Milford, Mich., from 1888 to 2002 is shown in figure 15. The PET values were estimated using Hargreaves' method, as described in Leavesly and Stannard (1995). Although specific studies have not been completed on this subject, increases in winter season temperature and winter PET rates would likely result in a smaller volume of water stored in snow pack and potentially lower spring ground-water-recharge volumes.

Land cover

Each expansion in population requires an expansion in housing, infrastructure, and commercial services such as grocery stores and gas stations. These expansions can be seen in the patterns of land cover change in the county. The growth of urban areas surrounding the city of Detroit up until 1980, based on aerial photography and historical maps, is shown in figure 16. Land-cover change from 1980 to 2000, based on land-cover data from the Southeast Michigan Council of Governments (SEMCOG), is shown in figure 17.

Although much of the growth in the period before 1980 was in the southeast corner of the county between Detroit and Pontiac, most of the growth since then has occurred in an arc from Novi around the west and north sides of Pontiac and across to Rochester (fig. 17). During this period, the type and structure of developments have also changed. Whereas most suburban neighborhoods of the 1950's and 60's were built at relatively high density, with curbs and storm sewers (fig. 18), many newer suburban homes are built on larger lots with more green space and less impervious surface. Nearly all new development also has to meet requirements regarding the construction of control structures, such as detention and retention basins, to control the amount of stormwater that runs off the land.

The Hydrologic Cycle

The air, the land surface, and the subsurface can each be thought of as a reservoir, and a variety of processes move water from one reservoir to another. The interaction of these reservoirs and the processes by which water is moved from one reservoir to another are usually described as the hydrologic cycle (fig. 19); this figure, and much of the following discussion of the hydrologic cycle, is drawn from Winter and others (1998).

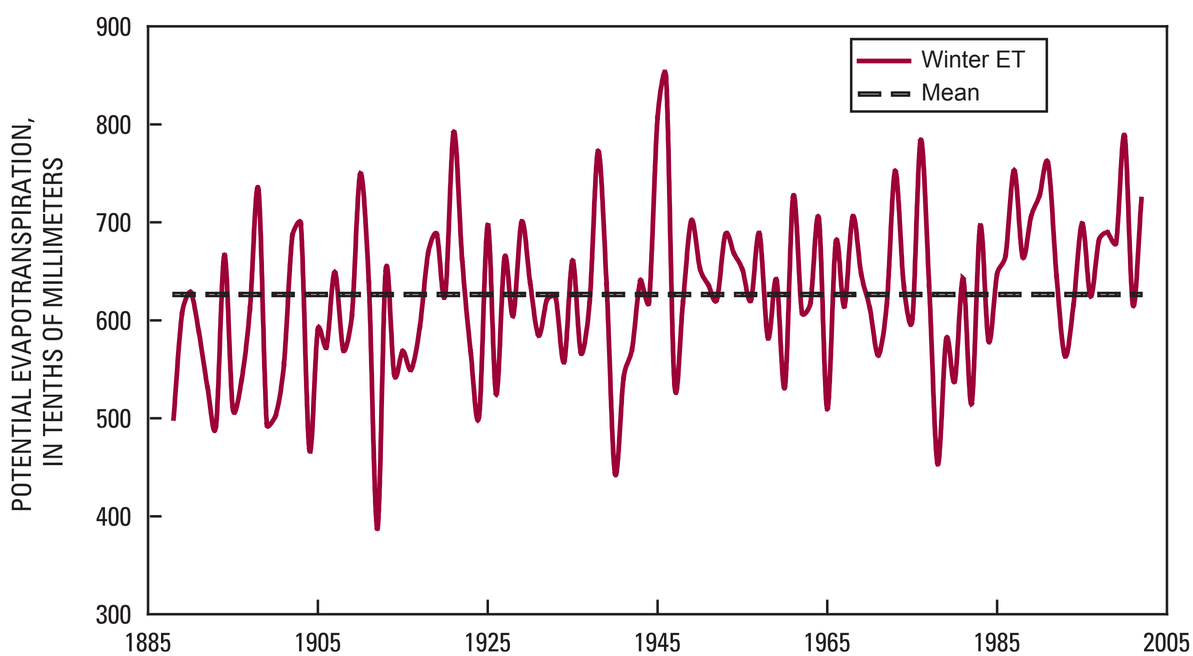
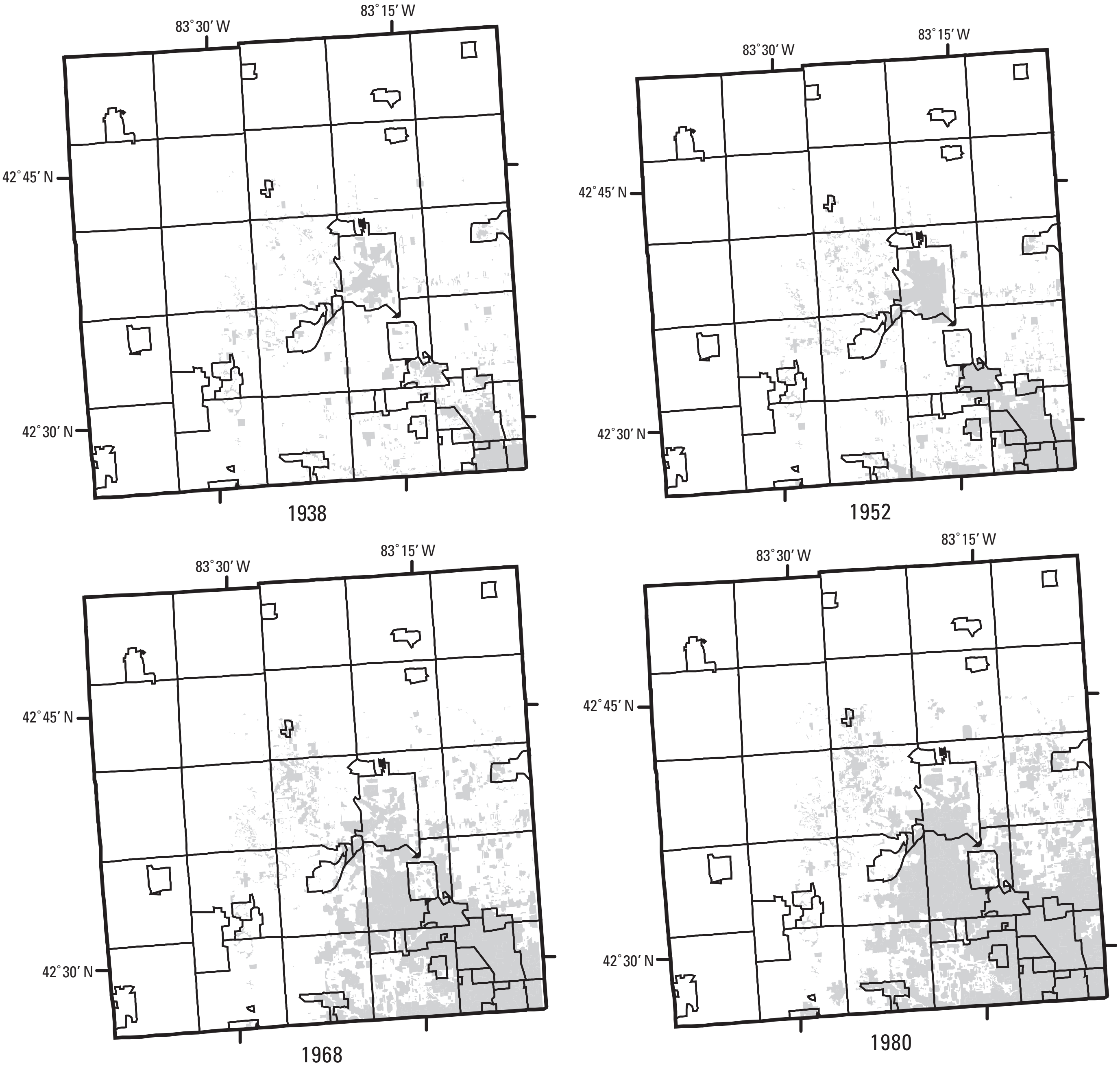


Figure 15. Winter potential evapotranspiration in southeastern Michigan, measured at Ann Arbor, has been greater than the long-term mean for most of the last 20 years. Mean potential evapotranspiration is shown with a dashed line.



Political boundaries from Oakland County GIS Utility, 2003.

EXPLANATION

Scale 1:700,000

——— Municipal boundaries

Urban areas

Figure 16. The southeastern nine townships of Oakland County, Michigan were largely urbanized between 1938 and 1980. (Courtesy U.S. Geological Survey Urban Dynamics Project.)

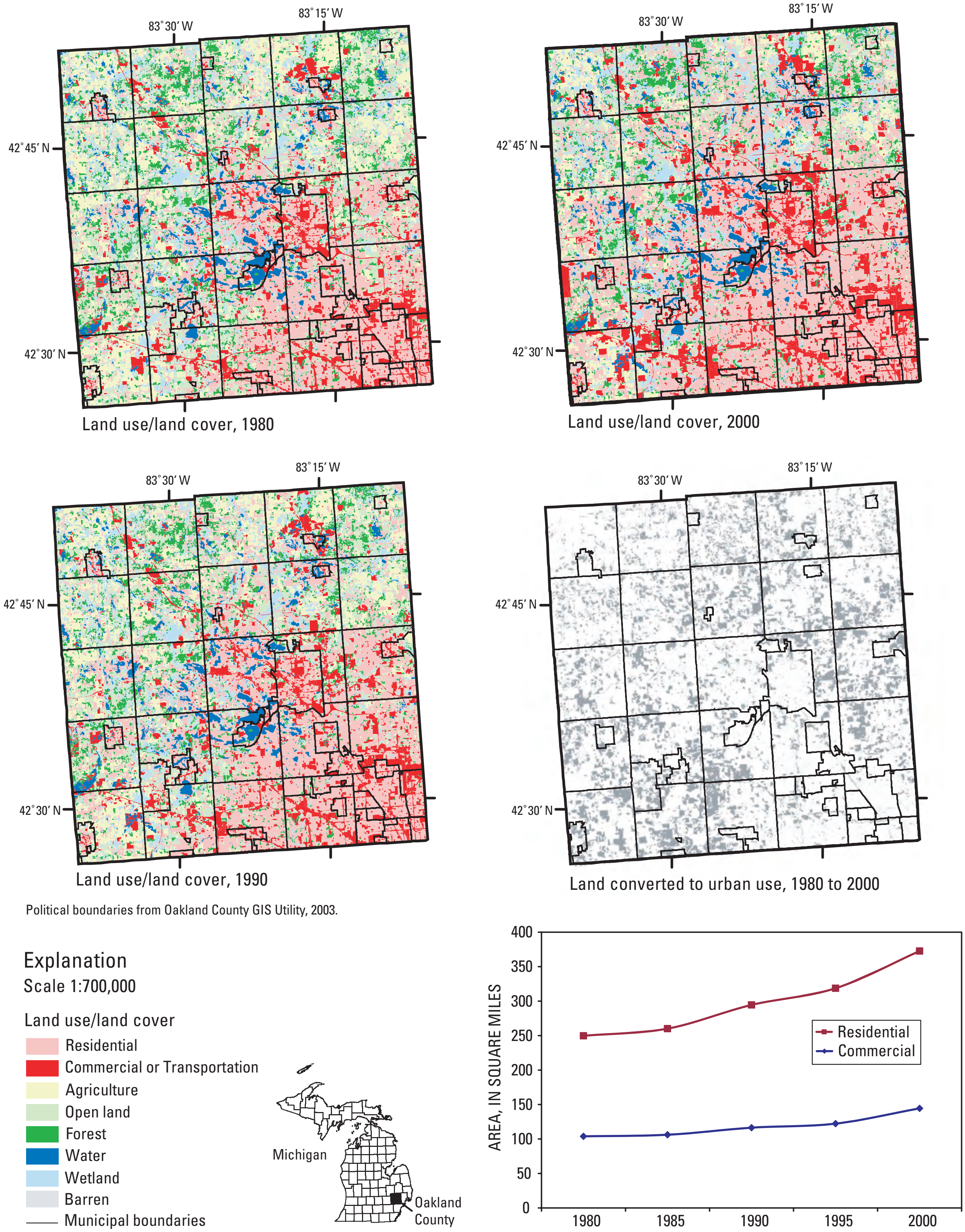


Figure 17. Urban areas expanded from southeast to northwest across Oakland County, Michigan from 1980 to 2000.

Figure 18. As these aerial (above) and groundlevel (below) photographs show, more recent suburban development (right) in an area outside of Milford, Michigan frequently includes lower housing densities, more green space, and less impervious surface per unit area than earlier 1950's and 1960's suburbs (left) like the area in Ferndale, Michigan.

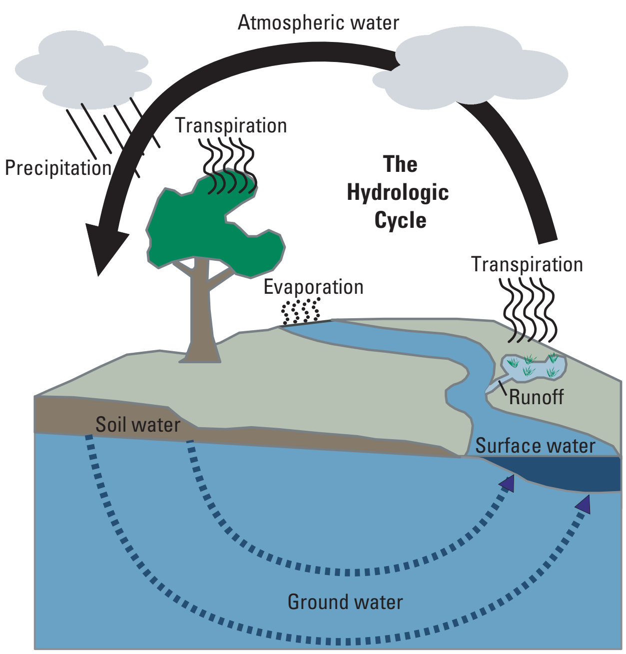


Figure 19. Water is constantly circulating through the hydrologic cycle.

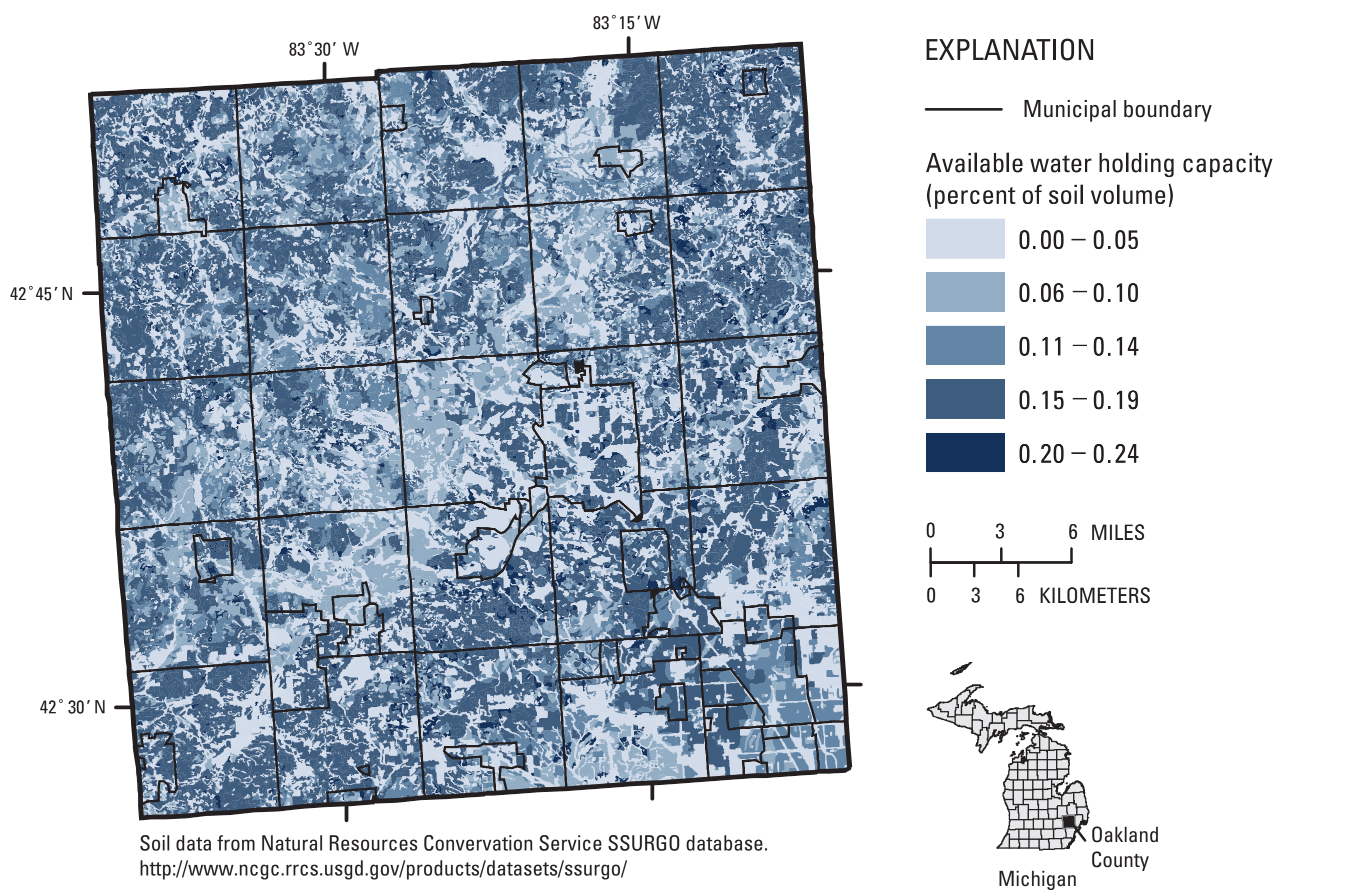
Although a description of the hydrologic cycle can start at any point, it is convenient to begin with precipitation. Oakland County includes the headwaters of six major rivers, all of which flow out of the county. As a result, the only natural means for water to enter the county is through precipitation. Precipitation replenishing streams and lakes is apparent to any observer; what is not apparent is that precipitation also replenishes the ground water by infiltrating through the soil into the underlying aquifer(s).

As mentioned previously, Oakland County receives slightly less than 30 inches of precipitation in an average year, although the overall average quantity of precipitation in Oakland County has been increasing slightly through time. The actual quantity of precipitation in any given year, however, can vary by 10 inches or more above and below this average. Oakland County usually receives precipitation in every month of the year, but there is a slight seasonal bias toward more precipitation during the summer.

Once precipitation has fallen, whether as rain or snow, that water either infiltrates into the soil, is stored on the surface in closed depressions or as snow and ice, or runs off the surface into lakes and rivers. The path precipitation follows once on the land surface is determined by various factors, with soil characteristics playing an important role. The most important soil properties are those that affect the infiltration rate; that is, the ability of the soil to absorb and transport water downwards. Soils with large amounts of clay, such as those typical in the southeastern part of Oakland County, generally have lower infiltration rates than sandy soils, such as those in the middle of the county. Infiltration rates of a particular soil can also decrease if the soil is frozen, compacted, or already saturated from prior precipitation. In extreme conditions, precipitation or meltwater delivery may exceed the infiltration capacity of the soil, resulting in ponding or runoff. If the soil is sealed at the surface by pavement or a structure, the infiltration capacity of the soil drops to nearly zero.

Some infiltrated water is also retained in the soil. Depending on the soil, the amount retained can range from as little as 2 percent to as much as 24 percent of the soil volume in mineral soils (Soil Conservation Service, 1980). The ability of soils in Oakland County to retain and hold water is shown in figure 20. Once this holding capacity has been exceeded, excess water drains through the soil column to the water table. The water table is an interface between the unsaturated zone, where water fills only a fraction of the pore space in the rocks and soil, and the saturated zone, where water fills nearly all the pore space. The drainage of water from the soil to the water table is frequently referred to as "recharge."

In humid climates such as that of Oakland County, recharged ground water is slowly transported downgradient toward streams, lakes, rivers, and wetlands where it is discharged. Thus, just as surface water is flowing from high areas to low areas, ground water is flowing—much more slowly—from recharge areas to discharge areas. In Oakland County, ground water is typically recharged and ground-water levels rise during April and May, by a combination of melting snow pack and spring rains. Ground-water levels are gradually drawn down through the summer and fall, with the lowest levels typically during September and October, just before the first hard frost. This cycle of seasonal recharge and discharge



Soil data from Natural Resources Convervation Service SSURGO database.
http://www.ncgc.rrcs.usgd.gov/products/datasets/ssurgo/

Figure 20. The ability of soil to retain water varies widely across Oakland County, Michigan from almost zero to 24 percent, compared to the soil volume.

is shown in the ground-water hydrograph in figure 21. Alteration of winter-season temperatures— specifically the increases in winter evaporation rates observable in recent decades—could have measurable effects on the amount of recharge delivered to aquifers.

Despite larger quantities of precipitation during the summer months, little or no recharge occurs during the summer because evaporation of water from the surface and transpiration by vegetation consumes nearly all of the available water on the surface and in the soil. These different processes are difficult to quantify individually and are collectively termed "evapotranspiration," or ET. In some watersheds in Oakland County, ET can intercept more than 60 percent of the total precipitation. Evaporated water, whether from the land surface or from the oceans, makes up the moisture in the atmosphere and again becomes precipitation.

Water Budgets for Selected Basins

The different components of the hydrologic cycle can be cast into the form of a water budget, comparable to a household budget. Precipitation is analogous to income; runoff, ET, and human use can be thought of as expenses; and recharge can be thought of as a savings deposit for dry periods, such as late summer. This budget can be expressed as an equation:

$$P = RO + ET + HU + \Delta S$$

where P is precipitation, RO is runoff, ET is the combined loss to evaporation and transpiration, HU is human use, and ΔS is the change in storage. Storage is the amount of water in transit, primarily as ground water, within the system at any point in time. Managing this budget is difficult because "income" (precipitation), and the largest "expense" (ET) are beyond human control. Runoff can be affected to some degree by land-management decisions, and human use can be managed by either controlling the number of people using the water or by providing alternative sources for water, such as the DWSD supply infrastructure in parts of the county.

Precipitation is the principal means of conveying water into Oakland County. Runoff—in this case streamflow—is the next most familiar element of the equation. Runoff, however, is itself composed of three elements: overland flow, storm seepage or interflow, and ground-water runoff. Overland flow is the familiar process of rainfall or melting snow running across the landscape into streams and rivers. Storm seepage or interflow is a relatively minor element that involves shallow infiltration and seepage to the stream channel,

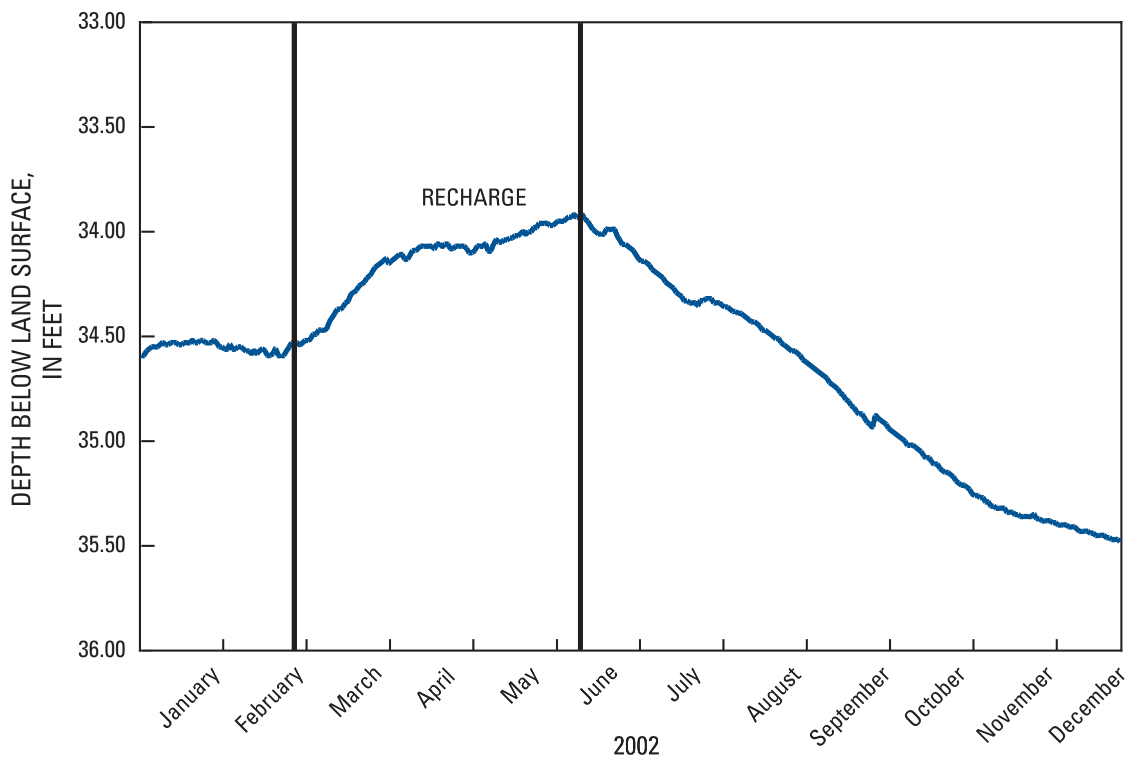


Figure 21. Ground water is recharged, and ground-water levels rise, during the spring and early summer, then ground-water levels decline through the remainder of the year. (Data from USGS monitoring well on Fish Lake Rd. in Oakland County, Michigan.)

typically over a period of days. Storm seepage does not actually recharge the aquifer. However, particularly during the summer, there may be days, weeks, or even months with little or no rain, yet the rivers continue to flow. River flows, and the aquatic habitats within the rivers, are sustained by ground water gradually seeping from the aquifer into the stream channel. This ground-water seepage is generally referred to as “base flow.”

Streamflow is measured at various locations around the county by the USGS, MDEQ, Oakland County Drain Commission, and others. By analyzing daily streamflow records, it is possible to estimate the separate event-driven overland and interflowflow contributions to streamflow from ground-water-derived base flow (Sloto and Crouse, 1996; Appleby, 1970). The relative magnitude of these contributions is determined by a combination of the geologic setting of the basin and land cover within the basin. Long-term average base-flow values for selected basins in southeast Michigan are shown in table 2.

Using precipitation data from the SEMCOG rain-gage network (Peter Kurtz, Michigan Climatological Resources Program, written commun., 2004), annual water budgets were developed for three representative watersheds in Oakland County—Sashabaw Creek, Paint Creek, and the River Rouge—for the 2002 water year (table 3). It is evident from comparing these results to the average values in table 2, that fluctuations from year to year are relatively large. The majority of the surface runoff occurs during the spring months, primarily April and May, and surface runoff constitutes most of the streamflow during that period. In contrast, in August and September, more than 90 percent of the total streamflow is derived from ground water. Decreases in this ground-water contribution would have direct effects on the aquatic habitat within the stream. Therefore, the continued health of the surface-water resources in Oakland County, such as Paint Creek, relies on the continued abundance of ground water to sustain streamflow during periods of low precipitation and high ET.

How Humans Can Alter the Hydrologic Cycle

Human alteration of the hydrologic cycle can take a variety of forms, but three are most common in Oakland County. First, paving and creating other impervious areas, such as buildings, prevents water from infiltrating the land surface and therefore reduces the amount of water entering the ground-water system. In many cases, impervious surfaces also divert the water directly to streams and rivers, increasing the amount of overland flow in a watershed and increasing the likelihood of floods and damage to ecological communities and habitat. To some extent, these effects can be reduced by the use of runoff-control structures, such as retention basins.

Second, ground-water withdrawal reduces the amount of ground water available to discharge to rivers and lakes in the summer. If ground water is pumped for domestic use and discharged to a septic system, the total loss of water from an area may be relatively small, perhaps as little as 10 percent of total pumpage (Horn, 2000). If ground water is pumped and then discharged to a river through a wastewater treatment plant (WWTP), the water is lost from the ground-water system. Wastewater discharged in this manner essentially exports water

Table 2. Ground-water component of streamflow for selected U.S. Geological Survey streamflow-gaging stations in southeastern Michigan.

[Data from Holtschlag and Nicholas, 1998; all streamflows are in cubic feet per second; percentages are rounded to the nearest whole number]

USGS station number	Station name	Average streamflow	Average ground-water component of streamflow	Average ground-water component of streamflow (percent)
04144000	Shiawassee River at Byron	251	202	80
04160800	Sashabaw Creek near Drayton Plains	13.3	11.9	90
04160900	Clinton River near Drayton Plains	53.1	48.2	91
04161540	Paint Creek at Rochester	53.6	46.1	86
04161580	Stony Creek near Romeo	17.6	14.9	85
04166000	River Rouge at Birmingham	20.8	14.1	68
04166100	River Rouge at Southfield	68.8	40.0	58
04166200	Evans Ditch at Southfield	8.91	3.56	40
04166300	Upper River Rouge at Farmington	13.8	8.66	63
04170000	Huron River at Milford	102	89.8	88

Table 3. Annual water budgets for watersheds in Oakland County, Michigan can vary considerably, from year to year and between watersheds.
[precipitation and flows in inches]

	04160800 Sashabaw Creek near Drayton Plains, Mich.				04161540 Paint Creek near Rochester, Mich.				04166100 River Rouge at Southfield, Mich.			
	Precipitation	Total streamflow	Base flow	Base flow fraction	Precipitation	Total streamflow	Base flow	Base flow fraction	Precipitation	Total streamflow	Base flow	Base flow fraction
1975	37.2	15.7	13.8	0.88	36.5	17.4	12.8	0.74	34.2	13.8	6.6	0.48
1976	29.2	11.8	10.8	0.91	29.2	14.6	12.0	0.82	29.7	13.4	7.3	0.55
1977	26.7	5.0	4.5	0.89	26.3	7.5	6.1	0.81	29.4	10.0	4.8	0.48
1978	23.5	5.8	5.3	0.90	23.2	8.1	6.8	0.83	24.5	7.8	4.9	0.64
1979	30.0	7.1	6.2	0.87	29.2	8.2	6.0	0.73	27.5	10.0	5.4	0.54
1980	32.0	8.5	7.6	0.90	32.1	10.1	8.0	0.79	32.0	10.8	6.1	0.57
1981	33.6	10.7	9.5	0.88	32.9	12.3	9.8	0.80	32.1	11.0	5.9	0.53
1982	29.2	9.9	9.0	0.91	29.0	11.6	8.8	0.76	29.7	12.7	7.8	0.61
1983	31.6	7.4	6.6	0.89	32.7	9.5	7.0	0.74	31.8	11.2	6.7	0.59
1984	26.9	6.1	5.2	0.86	28.3	8.1	6.6	0.82	26.6	9.3	5.1	0.55
1985	40.7	14.4	12.8	0.89	41.4	15.2	11.5	0.76	36.8	15.1	8.3	0.55
1986	33.6	12.3	11.0	0.90	34.0	12.9	10.5	0.82	32.6	14.4	8.5	0.59
1987	32.3	7.6	6.7	0.89	32.4	8.6	7.1	0.83	31.9	10.9	6.4	0.59
1988	29.1	7.3	6.4	0.87	28.2	8.0	6.5	0.81	26.9	9.2	5.6	0.60
1989	33.6	9.4	8.1	0.86	33.4	9.9	7.4	0.75	31.8	12.2	6.0	0.49
1990	38.1	13.0	11.3	0.87	37.0	12.6	9.8	0.78	39.3	17.5	8.2	0.47
1991	32.5	8.4	7.5	0.89	31.4	9.8	8.1	0.82	30.7	12.1	6.6	0.54
1992	36.1	11.8	10.6	0.90	35.1	11.9	9.5	0.80	35.3	13.6	7.9	0.58
1993	31.1	10.9	9.9	0.90	30.2	12.6	9.5	0.75	30.6	14.3	7.9	0.55
1994	32.4	8.5	7.4	0.87	32.0	10.1	7.5	0.74	32.3	13.0	6.1	0.47
1995	30.3	7.3	6.5	0.89	30.1	9.0	7.1	0.78	32.3	13.9	7.0	0.50
1996	34.4	9.8	8.6	0.87	34.6	12.1	8.6	0.71	32.6	14.2	7.0	0.49
1997	30.9	10.1	9.1	0.90	30.9	12.7	10.0	0.79	34.9	14.7	7.8	0.53
1998	27.4	7.4	6.6	0.89	27.0	9.5	7.2	0.77	31.0	12.3	6.6	0.53
1999	31.4	5.2	4.5	0.86	31.3	7.0	4.8	0.68	31.4	10.6	5.8	0.55
2000	38.1	10.3	8.8	0.85	38.5	11.4	7.5	0.66	37.3	10.8	4.7	0.44

out of the immediate watershed. WWTP discharge may also have effects on the receiving water, because the quality of the water discharged from the plant may be different than that of ground water.

Third, the large-scale transfer of water into the county is a human effect on the hydrologic cycle not typically discussed. The DWSD pumps nearly 125 Mgal/d of water into the county. Although much of this water is used and discharged back to Wayne County for treatment, some is treated and discharged to rivers in Oakland County. In addition, some of the water leaks out of water mains and may recharge underlying aquifers.

In the area from Southfield north to the edge of the Rouge watershed, ground water has been replaced by DWSD surface water as the source for domestic use. Thus, the stress on the aquifer caused by pumping has been removed, and additional water is being diverted to the aquifer from DWSD. This effect can be seen in the low-flow record for the River Rouge, where low flows have increased by almost 400 percent since the introduction of DWSD water in the mid-1960s (fig. 22). In the case of the River Rouge, this is relatively clean water seeping through the ground and is probably a net improvement for the system. Some of the water imported into the county is discharged to rivers through wastewater treatment plants in Pontiac and Ferndale. These discharges also increase the low flow of the receiving rivers, but in a different way. Although the total amount of water in the Clinton and Lower River Rouge has increased, the streamflow is supplemented by treated wastewater. Although this water has been treated and is relatively clean, it has a higher nutrient content and a higher temperature than the river typically would have.

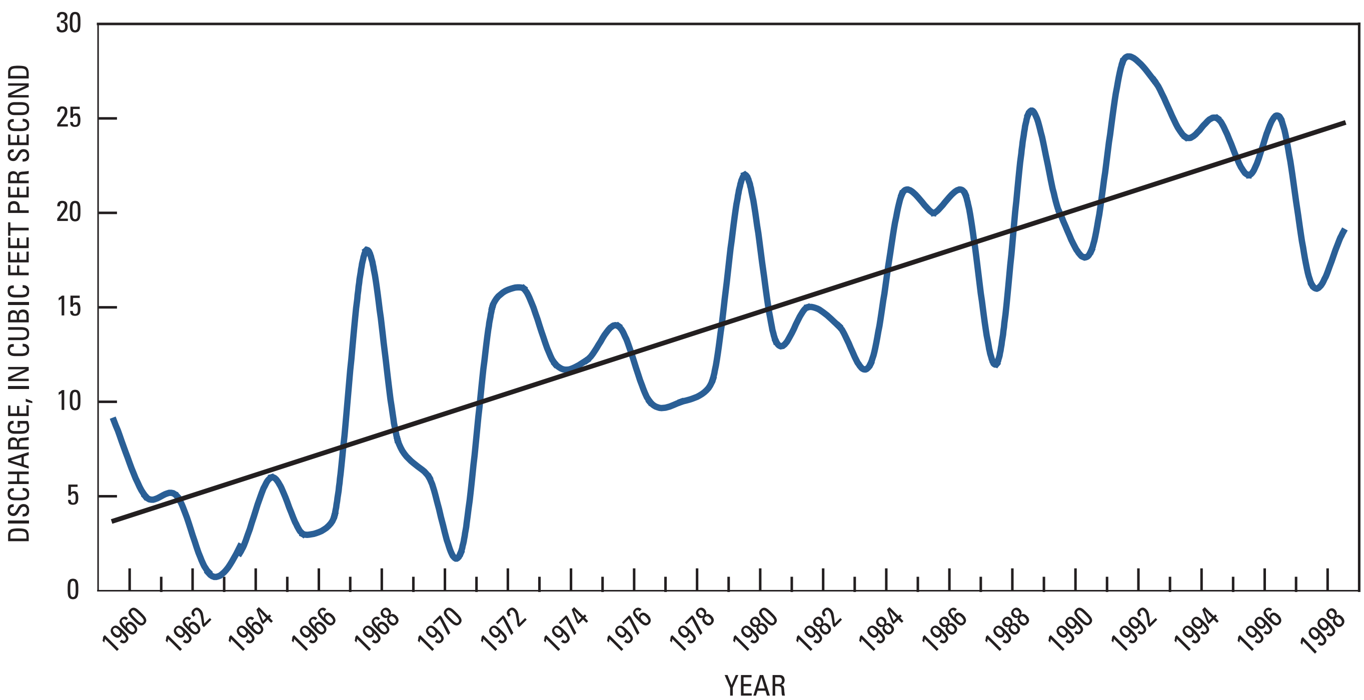


Figure 22. Annual low flows (95 percent exceedance) have generally increased in the River Rouge from 1960 to 2000. Black line represents trend. (Data from USGS streamflow gaging station 04166100, River Rouge near Southfield, Michigan.)

Water and the Land

Water resources and land resources are intimately related—the characteristics of the water are linked to the characteristics of the land surface, soils, and geologic material with which the water interacts. For instance, water flowing through a geologic unit rich in carbonate minerals will gradually acquire calcium, magnesium, and bicarbonate in solution. Similarly, water flowing across a roadway will acquire trace quantities of spilled antifreeze, fuel, metals, and solvent residues, as well as salts and sealants applied to the pavement.

Water in the Ground—The Ground-Water Resources of Oakland County

Ground-water resources are a vital part of Oakland County's present and future. More than 400,000 Oakland County residents, primarily in the northern and western parts of the county, rely on ground water for their drinking water. Of these, approximately 240,000 use private domestic-supply wells, and 169,000 are connected to systems using public water-supply wells. An additional 1,923 well permits were issued for new wells in Oakland County in 2004.

In addition to this domestic use, which accounts for more than 43 Mgal/d of ground water, nearly all of the surface-water bodies in Oakland County rely on ground water to sustain them during some part of the year. These systems in turn support fish, waterfowl, and other ecological uses of water. Thus, although ground water is seldom seen while below ground, it is a critical component of water management in Oakland County.

Aquifers of Oakland County can be separated into two major groups. Near the surface is a fairly continuous glacial aquifer system, where water is stored and transported in the pore space between grains of sand or silt. Below that system are bedrock units, some of which can provide sources of water with sufficient quantity and quality for domestic use. In these bedrock units, most of the water is stored and transported through fractures or cracks rather than through pores. The properties of both the glacial and bedrock aquifers can be highly variable. Among the bedrock units in the county, only the Marshall Sandstone is an important source of drinking water.

The Glacial Aquifer in Oakland County

The glacial aquifer in Oakland County consists of sediments deposited by the continental glaciers, which retreated across the area approximately 12,000 years ago. The environment at the time of glacial recession was dynamic, with large volumes of water and sediment flowing across the landscape. As a result, the glacial aquifer is a complex series of overlapping sedimentary deposits. In addition to these mixed depositional settings, lakes may have briefly formed on the landscape, producing beds of low-permeability clay of varied areal extent (Aichele, 2000).

The glacial aquifer system ranges in thickness from about 100 ft in the southeastern part of the county to nearly 400 ft in the central part of the county (fig. 23). In general, potable water is available from the glacial aquifer throughout the county. Yields in excess of 20 gal/min are common, and the water table is generally less than 30 ft below the land surface. In areas of the southeast, notably near Birmingham, the glacial aquifer may actually be confined beneath tightly layered lakebed sediments, and flowing wells can result (Aichele, 2005). Very little data are available in this area, however, so it is difficult to interpolate a continuous water surface (fig. 24).

Although treating the glacial aquifer as one unit is frequently convenient, this interpretation is seldom correct. The hydraulic characteristics of the glacial material can vary dramatically over relatively short horizontal and vertical distances. Throughout much of Oakland County, and particularly in the north and west where till is prevalent, the glacial aquifer system is frequently divided by thick confining clay layers into two or more relatively distinct units. Localized clay layers do underlie some parts of the county and may provide some level of protection to ground-water resources. However, understanding or predicting where these confining clay units can be found is practically impossible, except where wells have already been drilled. Even then, it is difficult to say with any degree of certainty whether the well intercepts the clay at the middle of a vast unbroken layer or whether a given well falls at the edge of the clay layer. There do not appear to be any distinguishable clay layers of countywide extent, or even townshipwide extent.

Several previous authors (Leverett, 1906; Mozola, 1954; Twenter and Knutilla, 1972, Aichele, 2000) have attempted to characterize the stratigraphy of the glacial aquifer using conventional cross-section approaches commonly applied to bedrock and well-ordered glacial systems. These techniques are of limited value in a complex glacial environment such as that in Oakland County, not only because of the natural heterogeneity of the glacial aquifer but also because of variations in the way glacial lithologies are reported in drillers' logs. A recent report (Bissell and Aichele, 2004) applied geostatistical techniques to document several aspects of the glacial aquifer system, including the vertical hydraulic conductivity of the upper part and the probability that a clay layer 10 or more feet thick might be present. More than 36,000 drillers' logs were considered in the analysis. Variography was applied as a quality-control procedure to evaluate the consistency of each driller's interpretation

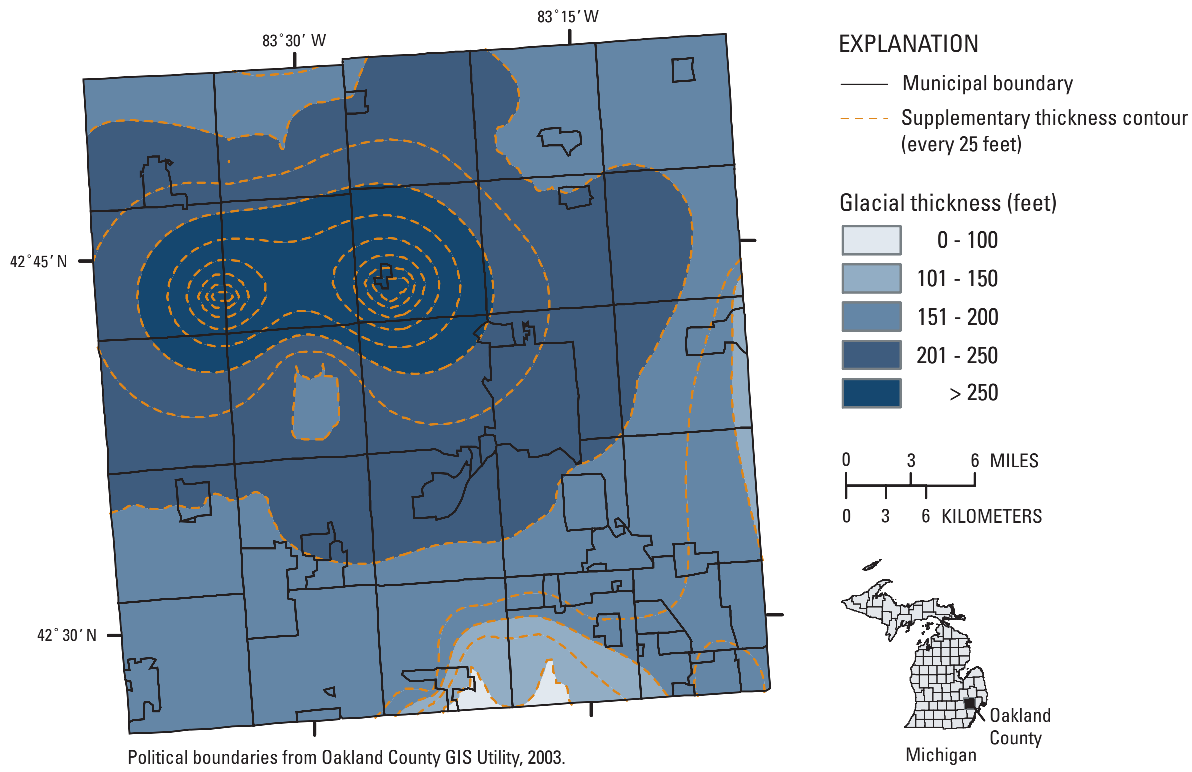


Figure 23. Glacial deposits in Oakland County, Michigan range in thickness from less than 50 feet to more than 250 feet.

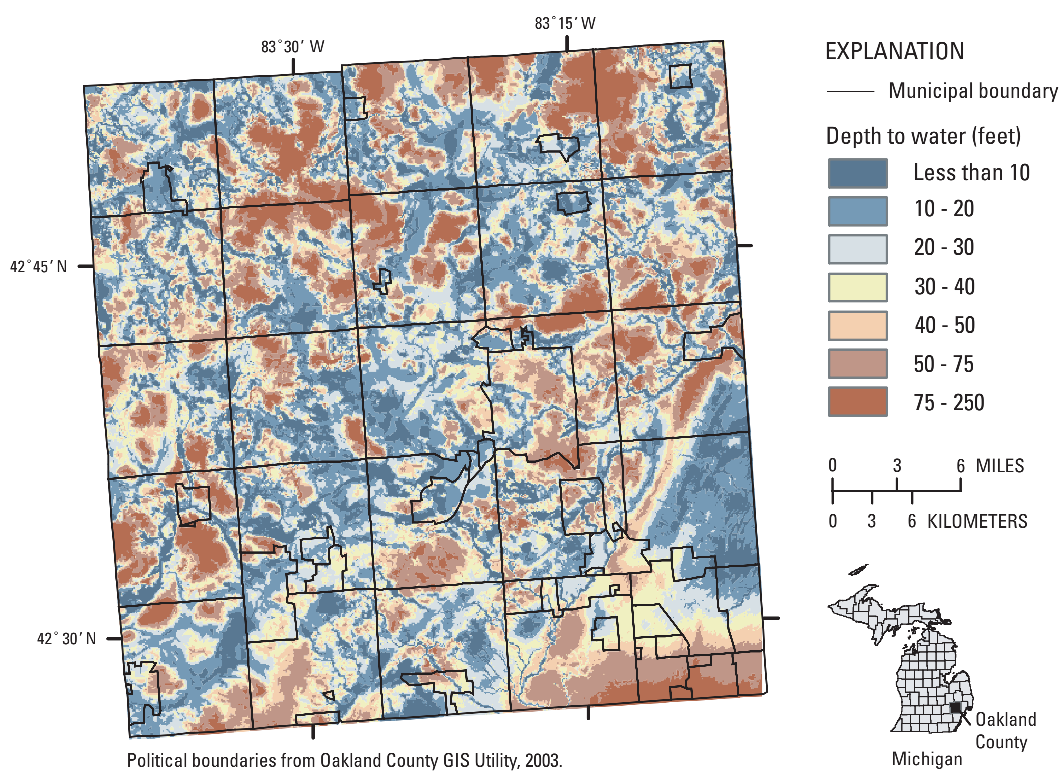


Figure 24. Ground water is frequently less than 50 feet below the land surface in Oakland County, Michigan.

of the geologic environment. Slightly more than 17,000 logs were considered to be consistent and were used to develop predictive maps. In the southeastern part of the county, in the area of lacustrine glacial deposits, well-log data were insufficient to complete the analysis.

Vertical hydraulic conductivity (the rate at which water will move downward through an aquifer) is one commonly used indicator of the susceptibility of ground water to contamination. Estimates of susceptibility to contamination are shown in figure 25. The most susceptible areas are found through the central outwash plain region, where the glacial aquifer is predominantly composed of sand and gravel. Lower susceptibilities are found in the northwestern part of the county, where more clay is present. The map showing the predicted probability of encountering a clay layer 10 or more feet thick (fig. 26) is very similar to figure 25. Relatively low probability is typical in the central outwash plain region, whereas the probability is higher in the northwestern part of the county.

Even with the quality-control procedures applied, however, the results of Bissell and Aichele (2004) were not definitive. Neither statistical model described more than half of the overall variability in the dataset. There are two likely causes for this relatively poor model performance. First, the glacial aquifer is highly variable and heterogeneous. Second, although more than half of the well logs were discarded because they were inconsistent, the remaining logs still may not be entirely accurate interpretations of the geologic environment.

Bedrock Aquifers in Oakland County

The primary bedrock aquifer in Oakland County is the Marshall Sandstone, a Mississippian sandstone unit with inclusions of limestone, dolomite, siltstone, and shale (Westjohn and Weaver, 1994). In the northwestern part of the county, the Marshall Sandstone can be a very productive aquifer, with yields exceeding 100 gal/min. The quality of water in the Marshall Sandstone, rather

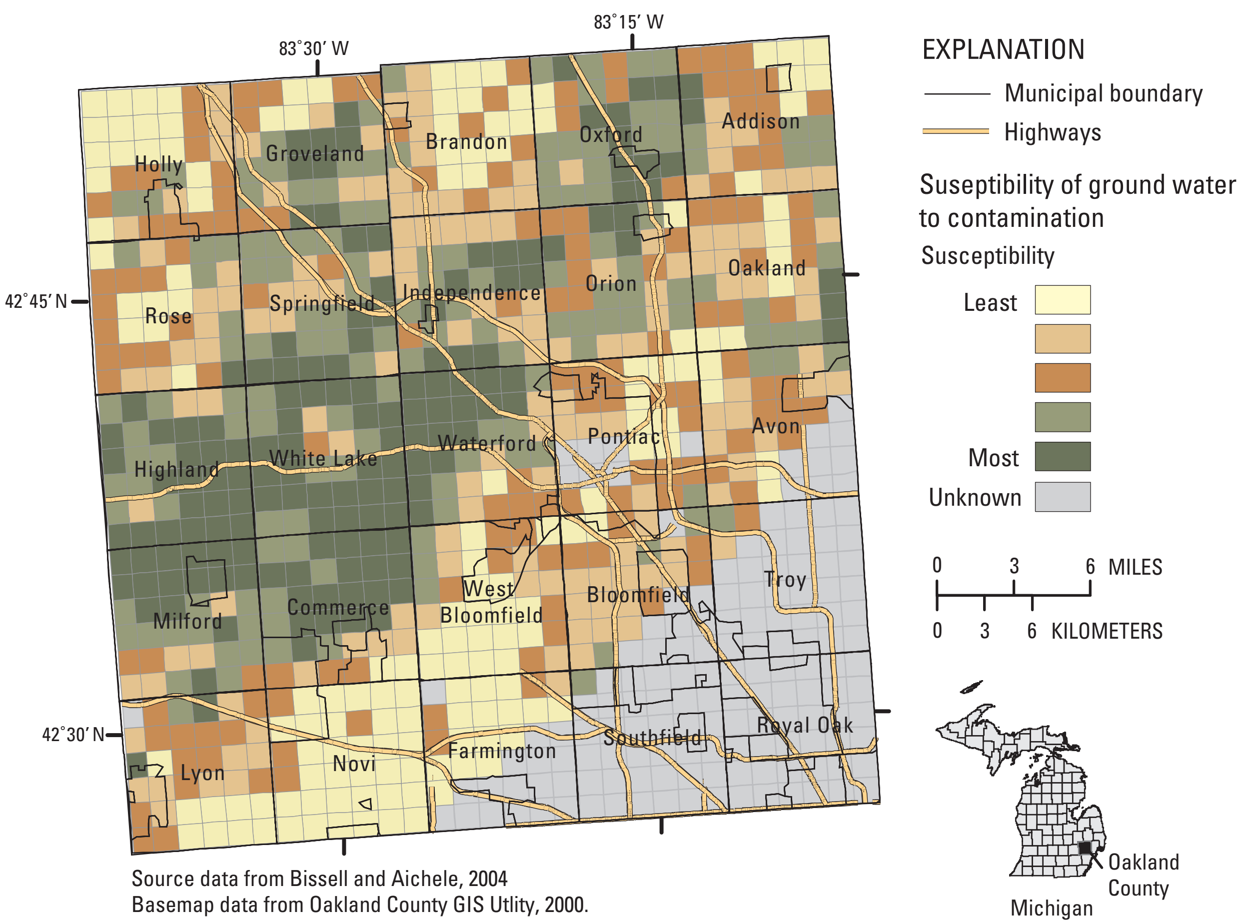
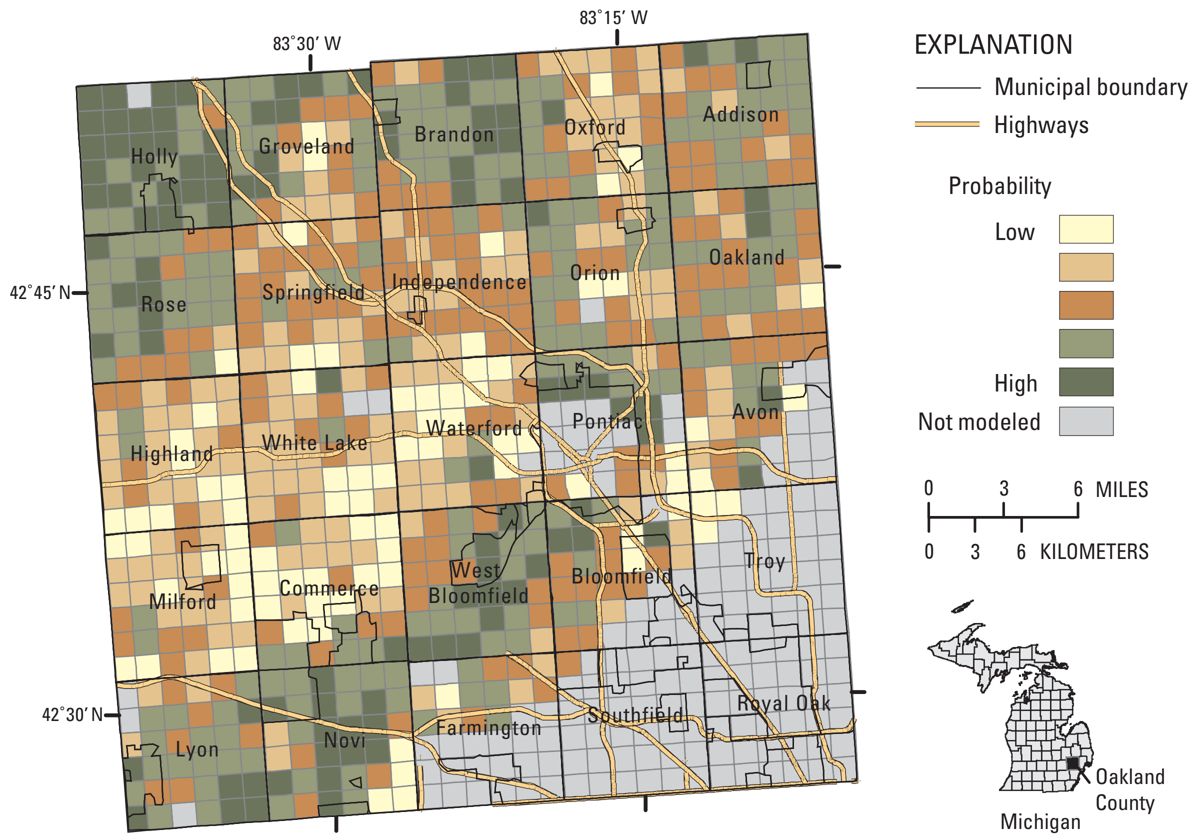


Figure 25. Predicted susceptibility of ground water in Oakland County, Michigan to contamination by contaminants like nitrate and chloride (modified from Aichele, 2004).



Source data from Bissell and Aichele, 2004
Basemap data from Oakland County GIS Utlity, 2000.

Figure 26. Predicted probability of encountering a clay layer 10 or more feet thick in the glacial aquifer, Oakland County, Michigan (modified from Aichele, 2004).

than the quantity, is usually the limiting factor. The Marshall Sandstone underlies parts of Holly, Groveland, and Brandon Townships but is not present in other parts of the county. Deeper parts of the Marshall Sandstone can contain saline waters unsuitable for drinking or industrial purposes.

The remaining parts of the county generally do not have access to high-quality bedrock aquifers. In very specific areas, layers of sandstone or fractures in the Coldwater Shale can serve as acceptable drinking-water sources.

Ground-Water Quality

In most areas of Oakland County, the chemical quality of ground water from either the glacial aquifer system or bedrock aquifers is suitable for household drinking water or for industrial purposes. The U.S. Environmental Protection Agency sets Maximum Contaminant Levels (MCL) and Secondary MCLs (SMCLs) for a variety of potential contaminants. The MCLs and SMCLs for chemicals commonly found in ground water in Oakland County are listed in table 4.

Table 4. U.S. Environmental Protection Agency primary and secondary maximum contaminant levels for ground-water contaminants common in Oakland County, Michigan. Source: http://www.epa.gov/safewater/mcl.html.

[mg/L, milligrams per liter; mg/L, micrograms per liter; MCL, maximum contaminant level; SMCL, secondary maximum contaminant level]

Contaminant	Limit	Units	Type of Limit
Nitrite, as N	1	mg/L	MCL
Nitrate, as N	10	mg/L	MCL
Chloride	250	mg/L	SMCL
Sulfate, as SO_4	250	mg/L	SMCL
Flouride	4	mg/L	SMCL
Arsenic	10	mg/L	MCL
Iron	0.3	mg/L	SMCL
Manganese	0.05	mg/L	SMCL
Dissolved solids	500	mg/L	SMCL

The quality of ground water in Oakland County was described in a recent USGS report (Aichele, 2000). The most common use impairments involve esthetic issues, primarily hardness or high concentrations of sulfur or iron, as opposed to health concerns. Hardness refers to the calcium and magnesium content of water, which makes water less suitable for use in a steam boiler. However, high concentrations of calcium and magnesium also affect the way soaps dissolve in water and can result in clogging or corrosion of plumbing fixtures and pipes. Generally, water containing more than 120 mg/L as $CaCO_3$ is considered hard, and water containing more than 180 mg/L as $CaCO_3$ is considered very hard (Hem, 1985). On the basis of samples collected by the USGS since 1980, most wells in Oakland County produce water classified as very hard. Of 109 samples analyzed, 101 had hardness greater than 180 mg/L as $CaCO_3$, while two additional samples had hardness in excess of 120 mg/L as $CaCO_3$.

Iron, manganese, and sulfur in ground water are indications of a chemically reducing environment in the aquifer. This chemical environment can occur naturally in Oakland County, because of the large amount of carbon debris in the glacial aquifer system. Naturally occurring microbes in the subsurface consume carbon and release electrons as a byproduct, which results in the reduction of iron, manganese, sulfur, and other electron acceptors. High concentrations of iron and sulfur in ground water can also be indications of human-generated carbon sources, such as gasoline, fuel oil, or sewage. Consumption of water with iron or manganese concentrations greater than the SMCL is not considered dangerous from a health perspective; however, both materials leave deposits in pipes and fixtures, impart taste, and can discolor laundry (Shelton, 1997). Elevated concentrations of sulfur in water impart a characteristic “rotten egg” smell and can stain laundry and fixtures. Consuming water with sulfate concentrations in excess of 250 mg/L as SO_4 can cause diarrhea (Shelton, 1997). Softening the water may also help remove iron, although using a softener in a situation where the natural ground water is not hard may not be as effective.

The most common health-related ground-water-quality impairments are associated with nitrate and chloride. Both can occur naturally in ground water; however, elevated concentrations within the glacial aquifer system are usually caused by human activities. Common sources of nitrate contamination include household septic tanks, animal waste, and fertilizers. The USEPA MCL for nitrate in ground water is 10 mg/L as N. This threshold is set based on potential health effects; of particular note is an impairment of the ability of hemoglobin to carry oxygen, potentially leading to cyanosis or “blue-baby syndrome.” Only 2 of 109 samples collected by the USGS in Oakland County since 1980 have had nitrate concentrations greater than 10 mg/L as N, although Aichele and others (1998) identified nitrate concentrations exceeding 10 mg/L as N in 84 of 6,197 samples of public and private drinking water analyzed by the MDEQ laboratory between 1988 and 1997.

Chloride can be present in wastewater, but its presence in ground-water sources is more commonly the result of application of road salt for either deicing or dust control. Of 109 samples analyzed for chloride by the USGS since 1980, 9 have had concentrations greater than 250 mg/L. A 1998 USGS study (Aichele, 1998) identified chloride concentrations exceeding 250 mg/L in 366 of 6,227 samples of public and private drinking water analyzed by the MDEQ laboratory between 1992 and 1998. The 250-mg/L concentration is an SMCL set by the USEPA on the basis of esthetic concerns. Water with higher concentrations of chloride tastes salty to most people. Although several bedrock units in Oakland County have naturally high concentrations of chloride, concentrations of chloride in lakes and rivers have been increasing significantly (Aichele, 2005) and chloride, because it has many uses to society, has been identified as an indicator of human effect (Thomas, 2000).

Arsenic has been found in low concentrations in ground water throughout the county. Although none of the observed concentrations has been high enough to cause acute or immediate symptoms, the USEPA recognizes arsenic as a carcinogen and has reduced the concentrations permissible in drinking water to 10 μg/L. Exposure to concentrations above the MCL over a lifetime could increase the risk of certain types of intestinal and urinary-tract cancers. A USGS report (Aichele, 2004) identified arsenic concentrations exceeding 10 μg/L in 663 of 1,988 samples of public and private drinking water analyzed by the MDEQ laboratory.

Very few chemical differences distinguish the water in the Marshall Sandstone from the water in the glacial aquifer immediately above it. Throughout both the glacial aquifer and the upper parts of the Marshall Sandstone, increasing well depth correlates to increasing dissolved solids concentration, water that is more chemically reducing, and generally decreasing desirability as a drinking-water source because of elevated chloride, iron, and sulfur content. The lower parts of the Marshall Sandstone contain water that is saline enough to preclude it from domestic use.

Concentrations of ground-water contaminants in Oakland County are highly variable both across the county and with depth across very short distances. Some evidence also indicates that concentrations of sulfur, iron, arsenic, and other contaminants may vary seasonally. Public water supplies are required to test their water several times during the year, at varying frequencies depending on the type of water supply, to ensure the water meets health standards. The only way for a private well owner to be certain that his or her water meets health standards is to have it tested regularly.

Surface Water

Water in the streams, rivers, and lakes of Oakland County is a prime asset to the quality of life and environment in the county. Oakland County's many lakes and rivers provide recreational, esthetic, and utilitarian benefits found in few other places. Although surface water includes rivers and lakes, each of these features functions in its own way and has unique characteristics that require separate discussion.

Rivers

Because Oakland County is in an upland setting that includes the headwaters of six major river systems, nearly all of the streams and rivers are relatively small and are typically wadable. The actual volume of water flowing in a given stream is directly dependent on the size of the watershed. For comparison of flows and streams, it is useful to use a yield per unit area, obtained by dividing the streamflow rate by the area of the upstream watershed. Average annual streamflow yields in Oakland County range from 0.67 to 0.85 $(ft^3/s)/mi^2$ (table 5) depending on watershed. This amounts to approximately 447 gal/d in runoff countywide when the area of the watershed is taken into account. This figure can also be expressed as a fraction of the long-term average precipitation. The average annual precipitation in Pontiac is 29.6 in/yr for the period from January 1960 through December 1998. The average annual runoff from the basins accounts for 10.4 in/yr, or slightly more than one-third of annual precipitation. The remaining two-thirds is accounted for by either evapotranspiration, ground water discharging to points outside the county, or consumptive human uses within the county.

Human actions can have an effect on streamflow characteristics. Increased impervious surface (for example, pavement) can increase the amount and speed of runoff during a storm and decrease the amount of water recharged to ground water. Similarly, ground-water withdrawal will decrease the amount of base flow to streams and rivers, although the actual effect is difficult to predict without site-specific information. A recent study (Aichele, 2005) evaluated the effects of land-cover change—specifically conversion of forest and agricultural areas to urban covers—in Oakland County from 1970 to 2003. Although very little effect was observed in peak flows or the variability of streamflow, several sites exhibited statistically significant trends in low-flow characteristics. Two sites in the River Rouge watershed, where nearly all water demand is met by DWSD supply, have significant upward trends in low flows, despite being nearly entirely urbanized. One site on the Upper River Rouge and two sites on the Clinton River had significant downward trends in low flows; in substantial areas of the watersheds upstream of each of these sites ground water is used for household use and wastewater is discharged to a river system. None of these sites received WWTP discharges from upstream.

Lakes

Oakland County has more than 1,600 lakes of various sizes, and more than 450 of them have surface areas greater than 25 acres. These lakes are valuable esthetically, ecologically, and financially. In addition to

Table 5. Streamflow yields for selected watersheds in Oakland County, Michigan.

[ft^3/s, cubic feet per second; mi^2, square miles]

Watershed	Measurement location	Years of record	Drainage area	Annual discharge		Base flow		Runoff		Evapotranspiration	
			(square miles)	$(ft^3/s)/mi^2$	Inches	$(ft^3/s)/mi^2$	Inches	$(ft^3/s)/mi^2$	Inches	$(ft^3/s)/mi^2$	Inches
Shiawassee River	Linden	30	83.7	0.75	10.25	0.57	7.79	0.18	2.46	1.43	19.35
Stony Creek	Romeo	40	25.6	0.67	9.07	0.55	7.43	0.12	1.64	1.51	20.53
Paint Creek	Rochester	45	70.9	0.76	10.27	0.65	8.81	0.11	1.46	1.42	19.33
Sashabaw Creek	Drayton Plains	45	20.9	0.63	8.49	0.57	7.78	0.05	0.71	1.56	21.11
Clinton River	Auburn Hills	42	123.0	0.85	11.48	0.72	9.82	0.12	1.66	1.33	18.12
Rouge River	Southfield	46	87.9	0.80	10.89	0.47	6.34	0.33	4.55	1.38	18.71
Upper Rouge River	Farmington	46	17.5	0.81	11.06	0.51	7.01	0.30	4.05	1.37	18.54
Huron River	Milford	56	132.0	0.77	10.46	0.68	9.23	0.09	1.23	1.41	19.14

income generated by recreation and tourism, Oakland County has more than 29,000 waterfront parcels, with an estimated value of over $10.6 billion (Ryan Runnels, Oakland County GIS Utility, written commun., 2004). Most lakes in Oakland County receive a large part of their water from ground-water seepage. Thus, lake levels are sensitive to fluctuations in water-table depth. Many lakes in Oakland County have regulated lake levels, meaning that the elevation of the surface of the lake must be maintained within a certain range by order of a court or other regulatory body. Lakes with regulated levels use either a system of diversions or controls such as dams to retain streamflow within a lake or augmentation wells that pump ground water into the lake. Either of these methods can pose problems. The record of streamflow in the Clinton River at Drayton Plains when flow was being retained at an upstream lake to maintain a lake level is shown in figure 27.

The summer 2002 streamflow values shown in figure 27 are period-of-record low flows for this site, based on daily records since October 1959. Although the effects of these low flows on the aquatic ecosystem of the stream are unknown, this diversion of water to maintain lake levels is not without consequence—that is, the water is diverted from somewhere, in this case the normal streamflow downstream of the lake.

Similarly, augmentation wells are used in many parts of Oakland County in an attempt to maintain lake levels. In many cases, lakes are directly connected to the underlying glacial aquifer, and the augmentation well eventually ends up recirculating water from the aquifer to the lake, then drawing it back through the lake bed to the well. In situations where there is truly a separation between the lake and the aquifer, augmentation wells can be effective at maintaining lake levels. However, they remove water from the ground-water system, which effectively removes it from nearby streams and wetlands that would receive that water as ground-water discharge.

Surface-Water Quality

Because surface water serves as a drinking-water, recreational, esthetic, and ecological resource, and as a means for removal of excess stormwater, treated wastewater, and other waste products there is an obvious need to strike a balance between these sometimes competing functions. For this reason, various standards have been

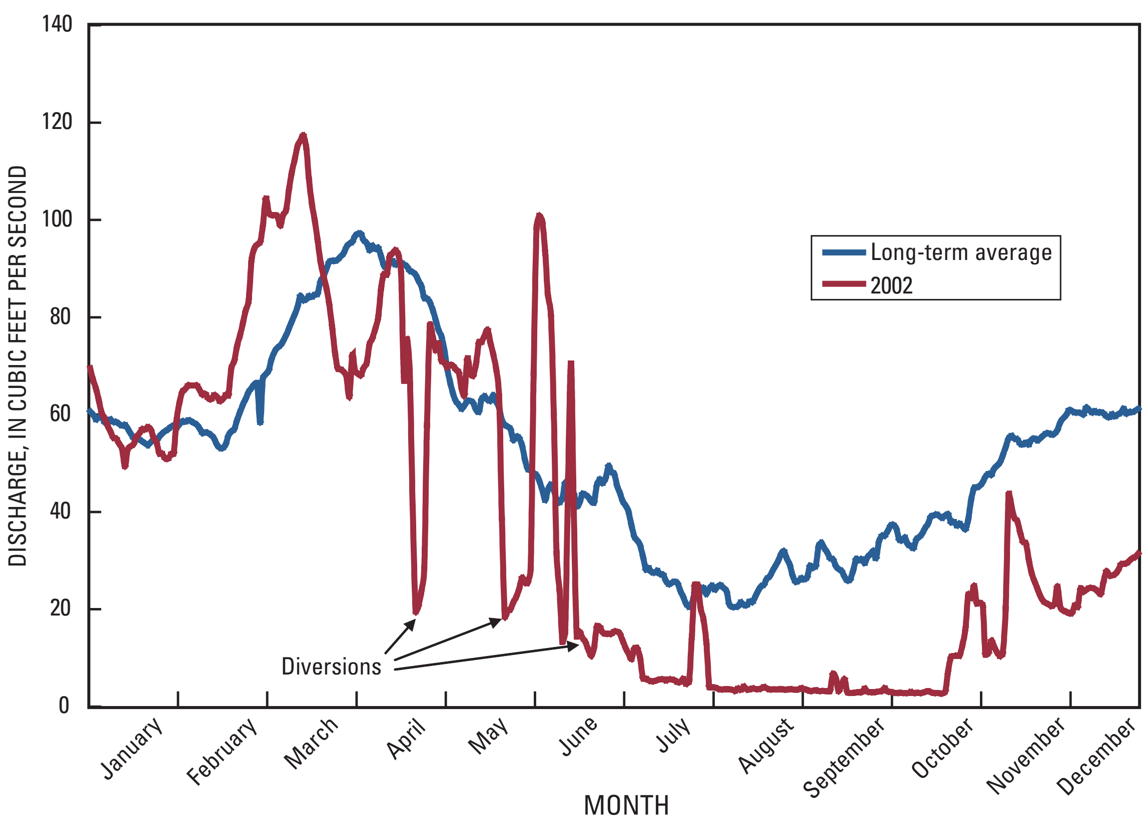


Figure 27. Diversion of water for lake augmentation can substantially alter stream flows. (Data from USGS streamflow gaging station 04160900 — Clinton River at Drayton Plains, Mich.)

developed by MDEQ to evaluate the quality of surface water, on the basis of its use.

River-Water Quality

Because Oakland County is located in the headwaters of its river systems, the relatively small streams present have not been developed as a source of drinking water. However, all surface-water bodies in the county, and throughout Michigan, are required to meet water-quality standards for recreational waters.

It is possible to compare the current (2001–2003) chemical quality of surface water in Oakland County (Aichele and others, 2004) to the period from 1966-1970, when data for Twenter and Knutilla's report (1972) were collected (Aichele, 2005). Based on these comparisons, the chemical quality of stream water is generally better than in the late 1960s, with concentrations of nutrients such as nitrate, phosphorus, and sulfate decreasing. In contrast, specific conductance (a measure of the dissolved-solids concentration of the water) and concentrations of chloride and have approximately doubled. Chloride is very stable in the environment and is seldom consumed or absorbed. Uses of chloride vary widely, from food seasoning to water softening and from dust control to snow removal. As a result, it has become a common indicator of human influence (Thomas, 2000). Dietary consumption varies widely, but a recent study estimated U.S. salt (sodium chloride) consumption at 10,000 milligrams per person per day (Intersalt Cooperative Research Group, 1988), which equates to approximately 6 grams of chloride per day or 2.2 kilograms (4.8 lb) of chloride per year. Distributed across the 1.2 million residents of Oakland County, that totals nearly 2.6 million kilograms per year, or roughly 2,900 tons/year. Salt use by the Oakland County Road Commission for road deicing averages roughly 77,000 tons/year (Earryl Heid, Oakland County Road Commission, oral commun., 2005), and does not include state, local, or private use. A recent study in Ohio (Kunze and Sroka, 2004) has documented increases in chloride concentrations in ground water of as much as 100–300 mg/L as a result of road deicing. Records of specific conductance at three sites in three separate watersheds (Shiawassee, Clinton, and Rouge) are shown in figure 28. Chemical analysis indicates the overwhelming component of the spike observable in the Clinton and Rouge watersheds is sodium chloride, from runoff associated with a midwinter snowmelt.

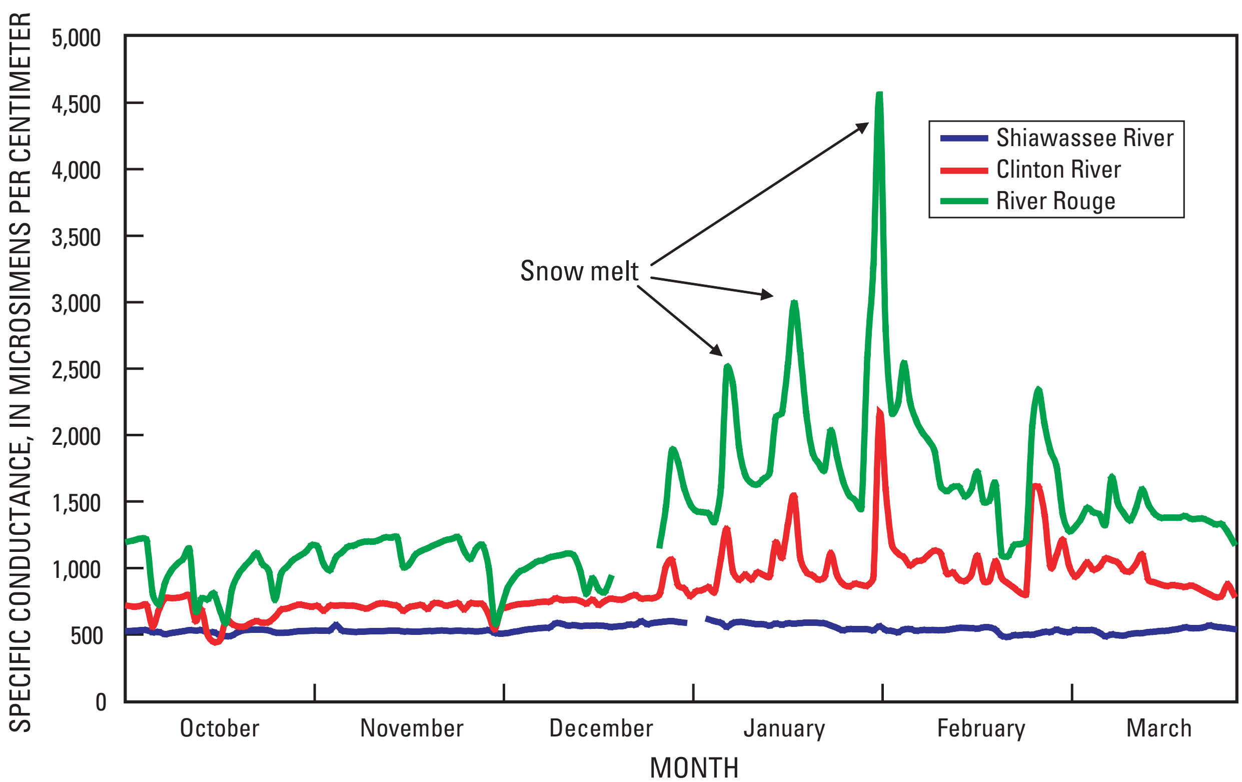


Figure 28. Specific conductance can increase rapidly in urbanized basins during snow melt because of contamination by road salt. The heavily urbanized River Rouge develops a much larger peak than the less urbanized Clinton and Shiawassee Rivers.

A variety of analyses are available now that were not available during the period of the previous study (Twenter and Knutilla, 1972). The most noteworthy of these are improved analyses for bacteria and for a group of chemicals collectively known as "emerging contaminants."

Within the group of emerging contaminants are several common indicators of human influence, such as personal-care products, detergents, pharmaceuticals, flame retardants, caffeine, and hormones. In addition, many of these compounds are relatively persistent in the environment and can be detected at very low levels. Many of the compounds are also used in multiple applications; for example, a specific compound in a detergent may also be an inert ingredient in a pesticide. Therefore, interpretation of these emerging contaminants data can be difficult, but all of these compounds are generated by humans.

Samples were collected by the USGS from 12 sites in August 2002 and from 14 sites in September 2003 under low-flow conditions (table 6). A subset of the compounds analyzed have been grouped into three categories: household-waste products, likely associated with excreta or personal care products referred to as "waste stream" in table 6); flame retardants; and compounds found in petroleum products (referred to as fuels in table 6).

Among the household waste products, caffeine was detected at 6 of 12 sites in 2002 and 7 of 14 sites in 2003. DEET (N,N-diethyl-meta-toluamide), the insect

Table 6. Detection rates for common classes of organic compounds analyzed in stream-water samples from Oakland County, Michigan, August 2002 and Sept. 2003. Site locations shown in figure 1.

	Site number	Stream	Sampling date	Waste stream (of 10)	Flame retardants (of 5)	Fuels (of 8)
2002	04143830	Shiawassee River	Aug. 21	3	4	4
	04148035	Kearsley Creek	Aug. 21	2	1	5
	04160800	Sashabaw Creek	Aug. 20	3	2	5
	04160900	Clinton River	Aug. 20	4	1	5
	04161000	Clinton River	Aug. 28	6	5	0
	04161540	Paint Creek	Aug. 28	3	1	0
	04161810	Clinton River	Aug. 21	7	4	5
	04166000	Rouge River	Aug. 03	4	4	1
	04166100	Rouge River	Aug. 20	4	3	0
	04166315	Upper Rouge River	Aug. 21	3	4	4
	04170000	Huron River	Aug. 20	5	3	5
	04170500	Huron River	Aug. 28	2	3	0
2003	04143830	Shiawassee River	Sept. 09	5	4	1
	04148035	Kearsley Creek	Sept. 09	1	0	1
	04160800	Sashabaw Creek	Sept. 09	2	0	0
	04160900	Clinton River	Sept. 08	2	0	1
	04161000	Clinton River	Sept. 08	8	5	2
	04161540	Paint Creek	Sept. 09	2	0	1
	04161580	Stony Creek	Sept. 09	1	1	0
	04161810	Clinton River	Sept. 09	7	4	2
	04166000	Rouge River	Sept. 08	4	2	2
	04166100	Rouge River	Sept. 08	3	2	3
	04166200	Evans Ditch	Sept. 08	5	4	3
	04166315	Upper Rouge River	Sept. 08	1	2	1
	04170000	Huron River	Sept. 08	5	3	0
	04170500	Huron River	Sept. 08	1	1	2

repellent, was detected at all sites in both years. Cholesterol was detected at 6 of 12 sites in 2002 and 3 of 14 sites in 2003. AHTN (6-acetyl-1,1,2,4,4,7-hexamethyltetraline), a common musk fragrance used in personal care products, was observed at 5 of 12 sites in 2002 and 4 of 14 sites in 2003. The most frequent detections of household waste products were observed in the Clinton River at Auburn Heights and at Dequindre Road and in the Huron River at General Motors Road near Milford. The Pontiac and Milford WWTPs are located upstream above the Auburn Hills and General Motors Road sites, respectively. The Dequindre Road site is approximately 12 mi. downstream from the Auburn Hills site. Interestingly, samples from many sites with no obvious wastewater source contained one or more indicators of household wastewater.

Flame retardants are commonly used in clothing, building materials, electronics, and a variety of other applications, making determination of a source difficult. Water samples from every one of the 12 sites sampled in 2002 contained at least 1 of the 5 fire retardants analyzed for. In 2003, water from only 10 of 14 sites contained 1 or more fire retardants. The most frequent detections were again in the Clinton River at Auburn Hills, which had five of five analyzed for, but the Shiawassee River and Clinton River at Dequindre Road both had four of five in both 2002 and 2003.

Compounds typically found in petroleum products were detected in 8 of 12 samples in 2002 and 11 of 14 samples in 2003. Compounds were detected more frequently in 2002; water from four sites, Kearsley Creek, Sashabaw Creek, Clinton River near Drayton Plains, Clinton River at Dequindre Road, and Huron River at General Motors Road near Milford all had detections of each of the five compounds analyzed for. In 2003, the most frequent detections were in the River Rouge at Southfield and in Evans Ditch. Water samples from both sites contained three of the five compounds analyzed for.

No site was completely free of the compounds described above. All of the detections were at very low concentrations—much lower than would pose an immediate threat to human health. However, the long-term effects of these compounds in the environment are poorly understood, either in the context of human health or of ecosystem health. A more detailed description of these sample results can be found in Aichele and others (2005). Although the presence of these compounds in surface water does not pose an immediate threat to human life, it indicates that the quality of surface water in Oakland County is affected by human activity.

Concentrations of the bacterium *Eschericia coli* (*E. Coli*) in Oakland County river water frequently exceeded standards set by the MDEQ for recreational waters (table 7). For partial-body contact such as wading, canoeing,

Table 7. Number of times samples from selected surface-water sampling sites in Oakland County exceeded the Michigan Department of Environmental Quality full-body or partial-body contact standard for *Eshericia coli*, 2001-2003. Site locations shown on figure 1.

[CFU, colony forming unit; ml, milliliter]

Site number	Stream	Number of samples analyzed	Number of samples exceeding 300 CFU/100 ml	Number of samples exceeding 1000 CFU/100ml
04143830	Shiawassee River	9	0	0
04148035	Kearsley Creek	4	3	0
04160800	Sashabaw Creek	10	3	1
04160900	Clinton River	6	2	2
04161000	Clinton River	10	4	2
04161540	Paint Creek	10	6	2
04161580	Stony Creek	3	0	0
04161810	Clinton River	9	5	2
04166000	Rouge River	9	7	1
04166100	Rouge River	9	6	4
04166200	Evans Ditch	2	1	1
04166315	Upper Rouge River	10	6	5
04170000	Huron River	8	2	0
04170500	Huron River	7	0	0

and fishing, the MDEQ standard is 1,000 colony forming units (CFU) per 100 ml of sample water. The full body contact (bathing) standard is 300 CFU per 100 milliliters (mL). Of 14 sites sampled, 11 exceeded the full-body contact standard at least once, and 9 of the 14 exceeded the partial contact standard at least once. The site in the county that is most representative of a bathing location is the Huron River near New Hudson, just downstream from the Kent Lake Dam. All seven samples analyzed at this site had *E. coli* concentrations well below both standards.

During August and September 2003, an effort was made to use antibiotic resistance to identify sources of *E. coli* and enterococci bacteria in surface water in Oakland County (Fogarty and others, 2005). The results of this project were inconclusive, but did indicate the presence of *E. coli* and enterococci that were resistant to clinical antibiotics at some sites. Genetic markers for *E. coli* O157, a human pathogen, were detected at sites throughout the county in August and September. Pathogens are organisms capable of causing illness. Although *E. coli* of type O157 are considered human pathogens, it is not clear what effect, if any, the presence of these organisms in surface water has on either public health or ecosystem function (Fogarty and others, 2005). Samples were also collected from two reference sites in Michigan, one near Grayling and one on Isle Royale in Lake Superior. Organisms in both of these reference samples also were somewhat resistant to clinical antibiotics, although resistance was generally at lower concentrations and to lower-order antibiotics compared to the resistance in samples from Oakland County. Comparable data from other developed counties in Michigan are not currently available, so it is difficult to state whether the results observed in Oakland County might be typical of other counties.

Lake-Water Quality

Two methods were used to quantify lake-water quality in Oakland County. First, samples were collected from 12 lake basins. These samples were analyzed for nutrients, major ions, and other chemical characteristics. Second, lake trophic status, a broad indication of overall lake-water quality, was estimated for all large lakes in Oakland County by means of satellite imagery interpretation techniques developed by Fuller and others (2004). These estimates are shown in figure 29. Water-quality samples collected during the previous study (Twenter and Knutilla, 1972) had only been analyzed for a few select chemical characteristics. The more recent study

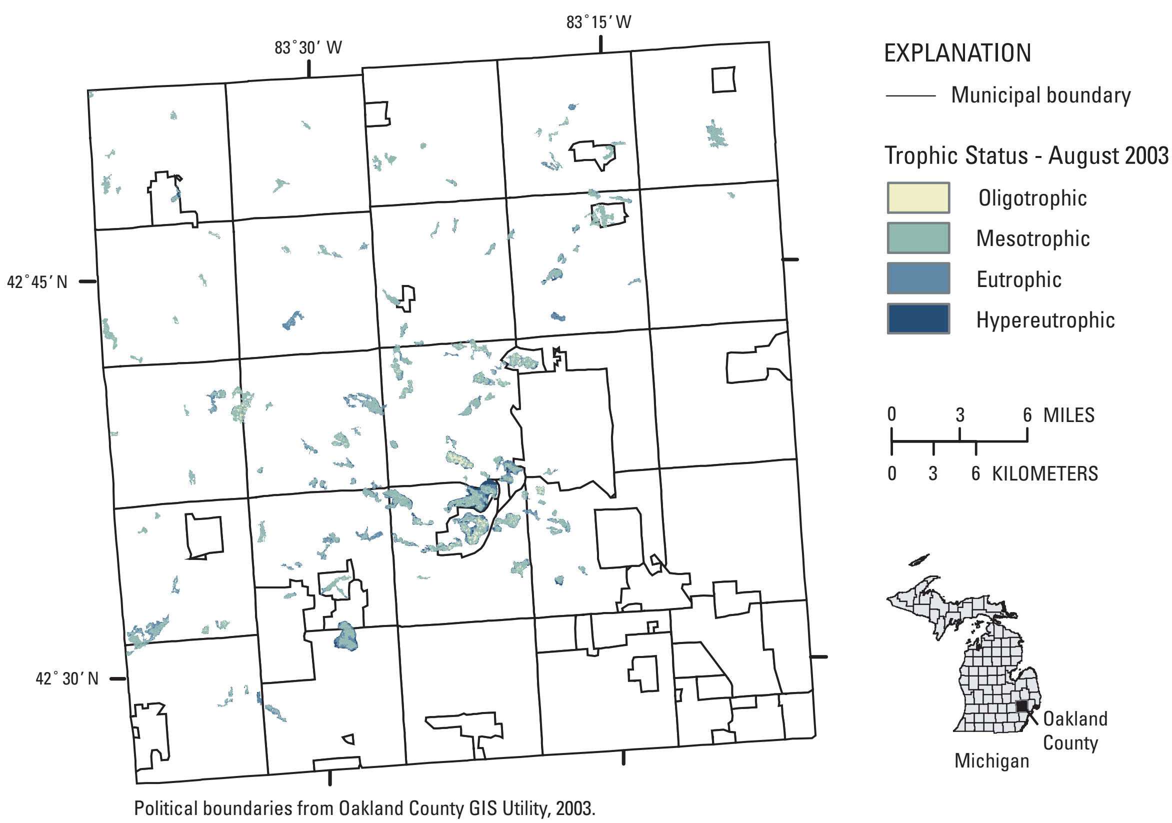


Figure 29. Trophic status of lakes in Oakland County, Michigan varies widely.

(Aichele and others, 2004) sampled for a more extensive suite of chemical characteristics. A comparison of selected water-quality characteristics is given in table 8.

Chloride concentrations have more than doubled at every site, paralleling the results from stream samples. Sulfate concentrations have generally decreased since the late 1960s, except in Kent Lake (part of the Huron River). Nitrate concentrations have also generally decreased since the late 1960s, except at Kent Lake. This pattern is similar to what was observed in stream water, and is likely caused by wastewater discharge to the Huron River upstream of Kent Lake.

Table 8. Lake water-quality data for selected lakes in Oakland County, Michigan, 1967 and 2002-2003.

[mg/L, milligrams per liter; N, nitrogen; SO_4, sulfate; Cl, Chloride; NO_3, nitrate; µs/cm, microsiemens per centimeter]

	1967 (Twenter and Knutilla, 1972)					2002-2003 (this study)			
	Sulfate mg/L as SO4	Chloride mg/L as Cl	Nitrate mg/L as N	Nitrate mg/L as N	Specific conductance µs/cm	Sulfate mg/L as SO4	Chloride mg/L as Cl	Nitrate mg/L as N	Specific conductance µs/cm
Kent Lake	39	26	0.2	0.045	457	--	117	0.144	730
Wolverine Lake	22	62	--	--	485	32.2	263	<0.022	1080
Union Lake SE	24	28	0.0	0.000	397	--	118	0.084	676
Lower Pettibone Lake	22	15	--	--	370	--	96	0.353	695
Big Lake	18	10	--	--	285	--	32	0.168	329
Tipsico Lake	12	2.5	0.1	0.023	166	5.1	23.3	<0.022	194
Lake Orion	62	16	1.6	0.361	785	32.5	66	<0.022	554
Valley Lake	19	7.2	--	--	295	15	38.5	<0.022	418
Lakeville Lake	36	12	0.6	0.135	402	25.6	39.9	<0.022	485

Summary

Water has always had an important role in Oakland County's economy and vitality. In 1972, the U.S. Geological Survey (USGS) published Water Supply Paper 2000, "Water for a Rapidly Growing Urban Community— Oakland County, Michigan" (Twenter and Knutilla, 1972). In 2001, Oakland County and the USGS initiated a cooperative project to update the 1972 study in light of changes in the county as well as advances in the field of hydrology. Several recent USGS technical reports document specific aspects of the study. This report summarizes the results and conclusions in the above-mentioned USGS technical reports and serves as a current overall assessment of the current quantity and quality of water resources in Oakland County.

Demand for water in Oakland County grew steadily during the first half of the 20th century, reaching nearly 85 million gallons per day (Mgal/d) in the early 1960's. Although the county typically receives about 30 inches per year of precipitation, this quantity can vary annually by as much as 10 inches. Not all parts of the county are equally suited for water development. The southeastern part of the county is underlain primarily by lakebed sediments, which have very low infiltration rates. The central part of the county is underlain by sandier outwash deposits, with relatively high infiltration rates but also with a relatively high susceptibility to contamination from surface sources like septic tanks and road runoff. The northwestern part of the county has a mixed geologic setting, with both high- and low-permeability sediments. Drillers' log data available are insufficient to accurately characterize the subsurface environment in much of the county, because of high variability in both the geology itself and the quality of the drillers' logs.

During the drought of the early 1960s, stress on water sources, primarily ground water within the county, became evident. Much of the southern and eastern parts of the county connected to supply mains and sanitary sewers operated by the Detroit Water and Sewerage Department, removing approximately 80 percent of the demand load from the county. Further population expansion beyond the geographical extent of this supply network has increased water use from ground-water sources within the county to more than 43 Mgal/d in 2000. These areas in the northern and western parts of the county are currently experiencing the highest level of ground-water use ever. Demand for water will continue to increase as population increases in these parts of the county.

The removal of ground water from the hydrologic cycle may result in decreased ground-water levels, summer streamflows, and lake levels in the northern and western parts of the county. Although little change was observed in most streamflow characteristics for most sites in the county, three sites exhibited statistically significant downward trends in low-flow characteristics. At these sites, streamflow is measured from watersheds that have sewers but pump ground water for domestic use. Thus, this water is discharged as wastewater (downstream from the measurement sites) and is not available as base flow to sustain lake and river levels during dry summer months.

Relatively little water-quality data are available for direct comparison with the recent studies. However, data available from Twenter and Knutilla's study (1972) indicate that concentrations of nitrogen, phosphorus, and sulfate have generally decreased in surface water. Chloride concentrations have increased between two- and ten-fold over the last three decades in all lakes and rivers sampled, indicating widespread chloride contamination. Subtler indications of human effects, such as the presence of petroleum compounds, flame retardants, and personal care products indicative of household wastewater, were observed at every surface-water site sampled. Relatively high concentrations of *E. coli* and enterococci bacteria were observed at sites in the Clinton and River Rouge watersheds. *E. coli* and enterococci bacteria resistant to multiple clinical antibiotics were detected in water samples from all sites, as well as in samples from reference sites in relatively unpopulated areas.

Water for the 21st Century – Meeting the Need

An Oakland County population projected to increase by as many as 200,000 people in the next 20 years will demand as much as 20 Mgal/d of additional water for human use. Several areas in the northern and western parts of the county are already experiencing decreasing streamflows, likely related to increasing ground-water use. Human activity also results in water-quality effects, specifically effects related to the disposal and treatment of wastewater, and the transportation infrastructure. Managing the quantity and quality of water available for future residents, and the quantity and quality of water returned to the environment, in such a way as to maintain the recreational, ecological, and esthetic value of the county's water resources, will be a continuing challenge for citizens and decision makers in Oakland County.

Relatively few options will be available to Oakland County to meet the increased water demands in coming decades. If this demand is to be met by ground-water sources within the county, then ground-water withdrawals would have to increase by approximately 50 percent. Water consumed by human use is water that is not available to sustain lake levels or summer streamflow, but this has always been the case (Alley and others, 1999). For example, parts of the Clinton and Rouge River watersheds are already experiencing reduced summer streamflows. Citizens and decision makers in the county will need to define a balance between human use and the needs of the ecosystem

Forecasting the effect of a specific development scenario requires detailed, site-specific information. However, at the county scale two general options are apparent. First, a reduction in either the rate of population growth or per capita consumption, particularly in areas served primarily by ground water, would help reduce the increase in demand for ground water. Alternatively, similar reduction of stress on water resources in the county might be achieved by extending public-water-supply infrastructure to deliver water from the Great Lakes into Oakland County.

Water quality is also of concern. Although the concentrations of most inorganic chemical constituents in Oakland County water have decreased in the last three decades, concentrations of chloride have increased at all sites sampled. Similarly, every site sampled contained trace concentrations of personal care products, petroleum products, and flame retardants. Most sites also had relatively high concentrations of fecal indicator bacteria and bacteria resistant to one or more clinical antibiotics. The ramifications of these emerging contaminants and antibiotic-resistant fecal indicator bacteria on stream ecosystems or public health are not known; however, the presence of these contaminants indicates that the treatment and disposal of wastewater may be as important an issue as the availability of water for domestic use.

As discussed previously, the use of on-site septic systems can be an effective way of reducing the consumptive use of a household, although septic systems require regular maintenance and periodic inspection (Dersch, 2002). They will eventually require replacement, and they are not suitable to construct in all parts of the county. Wastewater-treatment plants provide effective treatment of waste and are more effectively regulated than septic systems, but treatment plants route treated wastewater into rivers. If this water was with-drawn from local ground water, it will be lost to the aquifer. Even with treatment, wastewater discharges may adversely affect stream ecosystems.

Projected population growth in Oakland County will result in increased demand for water for human use, and a continuing need to effectively treat wastewater. Regardless of which approach or combination of approaches are used to meet the water needs of Oakland County in coming decades, these decisions will require decision makers balance competing needs for drinking water, lake levels, and aquatic-ecosystem stability with the economic benefits of continued development, recreation and tourism, and the quality of life afforded by "healthy" lakes, streams, and aquifers. Defining the balance between competing human and ecological demands for water is an inherently political decision of resource allocation and community values (Alley and others, 1999).

Acknowledgments

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