GROUND-WATER-USE TRENDS IN THE TWIN CITIES METROPOLITAN AREA, MINNESOTA, 1880-1980

By M. A. Horn

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Multiply inch-pound unit	By	To obtain SI unit
inch (in)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
gallon (gal)	0.003785	cubic meter (m^3)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons (Mgal)	3785	cubic meter (m^3)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

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ABSTRACT

Detailed ground-water-use information from 1880 to 1980 has been collected and analyzed for the Twin Cities metropolitan area. Interpretation of historic water-use data was required to help water-resource planners and managers assess future trends in water use. Data were also needed for three computer-simulation models of ground-water flow being developed in the Twin Cities area. Methods were developed to collect, evaluate, store, and retrieve information from all local, State, and Federal agencies' records and publications. A computerized water-use data base was constructed to facilitate generation of statistics on water-use trends and to store and retrieve data for the flow models.

Ground-water use was analyzed by use category and aquifer and several trends were observed. Eighty percent of ground water currently withdrawn is from wells in the Prairie du Chien-Jordan aquifer. Ground-water use increased from 1880 until the early 1970's, and then declined slightly in the late 1970's. Industrial use in particular declined during the 1970's as a result of conservation that was prompted by increased sewage-treatment and energy costs. The intensity of pumping has decreased within the St. Paul and Minneapolis city limits and increased outside the city limits. The seasonal variability of ground-water use became more pronounced as the percentage of water used for irrigation and air conditioning increased.

INTRODUCTION

The Twin Cities metropolitan area consists of seven counties and includes 2,968 square miles (fig. 1). Significant volumes of ground water are withdrawn in the Twin Cities area, even though the municipal water supply for Minneapolis is from the Mississippi River and supplies for St. Paul are from a combination of the Mississippi River and a chain of lakes north of St. Paul. Information on historical ground-water use is needed by regional and State water-resource planners and managers to help anticipate future trends and design management plans. Also, three ground-water modeling investigations are in progress that include all or parts of the Twin Cities metropolitan area (fig. 1). These studies use computer models to simulate ground-water flow, and water-use data compiled by aquifer and time interval are a vital component of the flow models. Each of the studies required water-use data at different time intervals (decades, years, and months). Therefore, a data base was developed with sufficient flexibility to meet the requirements for all three computer models, and to provide water-use information for planning and management purposes. Because the distinctions between water withdrawn and water consumed were not significant for the computer models, return flows were not analyzed to calculate total consumptive use. Therefore, water use and water withdrawals are used interchangeably in this report.

Purpose and Scope

The purpose of this report is to describe trends in ground-water use in the Twin Cities metropolitan area, Minnesota, from 1880 to 1980. Water-use trends are discussed in terms of use category, volume of water used over time, aquifer, and well location.

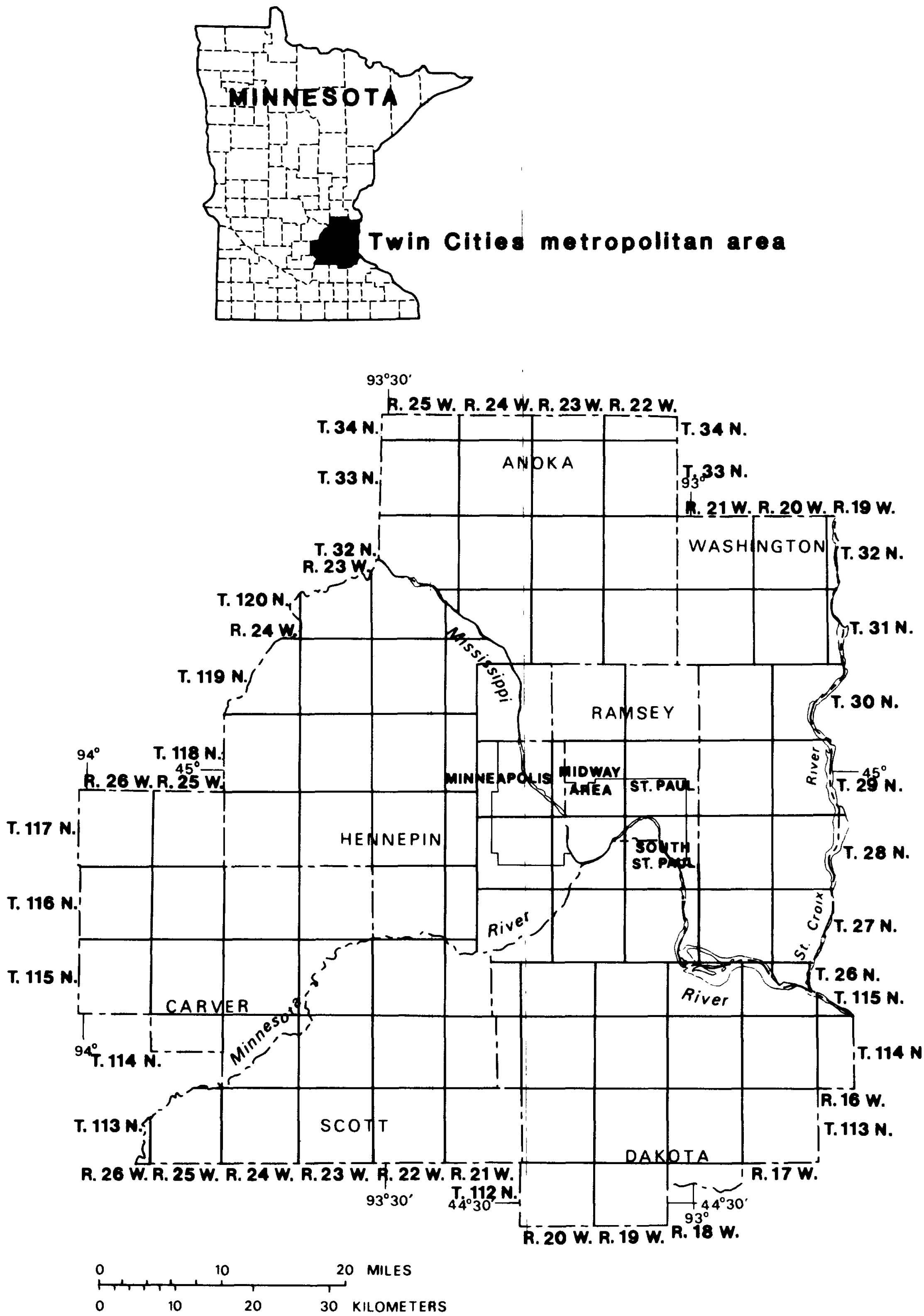


Figure 1.--Location of study area

The methods used for collecting, evaluating, and storing ground-water-use data are described in detail so that future studies will have a basis for comparison. Withdrawals are summarized by the use categories of public supply, self-supplied industrial (including air-conditioning), irrigation, dewatering, and lake-level maintenance. Withdrawals are also summarized for the five major aquifers in the area, the (1) Prairie du Chien-Jordan, (2) Mount Simon-Hinckley, (3) Ironton-Galesville, (4) St. Peter, and (5) glacial drift. Finally, withdrawals in the Twin Cities area are discussed in terms of seasonal variations.

Previous Investigations

The earliest published data on ground-water use are contained in county summaries of deep-well descriptions by Winchell and Upham (1884; 1888), Darton (1902), and Hall (1904). The first actual inventory of Minneapolis ground-water use is summarized by Winchell (1905). Hall and others (1911) summarized municipal water use for southern Minnesota, including depths, water levels and aquifer for each well, and average daily water consumption and population for each municipality. Partial summaries of municipal water use are in the reports by Dole and Westbrook (1907) and Follansbee (1912).

Declining surface-water availability during the 1930's drought resulted in increased interest in ground-water use. The report by the Minneapolis Water Supply Commission (1932) is an excellent inventory of commercial and industrial wells and water use in Minneapolis. Schwartz (1936) tabulated data on municipal, commerical, and industrial wells in the Minneapolis-St. Paul metropolitan area, although no water-use estimates were included. Two other reports, Chase (1937) and the Water Resources Committee Report (1937), provide additional data. Late in 1937, the St. Paul sewer department began to record water used by private wells within the city. Also, unpublished data compiled by the U.S. Geological Survey in 1937 summarizes ground-water pumpage for Minneapolis and St. Paul.

Bradley's (1949) report on declining ground-water levels in the Minneapolis-St. Paul area prompted more research on water use in the Twin Cities. In 1950, the U.S. Geological Survey obtained water-use data for private wells from the Minneapolis and St. Paul sewer departments and estimated industrial water use outside the city limits in order to estimate water use for the entire metropolitan area. These estimates were included as the Minnesota contribution to the first of a series of U.S. Geological Survey Circulars summarizing water use for the United States (MacKichan, 1951; 1957). These data were also used in a report on Minnesota water use (Frellson, 1952), and in a report on Twin Cities water use by Prior and others (1953).

Increased municipal and industrial expansion in the late 1950's and early 1960's prompted another series of water-use investigations. The report by the Minnesota Conservation Department (1961) estimated Twin Cities water resources and use. The report by MacKichan and Kammerer (1961) included estimates of Minnesota water use. Considerable water-use information was necessary for an electric-analog ground-water model of the Twin Cities area constructed by the U.S. Geological Survey in 1965 (unpublished), for which water use was estimated by aquifer for the first time. In 1966, the Minnesota Department of Natural Resources began collecting annual reported water use from water appropriators using more than 1 million gallons per year. Minnesota water use was estimated and included in the report by Murray (1968).

The first water-use report for the 1970's was the Minnesota part of the U.S. Geological Survey's 5-year report by Murray and Reeves (1972). A major effort was undertaken by the U.S. Geological Survey to again estimate water use in the Twin Cities area by aquifer for the report on the water resources of the Minneapolis-St. Paul metropolitan area by Norvitch and others (1973). The most recent U.S. Geological Survey report on water-use was by Murray and Reeves (1977). Finally, a review of Minnesota water resources and use was done by the Minnesota Water Planning Board (1979). The Water Planning Board compiled water-use information reported to the Department of Natural Resources and estimated non-reported water use for the report.

This report on Twin Cities water use depends heavily on data collected over the past century for all the previously described reports. The descriptions contained here of data sources and methods used to compile water-use information and the water-use data base should facilitate future water-use investigations.

METHODS

Methods were developed to compile ground-water-use information for modeling studies in the Twin Cities metropolitan area. Once the data requirements were defined, a comprehensive plan was developed to collect, evaluate, store, and retrieve ground-water-use information (fig. 2). Principal sources of information were reviewed in order to derive a preliminary list of water users and well descriptions. Secondary sources of data were used to identify additional water users, determine the amount of water used, and complete well descriptions. Data were evaluated and missing information was estimated. Finally, the data were coded, verified, and entered into a computerized data base. These procedures are discussed in greater detail in the following sections.

Data Collection

Data collected include (1) well and casing depths and diameters; (2) location of the well, by latitude and longitude, and township, range, section, and nearest $2\frac{1}{2}$-acre tract; (3) date of well construction and abandonment; and (4) reported or estimated water withdrawn from the well since its construction. Data were collected on municipal, industrial, irrigation, and other private wells from which more than 10 million gallons per year were withdrawn.

Principal sources of information were the Minnesota Department of Natural Resources, U.S. Geological Survey, and Minnesota Geological Survey. The Department of Natural Resources requires water-appropriation permits and annual water-use reports from water appropriators serving more than 25 persons, and (or) appropriating more than 10,000 gallons per day or 1 million gallons per year. These annual water-use reports for the years 1966-70, 1975, and 1976 were used to obtain a list of ground-water appropriators with permits and to determine the amount of water used.

The U.S. Geological Survey has extensive files containing drillers' logs of wells and ground-water-use summaries. These summaries include ground-water-use information collected for the Minnesota part of the U.S. Geological Survey Circulars summarizing water use in the United States from 1950 to 1980, the Twin Cities electric-analog model (1965, unpublished) and the study by Norvitch and others (1973).

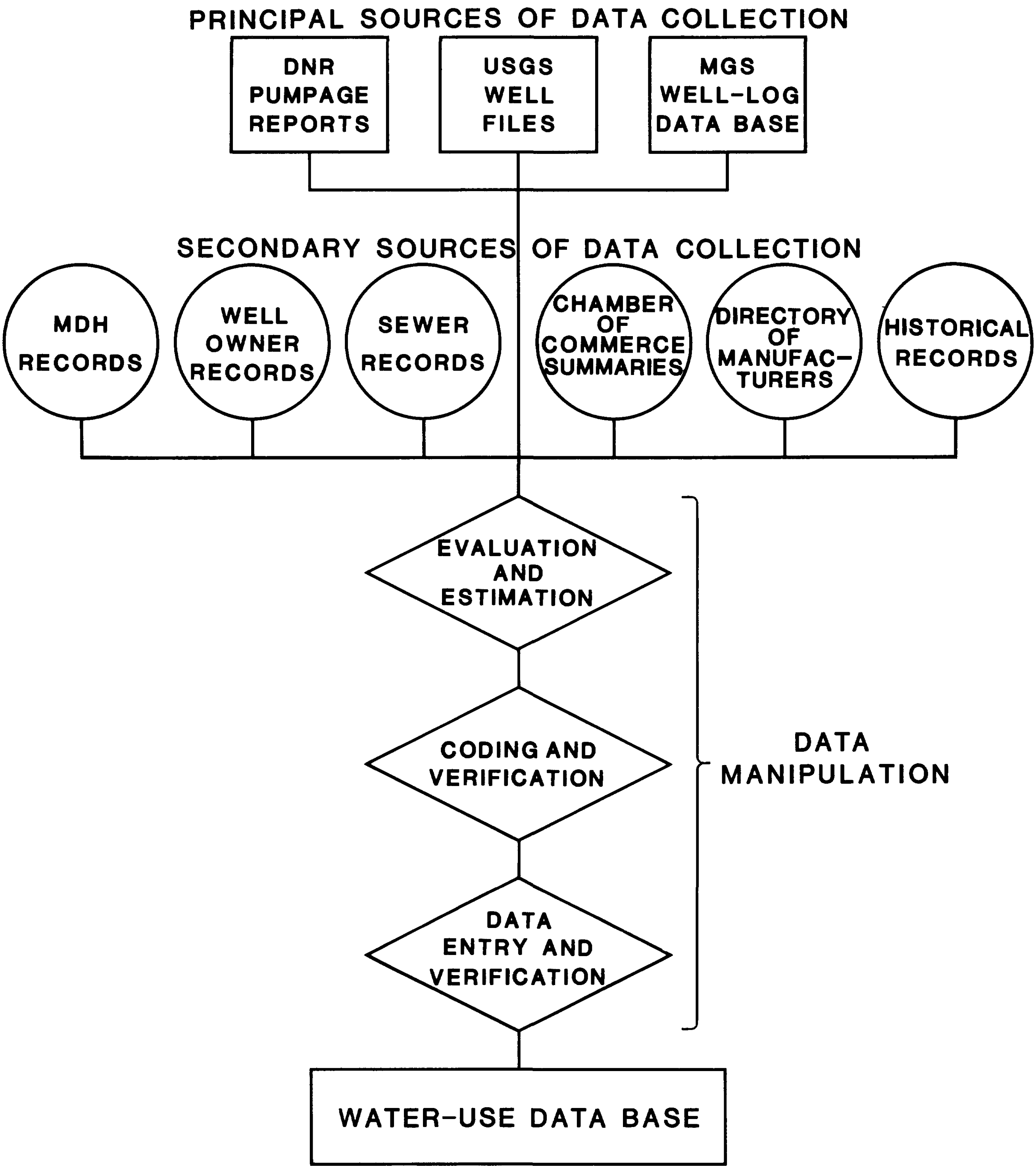


Figure 2.--Plan for assembly of ground-water-use data

The Minnesota Geological Survey's (MGS) well-log data base contains information that has been thoroughly checked to assure accurate location and aquifer designation. The MGS compilation of drillers' logs for municipal wells in the Minneapolis-St. Paul area is another valuable source of information.

Information from these three sources was correlated to derive a preliminary list of water users. Water-use and aquifer information was collected for each well. Secondary sources of data were then used to add to the list of ground-water users, complete well information, and provide estimates for the amount of ground-water used. Secondary sources include the (1) Minnesota Department of Health, (2) St. Paul and Minneapolis municipal sewer departments, (3) well owners and water superintendents, (4) Minnesota Directory of Manufacturers, 1979-1980, (5) Chambers of Commerce in large municipalities, and (6) other published and unpublished historical records.

The Minnesota Department of Health has reports of inspections of municipal waterworks for the past 80 years. These reports provided historical information on the number of wells, well construction, and estimates of water used. Fluoridation reports from municipalities contain recent daily water meter readings that provide accurate measurements of water use.

St. Paul and Minneapolis municipal sewer departments record water withdrawn from private wells and discharged into the municipal sewer system. These records supplied a list of active users and the amount of water used in recent years.

Municipal water superintendents and individual well owners were contacted to supply information not obtained from the sources previously discussed. The water superintendents were also asked for names of industries and institutions in their municipalities with large private wells. Other commercial and industrial well owners were identified from the Minnesota Directory of Manufacturers, 1979-1980, and from information provided by the Chambers of Commerce in large municipalities.

Descriptions of high-capacity wells and estimates of water use before 1965 were obtained from State and Federal publications, as well as from U.S. Geological Survey files. The report by Hall and others (1911) provided most of the data used in deriving water-use estimates from 1880-1910. The report by the Minneapolis Water Supply Commission (1932) was the main source of water-use estimates for Minneapolis during the 1930's and records kept by the St. Paul sewer department were the main source of estimates for St. Paul. Water-use estimates for the 1940's and 1950's were developed from water-use data compiled from the Minneapolis and St. Paul sewer departments, and the U.S. Geological Survey estimates of water use outside the city limits. The annual water-use reports required by the Minnesota Department of Natural Resources are the most valuable source of water-use estimates for individual wells from the late 1960's to the present, even though a comparison of known active users with those sending water-use reports indicated that for any one year only 60 percent of users in the Twin Cities area send in their annual water-use reports.

Data Evaluation and Estimation

Methods were developed to determine to which aquifer(s) a well is open and to estimate municipal and self-supplied industrial ground-water use when data were not available from any of the previously described sources. Data on each well were assigned a numeric reliability code based on the completeness and quality of information on the aquifer used and the amount of water withdrawn (table 1). These codes helped target wells for which more information was needed, and resolve problems in interpretation of water-level and water-use correlations. An aquifer's designation for a specific well was classified as "known" if the well and casing depths were available, and aquifer(s) to which the well is open could be substantiated by the well log or detailed geologic maps. A classification of "incomplete information" was used when only the well depth was available. In this case, an aquifer designation was made using geologic maps along with knowledge of the use of the well and the drilling practices used when the well was drilled. An aquifer designation was "estimated" when no well depth was known. In this case, the most commonly used aquifer in that area was assigned.

Table 1.—Reliability of ground-water-use data

Aquifer designations	Withdrawal rate		
	Known	Incomplete information	Estimated
Known	1	4	7
Incomplete information	2	5	8
Estimated	3	6	9

Water-use estimates were classified as "known" if the pumpage was known for more than 75 percent of the years the well was in operation. If pumpage was available for between 25 and 75 percent of the years of operation, the classification of "incomplete information" was used. If pumpage for fewer than 25 percent of the years was available, the classification was "estimated." A more detailed discussion of estimations of water use by use category is contained in the following section.

Ground-Water-Use Estimation

When the amount of ground water used by municipalities from 1910 to 1980 in southeastern Minnesota was not recorded, it was estimated from historical per capita water-use (ground-water and surface-water) and census data. Information from Hall and others (1911), U.S. Public Health Service surveys (1946; 1955; 1964), archived records of the Minnesota Department of Health, and Minnesota Department of Natural Resources water-use reports were combined for the 70 municipalities present in southeastern Minnesota in 1910. Ten percent of these municipalities were in the Twin Cities area. The municipalities were divided into three groups based on population: less than 1,000 (27 municipalities), 1,000 to 10,000 (32 municipalities), and greater than 10,000 (11 municipalities). (See fig. 3.) Per capita water-use values were available for the largest number of municipalities for the years 1910, 1940, and 1970. Per capita water use for other years was extrapolated based on these values.

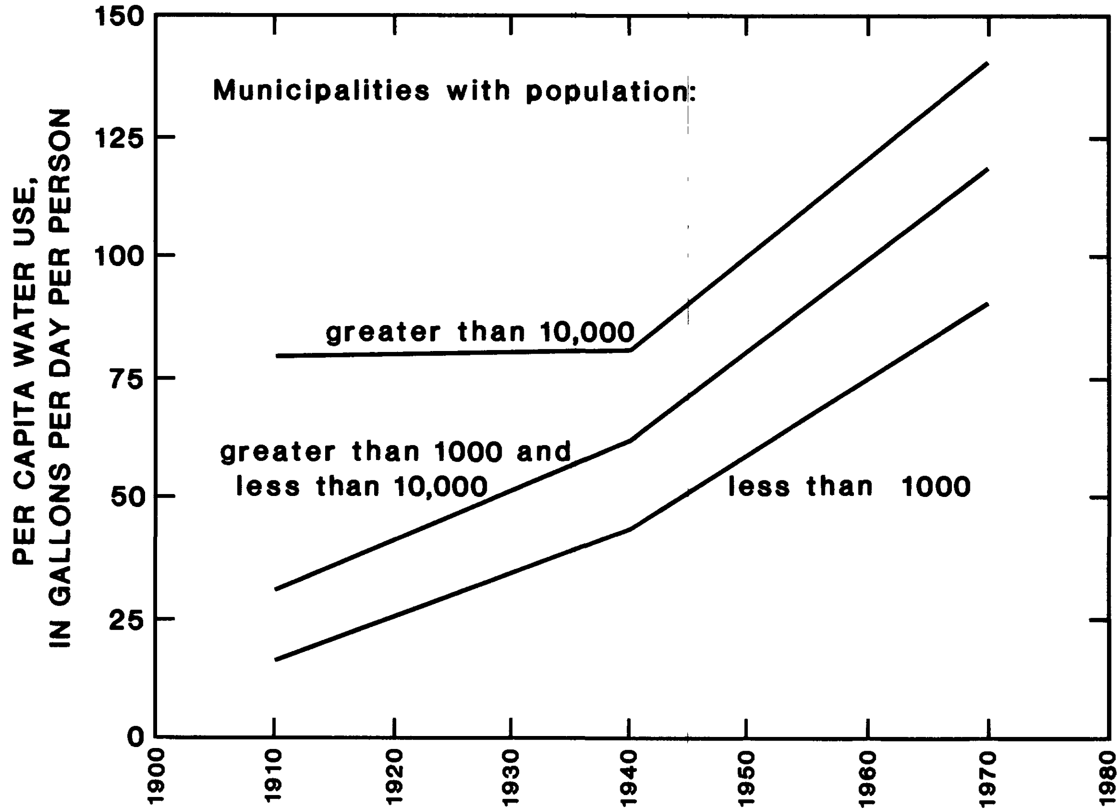


Figure 3.--Historical per capita water use for municipalities in southeastern Minnesota

Self-supplied industrial ground-water use was estimated based on analysis of the well-casing diameter, pump type and capacity, type of industry, and history of operation. Significant quantities of water, more than 10 million gallons per year, are generally used if the casing diameter is 8 inches or more, vertical turbine pumps are used, or the pump capacity is 70 gal/min or more. Food-processing plants and plants that require cooling water are types of industries that use large quantities of water. Well owners, plant engineers, or well-maintenance personnel were contacted for information on periods of plant inactivity or changes in plant design that would significantly alter water use in the plant. Such changes included increases in plant size and installation of cooling towers, holding tanks, or variable speed drives on pump motors.

Ground-water use for the other three major use categories, irrigation, dewatering, and lake-level maintenance, were based on water use reported to the Minnesota Department of Natural Resources.

Water-Use Data Base

After the water-use information was collected, estimated where necessary, assessed for reliability, and entered on coding forms, it was entered interactively into a SYSTEM 2000[1/] data base. SYSTEM 2000 was chosen because it offers flexibility to the user and has an English-like, self-contained query language that allows users without computer programming experience to retrieve information from the data base. The water-use data base is presently (1982) stored in the computers at the University of Minnesota, Minneapolis.

The Twin Cities water-use data base contains a number of data elements for individual wells, each with a single value, such as township, range, section, latitude, longitude, and county (fig. 4). Each well also has a unique U.S. Geological Survey site identification number. A series of multiple values or repeating groups were set up for (1) aquifers, (2) time periods, (3) annual water use, and (4) monthly water use. Water-use information is stored for every well as annual averages over 11 specific time periods, 1880-1900, 1901-10, 1911-20, 1921-30, 1931-40, 1941-50, 1951-60, 1961-65, 1966-70, 1971-75, and 1976-79. Annual and monthly reported water-use information is contained in the data base for each of the years from 1970 to 1979 if it was available from the Minnesota Department of Natural Resources (approximately 60 percent of the wells). Ground-water-use trends described in later sections of this report are from period to period, not year to year. Seasonal trends described are based on the reported monthly values.

Different retrieval formats were used to generate information contained in this report. Although data are stored for individual wells, summaries of water use by aquifer and by use category for different time periods can be obtained from the data base.

TRENDS IN GROUND-WATER WITHDRAWALS BY USE CATEGORY

The five major ground-water-use categories in the Twin Cities area are, from greatest to smallest amount of current use, (1) public supply, (2) self-supplied industrial (includes air-conditioning), (3) irrigation, (4) dewatering, and (5) lake-level maintenance. Each category has its own distinctive characteristics and is discussed separately.

Public Supply

Public supply includes all ground water supplied by municipal waterworks to domestic, commercial, industrial, and city (sanitation, fire) users. Ground water used for public supply was less than 1 Mgal/d from 1880 until the 1911-20 decade when it was 1.7 Mgal/d (fig. 5). Ground-water withdrawals for public supplies have increased from 8.9 Mgal/d in the 1940's to 87.6 Mgal/d in the late 1970's, nearly a tenfold increase (fig. 5). Factors that influence withdrawals of ground water for public supply are (1) population, (2) amount supplied by surface water, (3) per capita use, and (4) industrial and commercial use.

[1/]The use of the brand name in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

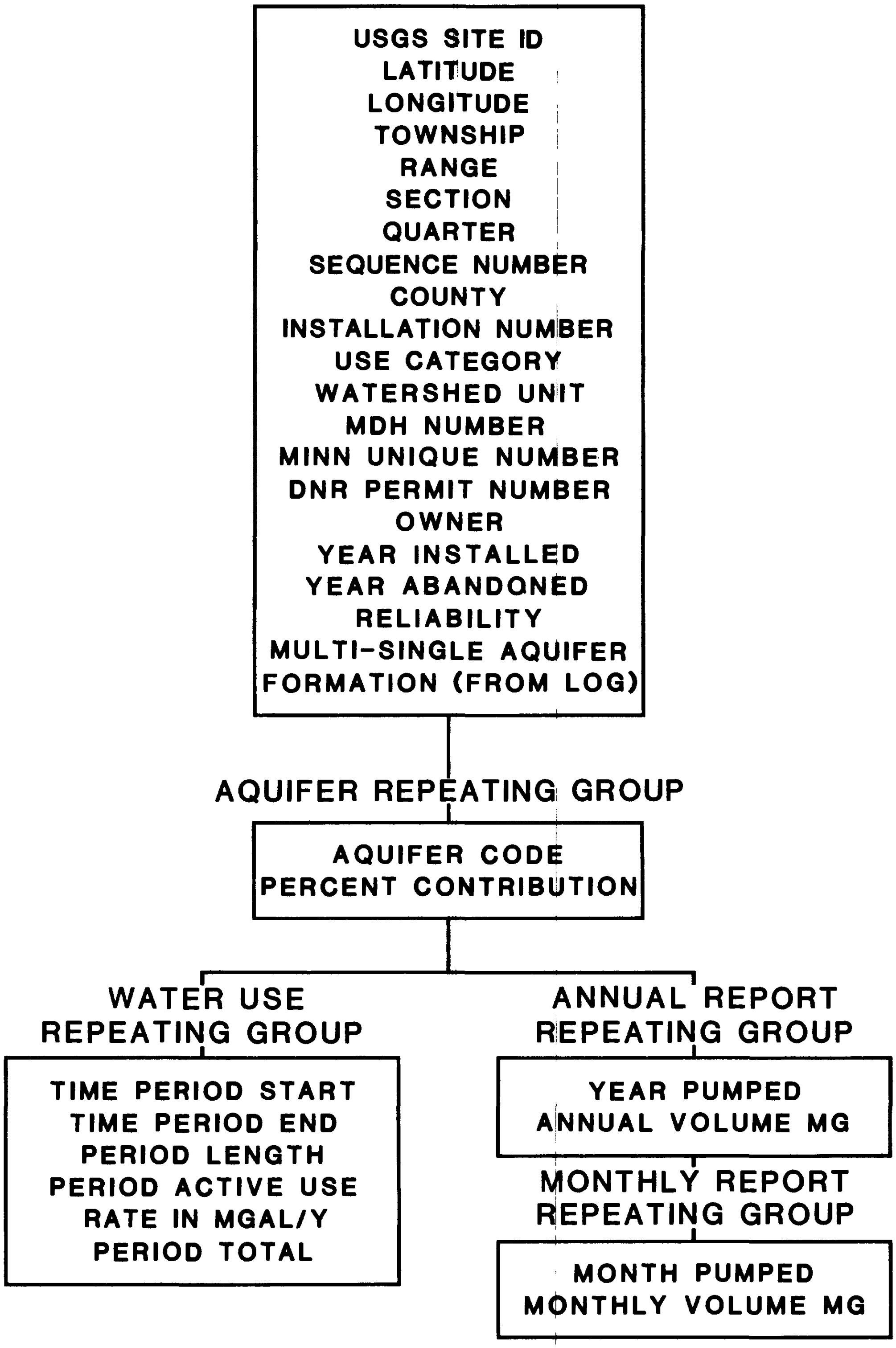


Figure 4.--Structure of the Twin Cities water-use data base

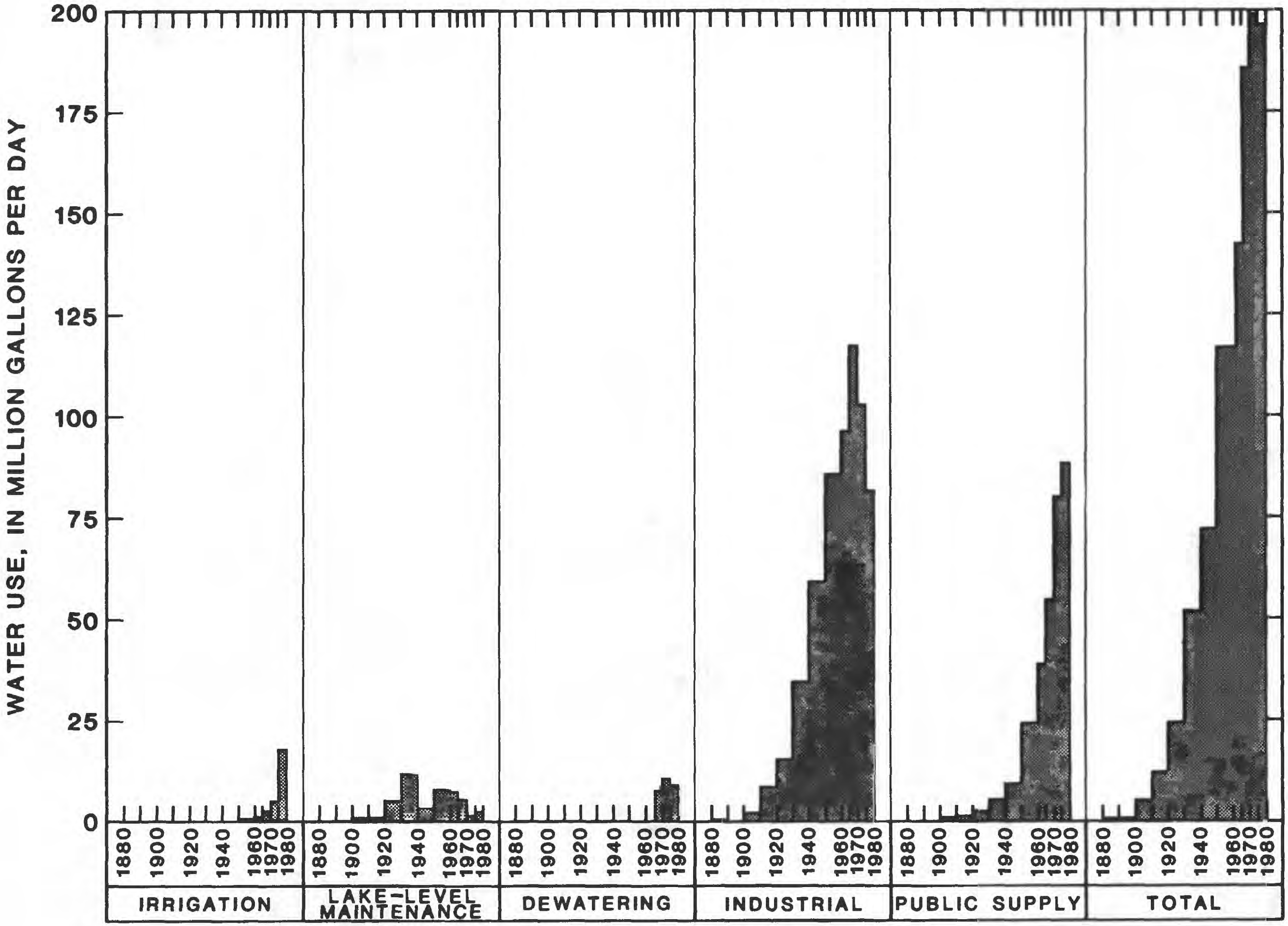


Figure 5.--Historical ground-water withdrawals by use category

During the 1940's, 88 percent of the Twin Cities area population served by public supplies used surface water from the Minneapolis and St. Paul waterworks. Although the population nearly doubled, from 906,788 to 1,795,000, by the late 1970's, the percentage of users supplied by surface water dropped to about 53 percent (table 2). A large part of the population increase was in suburban areas where ground water was used for public supply. Thus, from 1940 to 1979, the population in the Twin Cities area using ground water for public supply increased by seven times from 106,788 to 847,016, while the population using surface water for public supply increased by only 12 percent, from 800,000 to 947,985. Since 1970, the increase in ground-water withdrawals for public supply has been accompanied by a decrease in surface-water use (fig. 6).

Table 2.—Trends in use of ground water and surface water for public supply

[Mgal/d, million gallons per day]

Time period	Ground-water use (Mgal/d)	Surface-water use (Mgal/d)*	Total water use (Mgal/d)	Population supplied by ground water	Population supplied by surface water*	Total population on public supply
1941-50	8.9	78.1	87.0	106,788	800,000	906,788
1951-60	23.6	93.6	117.2	219,297	876,180	1,095,477
1961-65	38.2	105.8	144.0	436,976	906,210	1,343,186
1966-70	54.3	122.9	177.2	570,877	1,011,380	1,582,257
1971-75	79.4	122.6	202.0	765,395	1,022,300	1,787,695
1976-79	87.6	113.3	200.9	847,016	947,985	1,795,001

*Information obtained from annual reports of the Minneapolis and St. Paul waterworks (1940-80).

Another factor that affected the trend in ground-water use was per capita water use. Figure 3 shows that per capita water use for all municipalities approximately doubled from the 1940's to the late 1970's. This, along with increased population using ground water, accounts for the tenfold increase of ground-water withdrawals for public supply (table 2 and fig. 5). Although more industrial and commercial users are currently (1982) on public supply than in the 1940's, they have a minimal affect on ground-water use for public supply because high-volume industrial water users tend to develop their own water-supply systems.

Self-Supplied Industrial Water Use

Ground water used by self-supplied industry was less than 1 Mgal/d until 1911-20 when it increased to 8.8 Mgal/d (fig. 5). Self-supplied water for industrial use continued to increase to 116.4 Mgal/d during the late 1960's. Industrial ground-water use decreased 28 percent from the late 1960's to the late 1970's (fig. 5). Four time periods approximately 20 years apart are examined in detail to emphasize the changes in self-supplied ground water for industrial use that are dependent on changes in population, conservation efforts, type of industries, and location of industrial centers.

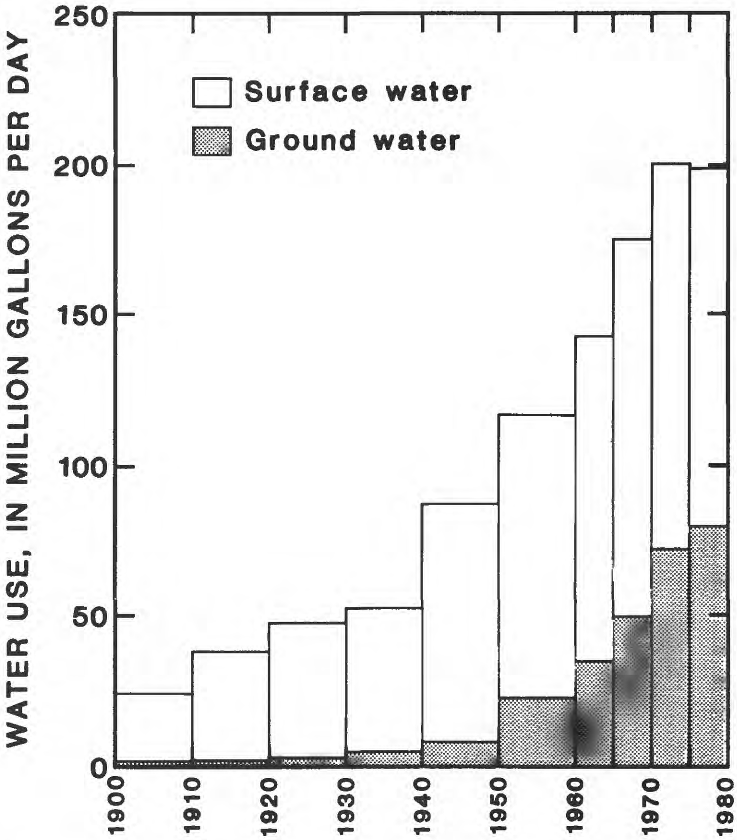


Figure 6.--Combined surface-water and ground-water withdrawals for public supply

The initial increase in industrial use (1911-30) resulted from increases in population and the establishment of more industries in the Twin Cities area. Major groups of water-using industries during the 1920's were stockyards, railroads (steam locomotives), ice manufacturers and cold-storage firms, commercial buildings (including offices, stores, hospitals, and hotels), heavy industry (paper processing, coking, scrap iron, and equipment manufacturing), and agricultural-products processing (creameries, breweries, grain milling, and stockyards). (See fig. 7a.) Most of these industries were located within the Minneapolis-St. Paul city limits.

During the 1940's, self-supplied ground water for industrial use increased to 3.5 times that of the 1920's, from 16 to 57 Mgal/d (table 3). The population in the metropolitan seven-county area increased from 759,500 to 1,000,600 during the same period, which provided the work force and consumers for a growing number of industries. The largest increases in water use from the 1920's to the 1940's were by heavy industry (7 times, requirements for World War II) and by breweries (6 times, the end of prohibition). Heavy industry accounted for 28 percent of all self-supplied water for industrial use in the 1940's (fig. 7b), and consisted of:

Paper processing, 5.2 Mgal/d,
Armament manufacture, 4.1 Mgal/d,
Equipment and appliance manufacture, 3.8 Mgal/d,
Coking, 1.1 Mgal/d,
Others, 1.9 Mgal/d.

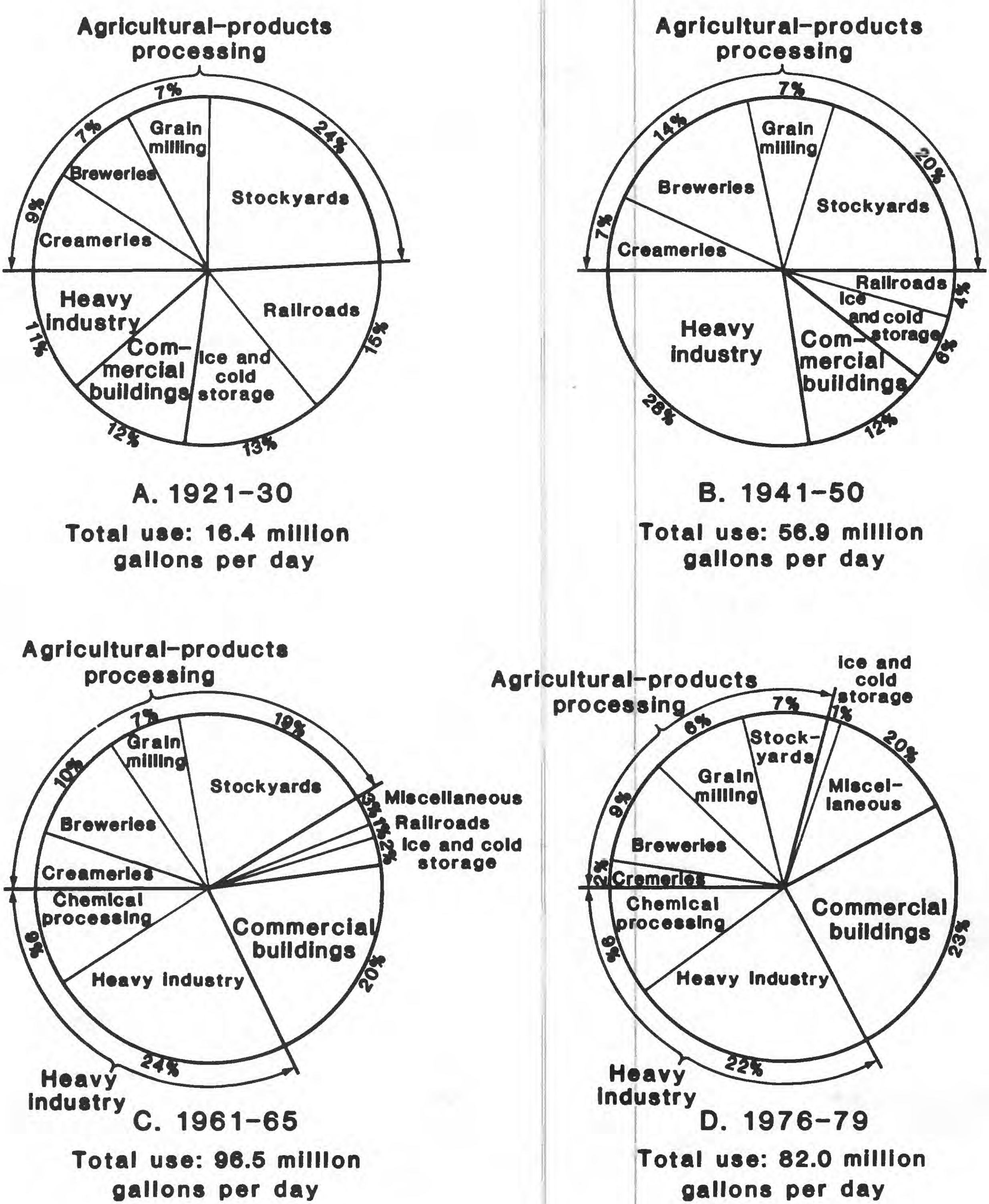


Figure 7.--Distribution of self-supplied industrial ground-water use

Table 3.—Trends in self-supplied industrial ground-water use

[Mgal/d, million gallons per day]

Category	1921-30	1941-50		1961-65		1976-79	
	Water use (Mgal/d)	Water use (Mgal/d)	Percent change from previous period	Water use (Mgal/d)	Percent change from previous period	Water use (Mgal/d)	Percent change from previous period
Commercial buildings	2.0	6.6	+230	19.6	+197	18.7	-5
Heavy industry	1.9	16.1	+747	22.5	+40	18.1	-20
Chemical processing	—	—	—	9.0	—	7.6	-16
Railroads	2.4	2.0	-17	0.9	-55	0.2	-78
Ice and cold storage	2.2	3.4	+55	1.7	-50	0.9	-47
Creameries	1.5	4.0	+167	4.5	+13	1.8	-60
Breweries	1.1	7.7	+600	10.2	+32	7.6	-25
Grain milling	1.0	4.1	+310	6.3	+54	5.1	-19
Stockyards	3.9	11.7	+200	13.9	+19	6.0	-57
Miscellaneous	0.4	1.3	+225	7.9	+508	16.0	+103
Total	16.4	56.9	+247	96.5	+70	82.0	-15

Percentages of self-supplied water used by other industries are also shown in figure 7b. Railroads were the only industry in which water use declined from the 1920's to the 1940's, which has been attributed to development of diesel locomotives. During the 1920's, 47 percent of water used by self-supplied industry in the Twin Cities area was for processing agricultural products (grain milling, breweries, stockyards, and creameries) while 11 percent was used by heavy industry (fig. 7a). By the 1940's, processing of agricultural products was still 48 percent of the totals, but heavy industry had increased to 28 percent (fig. 7b). However, during this period, most of the new industries continued to locate within the Minneapolis-St. Paul city limits.

From the 1940's to the early 1960's, self-supplied industrial ground-water use increased from 57 to 97 Mgal/d, a 70-percent increase (table 3). During this period, population increased 52 percent to 1,525,300 (table 2). The largest increase was in water used in commercial buildings (6.6 to 19.6 Mgal/d, table 3), due to construction of stores, office buildings, and hotels dependent on water-cooled air conditioning. In the early 1960's, ground water for air conditioning was pumped through the system once and then disposed into storm sewers. Because of air conditioning, commercial water use is highly seasonal, with greater water demands during the summer months.

In the early 1960's, water used in processing petroleum-based chemicals into ammonia, plastics, and industrial chemicals became significant (over 9 Mgal/d, table 3) and accounted for 9 percent of all industrial water use in the Twin Cities area (fig. 7c). Heavy industry increased to 22.5 Mgal/d and consisted of:

Paper processing (9.0 Mgal/d)
Manufacture of equipment and appliances (5.5 Mgal/d)
Armanents (4.1 Mgal/d)
Coking (0.5 Mgal/d)
Others (3.3 Mgal/d)

While the quantity of water used for agricultural-product processing increased, the quantity used relative to self-supplied industrial use declined to 41 percent. At the same time, the relative quantity of water used for heavy industry and chemical processing combined accounted for 33 percent (fig. 7c). The miscellaneous-use category shown in figure 7c consisted of water used for some light industry, small food processors, and water-contamination control.

During the 1960's, locations of most of the chemical processing companies, new heavy industries, and many of the new large commercial buildings moved outside the Minneapolis-St. Paul city limits. This trend was noted by the Metropolitan Council of the Twin Cities (1973). The development of new pumping centers in the suburbs caused pumpage to become less concentrated in the downtown area.

Self-supplied industrial ground-water use declined 15 percent to 82.0 Mgal/d from the early 1960's to the late 1970's (table 3). There was a decline in water use for all industrial categories except miscellaneous. Increased pumpage from barrier wells to confine water-contamination and increased ground-water pumpage at Twin Cities wastewater-treatment plants accounted for the increase in this category. Water use for processing of agricultural products decreased by 41 percent, or over 14 Mgal/d (table 3), primarily due to reduced activity at the stockyards. Water use by heavy industry also decreased 20 percent, or 4.4 Mgal/d (table 3), primarily as a result of conservation measures taken as the Metropolitan Waste Control Commission increased charges for sewage disposal. (Richard L. Berg, MWCC Comptroller, written commun., 1982). Many once-through cooling systems were replaced by three major techniques to conserve water. The first involved recirculating water through cooling towers so the water could be reused for cooling. Secondly, holding tanks were used to maintain constant pressure in the system by replacing water as it was used rather than having it pumped continuously. The third method was installation of variable speed drives on pumps to decrease the amount of water circulating through the system when demand was low.

During the late 1970's, ground water used for processing of agricultural products accounted for 24 percent of total use by industry (fig. 7d), which was less than heavy industry and chemical processing combined (31 percent) and about equal to commercial-building use (23 percent). Several industries began to supplement their ground-water withdrawals with municipal water supplies within the city limits. Old industries in the cities closed and new heavy industries opened outside the city limits, further dispersing the major pumping centers throughout the metropolitan area.

Four major trends in self-supplied industrial ground-water use have been discussed above. First, a rapid increase in ground-water use from the 1920's to the late 1960's occurred as population increased and new industries were established (table 3). Secondly, since the late 1960's, water use decreased because of conservation by large water users, increased reliance on public supplies, and closing of several industries. Thirdly, water used by self-supplied industry changed from use primarily for processing of agricultural products to use for heavy industry, chemical processing, and air conditioning for commercial buildings (fig. 7). Finally, pumping decreased within the city limits and increased in the five outlying counties resulting in decreased aquifer stress within the cities.

Irrigation

Little ground water was used for irrigation, except on golf courses, until the late 1960's when use was slightly over 4 Mgal/d (fig. 5), representing 1.5 percent of all ground-water use in the Twin Cities. Water used for irrigation increased by 75 percent during the early 1970's, but was still only 2.5 percent of the total. However, because of drought in the mid 1970's, ground-water use for irrigation increased 3.5 times in the late 1970's to 17.3 Mgal/d, about 9 percent of the total used in the Twin Cities area. Pumpage in Dakota County in 1980 accounted for about 84 percent of the ground water used in the Twin Cities area for irrigation.

Dewatering

Pumping of ground water to dewater quarries increased in the late 1960's to about 7 Mgal/d (fig. 5), representing just under 4 percent of total ground water used. In the early 1970's, withdrawals increased to 5.5 percent of total ground water used or 11 Mgal/d. During the late 1970's, dewatering decreased to 8.0 Mgal/d.

Lake-Level Maintenance

As early as 1904, 1 Mgal/d of ground water were used to maintain lake levels for recreation and maintenance of property values. This use accounted for 23 percent of all recorded ground water used in 1901-10. Withdrawals increased until 1940, when slightly more than 10 Mgal/d were used, representing 22 percent of the total (fig. 5). Since that time, withdrawals of ground water for maintenance of lake levels has decreased to 2.6 Mgal/d, or just over 1 percent of total ground-water use.

Summary of Withdrawals By Use Category

During the first decade of the century, self-supplied industry used 59 percent of all ground water withdrawn; public supply used 18 percent, and lake-level maintenance used 23 percent (table 4). Industry continued to be the primary user of ground water in the 1920's and 1930's as new plants were established in Minneapolis and St. Paul to process the State's agricultural produce. Ground water used for lake-level maintenance dropped to between 5 and 6 percent of all ground water used after the 1930's drought. Self-supplied industry within Minneapolis and St. Paul city limits expanded into paper, armament, and equipment manufacturing in the 1940's, using 82 percent of all ground water withdrawn. Rapid growth in the outlying areas began in the 1950's as new plants and new types of industries, including chemical processing, were established. Ground water used for public supply increased significantly in the 1950's because of population growth in the suburban areas and subsequent development of suburban municipal water works. Since the late 1960's, water conservation and closing of several industries have caused a decrease in self-supplied industrial water use to 42 percent of all ground water used in the late 1970's (table 4). Continued growth in the suburban areas has resulted in increased ground-water use for public supply, currently 44 percent. Irrigation use is now third, using 9 percent of all ground water withdrawn.

Table 4.—Percentage of ground-water withdrawal by use category

Time period	Public supply	Self-supplied industrial	Irrigation	Dewatering	Lake-level maintenance
1880-1900	37	63	0	0	0
1901-10	18	59	0	0	23
1911-20	15	75	0	0	10
1921-30	10	67	<1	0	22
1931-40	10	68	1	0	21
1941-50	13	82	<1	0	5
1951-60	20	73	1	0	6
1961-65	26	67	1	0	6
1966-70	29	63	1	4	3
1971-75	40	52	2	5	1
1976-79	44	42	9	4	1

TRENDS IN GROUND-WATER WITHDRAWALS BY AQUIFER

The five major aquifers in the Twin Cities area are composed of sandstone, dolomite, limestone, and glacial drift. Confining beds that consist of shale, siltstone, and sandstone separate the aquifers and retard vertical movement of water. The aquifers and confining beds are shown on figure 8, which is a hydrogeologic section of the Twin Cities area. The hydrogeologic characteristics of each aquifer and confining bed are described in detail by Norvitch and others (1973) and Guswa and others (1982).

The earliest industrial and public-supply wells in the Twin Cities area were generally completed in the uppermost bedrock aquifer (Winchell, 1905). In most of Ramsey, western Washington, and eastern Hennepin Counties (fig. 1), the uppermost bedrock aquifer is the St. Peter (fig. 9). In most of Dakota, eastern Washington, and parts of Hennepin and Ramsey Counties, the uppermost bedrock aquifer is the Prairie du Chien-Jordan. In the northwestern and western periphery of the seven-county area, the Ironton-Galesville is the uppermost bedrock aquifer.

Early in the century, the deeper aquifers were used to (1) meet the demand for larger quantities of water, (2) obtain water with lower dissolved-solids concentration, or (3) avoid the high concentration of sand particles in water pumped from the St. Peter. The demands for more water in the downtown Minneapolis-St. Paul areas were met primarily by wells completed in the Prairie du Chien-Jordan aquifer, particularly after 1910. Wells cased to the Mount Simon-Hinckley aquifer were first drilled in 1922 (Minneapolis Water Supply Commission, 1932) and yielded water with low dissolved-solids concentration. Many steam boilers, including those of railroad steam engines, used the soft water to prevent scale buildup. Mount Simon-Hinckley wells were also drilled for use by breweries, laundries, and hospitals.

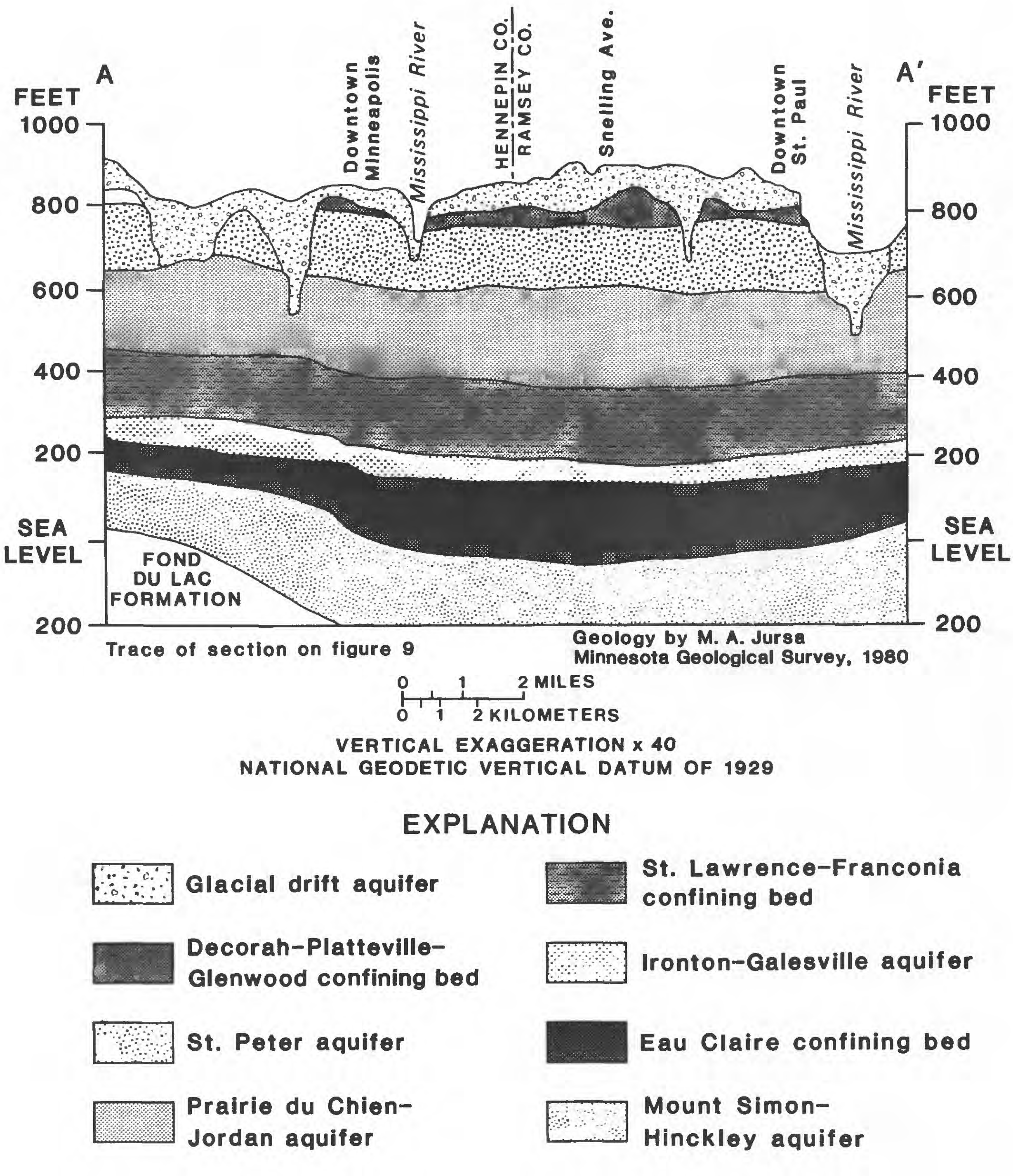
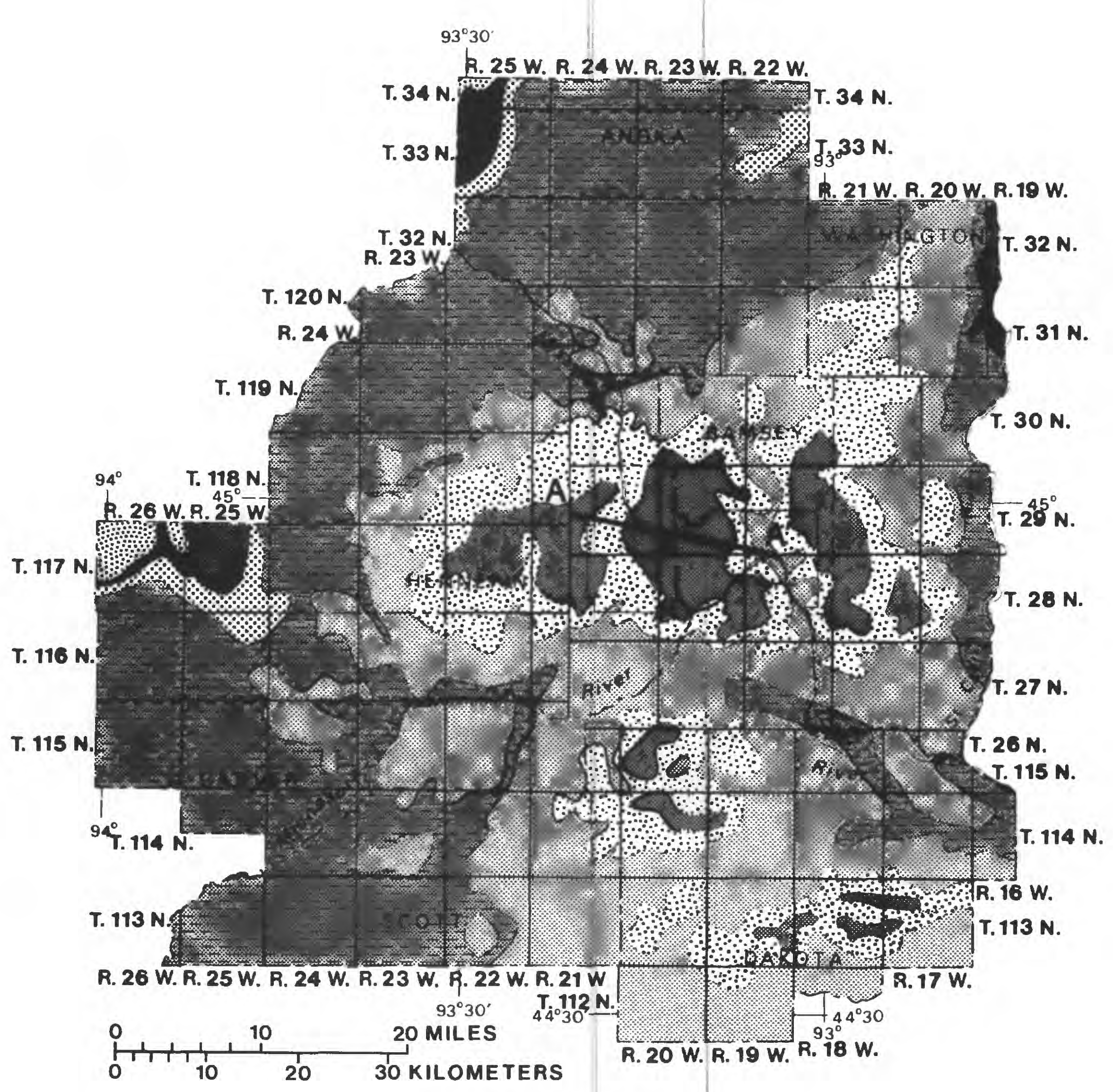


Figure 8.--Hydrogeologic section through Minneapolis and St. Paul



EXPLANATION

- Decorah–Platteville–Glenwood confining bed
- St. Peter aquifer
- Prairie du Chien–Jordan aquifer
- St. Lawrence–Franconia confining bed
- Ironton–Galesville aquifer
- Eau Claire confining bed
- Mount Simon–Hinckley aquifer
- A—A' Trace of section

Figure 9.--Bedrock hydrogeology in the Twin Cities area and location of hydrogeologic section A-A'

Many of the older high-capacity wells are open to more than one aquifer. Estimates of the amount of water contributed by each aquifer in multiaquifer wells have been compiled for use in current (1982) quantitative studies of ground-water flow in the Twin Cities area. The estimates are based on the thickness, hydraulic conductivity, and water level for each aquifer (table 5) and are stored in the water-use data base.

Table 5.—Estimated percentage of water contributed by each aquifer to multiaquifer wells

St. Peter	Prairie du Chien-Jordan	Ironton-Galesville	Mount Simon-Hinckley
35	65	—	—
30	65	5	—
25	60	5	10
—	95	5	—
—	70	5	25
—	—	15	85

Withdrawals of water from each aquifer are discussed separately in the following sections, beginning with the most heavily used aquifer, the Prairie du Chien-Jordan. Areal water-use patterns during significant time periods are depicted on a number of maps. The locations of counties and cities included in the description of the areal water-use patterns are shown in figure 1.

Prairie du Chien-Jordan

Withdrawals from the Prairie du Chien-Jordan aquifer have increased continuously since the beginning of the century (fig. 10). There were three periods when withdrawals from this aquifer increased significantly in comparison with withdrawals from other aquifers. The first increase was in the 1930's when use of the St. Peter aquifer began to decline. The second increase was in the 1950's when many new high-capacity wells were completed in the Prairie du Chien-Jordan. The third increase was in the late 1960's when withdrawals from the deeper Mount Simon-Hinckley aquifer declined. Presently (1982), about 80 percent of the ground water withdrawn in the Twin Cities area is from the Prairie du Chien-Jordan. Use trends for this aquifer have been studied by analyzing four time periods: (1) 1921-30, prior to the first major increase in use; (2) 1951-60, during the second major increase; (3) 1971-75, following the third and most recent major increase; and (4) 1976-79, the most recent time period.

In the 1920's, the primary pumping center (pumpage greater than 5.0 Mgal/d per township) for the Prairie du Chien-Jordan aquifer was near downtown Minneapolis. Secondary pumping centers (pumpage greater than 0.7 Mgal/d per township and less than 5.0 Mgal/d per township) were in northern Ramsey County (the lake-level maintenance wells), the Midway area, and the downtown St. Paul-South St. Paul area. These pumping centers are shown in figure 11a, where ground-water withdrawals by township are depicted. (See figure 1 for locations.)

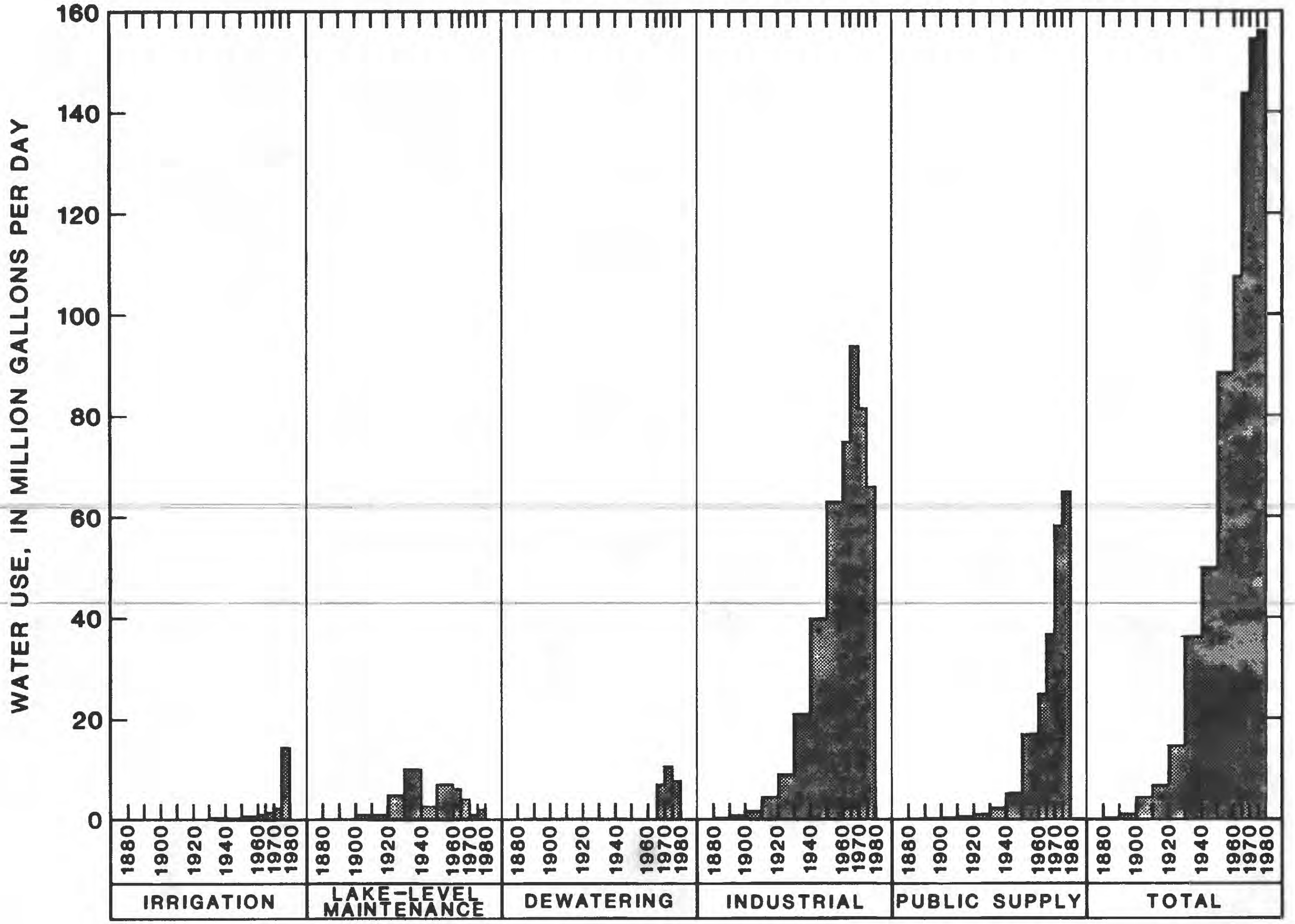
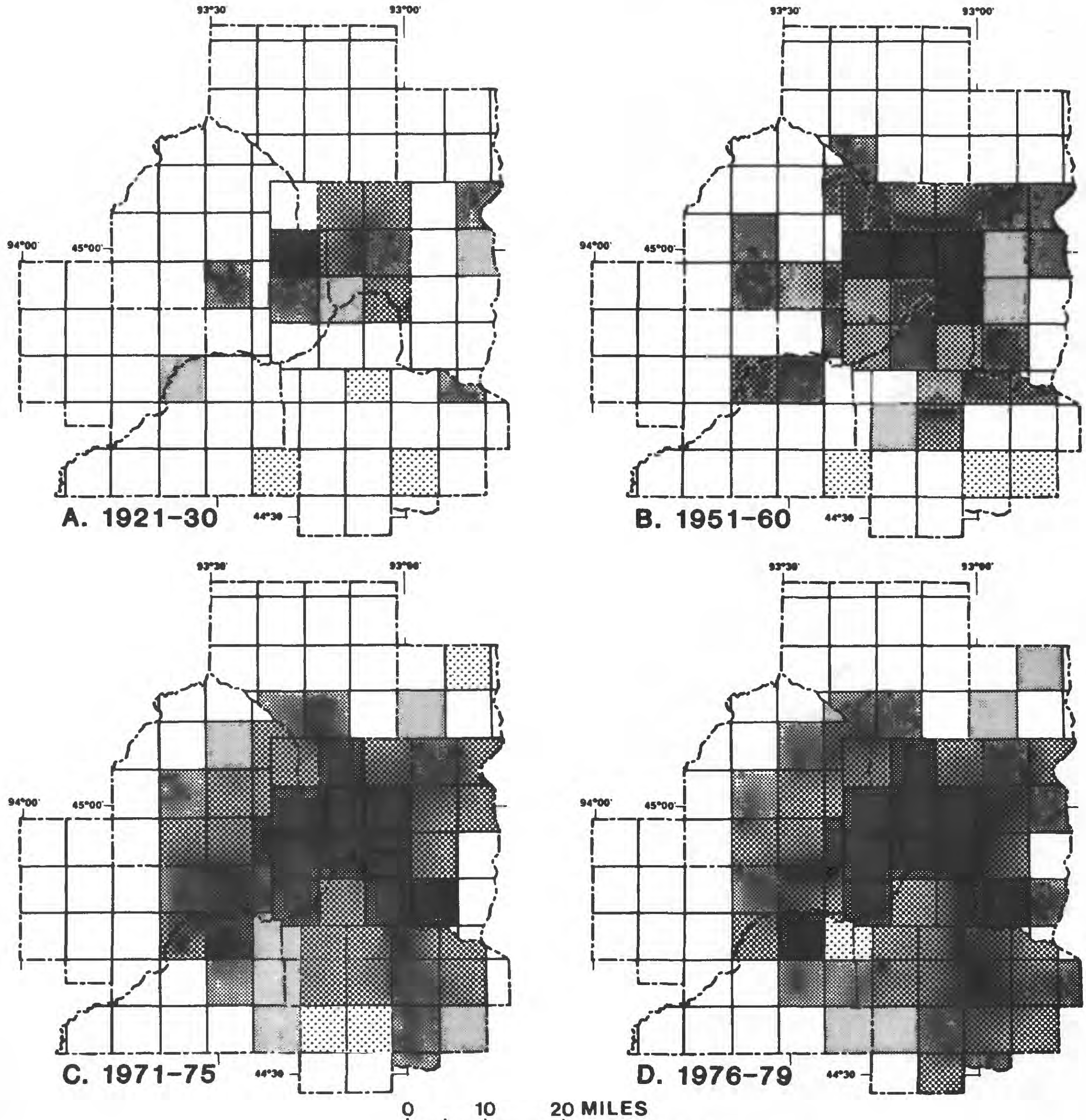


Figure 10.--Trends in withdrawals from the Prairie du Chien-Jordan aquifer by use category



Township locations are shown on figure 1

EXPLANATION

TOTAL WATER USE, IN MILLION GALLONS PER DAY PER TOWNSHIP

- Less than 0.002
- 0.002-0.02
- 0.02-0.1
- 0.1-0.7
- 0.7-5.0
- Greater than 5.0

Figure 11.-Withdrawals by township from the Prairie du Chien-Jordan aquifer

In the 1950's, the primary pumping center extended from downtown Minneapolis, through the Midway area to downtown St. Paul, including the downtown St. Paul-South St. Paul area (fig. 11b). Secondary pumping centers developed in suburban areas immediately surrounding the downtown areas. Many suburban municipalities established their own ground-water supplies but were not necessarily the primary users of ground water within each township. Self-supplied industries were the primary users in some suburbs and significantly affect total pumpage for some townships. During this period, the number of townships with total pumpage greater than 0.02 Mgal/d increased. Also, total pumpage from the Prairie du Chien-Jordan aquifer increased from 15 Mgal/d in the 1920's to 88 Mgal/d in the 1950's (table 6).

Table 6.—Trends in withdrawals from the Prairie du Chien-Jordan aquifer

[Mgal/d, million gallons per day]

Time period	Number of townships that had withdrawals: Greater than 5.0 Mgal/d	Number of townships that had withdrawals: Between 0.7 and 5.0 Mgal/d	Number of townships that had withdrawals: Greater than 0.02 Mgal/d	Total pumpage Mgal/d	Ratio of total pumpage to number of townships with pumpage greater than 0.02 Mgal/d
1921-30	1	4	13	15	1.2
1951-60	4	16	33	88	2.7
1971-75	12	21	49	156	3.2
1976-79	11	26	56	157	2.8

By the early 1970's, the primary pumping center had grown to include 12 townships, several in the suburban area adjacent to Minneapolis and St. Paul (fig. 11c). The number of secondary pumping centers increased to include 21 townships, and there were 49 townships in which total pumpage exceeded 0.02 Mgal/d (table 6 and fig. 11c). Total withdrawals from the Prairie du Chien-Jordan aquifer were 156 Mgal/d.

Withdrawals from the Prairie du Chien-Jordan aquifer during the late 1970's increased only slightly to 157 Mgal/d (table 6), and total pumpage was greater than 0.02 Mgal/d in 56 townships (table 6 and fig. 11d). The number of townships with secondary pumping increased to 26 (table 6), with most of the new centers in the Dakota County irrigation area (fig. 11d).

The intensity of pumpage decreased in the late 1970's as a result of pumpage increases in the suburbs surrounding Minneapolis and St. Paul. The average total pumpage per pumping township decreased from 3.2 Mgal/d per township in the early 1970's to 2.8 Mgal/d per township in the late 1970's (table 6).

Mount Simon-Hinckley

The Mount Simon-Hinckly aquifer is the second most used aquifer in the Twin Cities area, although it has never supplied more than 25 percent of the total ground water withdrawn. Presently (1982), 10 percent of all ground-water use is from the Mount Simon-Hinckley. Use trends for this aquifer have been analyzed for two time periods, the 1950's and the late 1970's. The total use during both periods was similar, 16.7 Mgal/d in the 1950's and 19.2 Mgal/d during the late 1970's (fig. 12). However, the types and patterns of use were distinctly different.

During the 1950's, industrial use from the Mount Simon-Hinckley peaked and constituted 87 percent of total withdrawals from the Mount Simon-Hinckley (fig. 12). Use was primarily concentrated within the city limits of Minneapolis and St. Paul (fig. 13a). Public-supply use was only 13 percent. Seventy percent of the Mount Simon-Hinckley wells were used by industry, especially industry that required soft water, such as laundries, breweries, and hospitals.

During the late 1970's, total use from the Mount Simon-Hinckley had declined from a peak of 22.8 Mgal/d during the late 1960's and early 1970's (fig. 12). Only 41 percent of the water from the Mount Simon-Hinckley was used by industry. Most new industrial wells were drilled in the Prairie du Chien-Jordan because pumping was less expensive than from the deeper aquifer. However, use for public supplies increased to 57 percent, primarily in the suburban areas where the Prairie du Chien-Jordan is missing. This change is shown in figure 13 in that pumpage was concentrated in the six townships that include downtown Minneapolis and St. Paul in the 1950's (fig. 13a), but was more evenly dispersed throughout the Twin Cities metropolitan area in the late 1970's (fig. 13b).

Ironton-Galesville

Trends in usage for the Ironton-Galesville aquifer parallel those of the Mount Simon-Hinckley aquifer, both in use categories (fig. 12) and areal distribution (fig. 13c). The primary reason for this is that most wells that tap the Ironton-Galesville also tap the Mount Simon-Hinckley. This was especially true of older industrial wells. Also, as with the Mount Simon-Hinckley aquifer, the Ironton-Galesville is used primarily in areas where the Prairie du Chien-Jordan is missing. Most recently drilled public-supply wells that utilize the Ironton-Galesville aquifer are single-aquifer wells because of the Minnesota Department of Health's prohibition on new multiaquifer wells. Because of the new single-aquifer Ironton-Galesville wells, withdrawals did not significantly decline during the late 1970's, as did withdrawals from the Mount Simon-Hinckley (fig. 12).

St. Peter

The St. Peter was the first bedrock aquifer used in the Twin Cities area, mainly in downtown Minneapolis and St. Paul. Early in the century, Minneapolis public wells were in the St. Peter aquifer, although its use was still less than 0.1 Mgal/d. After these wells became contaminated by bacteria and because St. Peter wells tend to pump sand, new high-capacity wells were drilled into deeper aquifers (Minneapolis Water Supply Commission, 1932). Withdrawals from the St. Peter peaked during the 1930's and have remained fairly steady since (fig. 12). The areal extent of the St. Peter is limited and urbanization has gone beyond where the St. Peter can be found. Current use of the St. Peter aquifer is primarily in the townships including downtown St. Paul and Minneapolis (fig. 14) from wells that are open to both the St. Peter and the Prairie du Chien-Jordan aquifers.

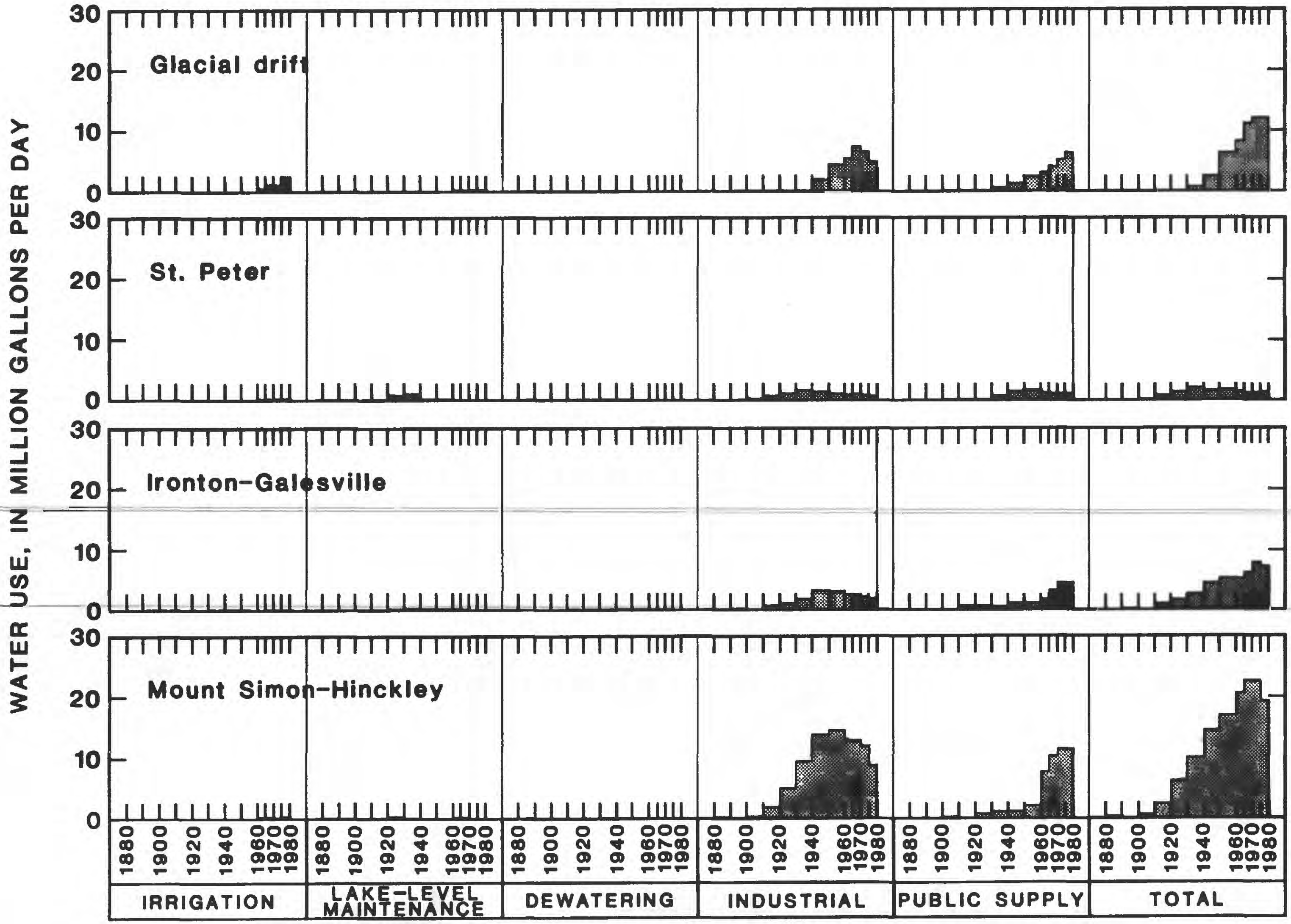


Figure 12--Trends in withdrawals from the Mount Simon-Hinckley, Ironton-Galesville, St. Peter, and glacial drift aquifers by use category

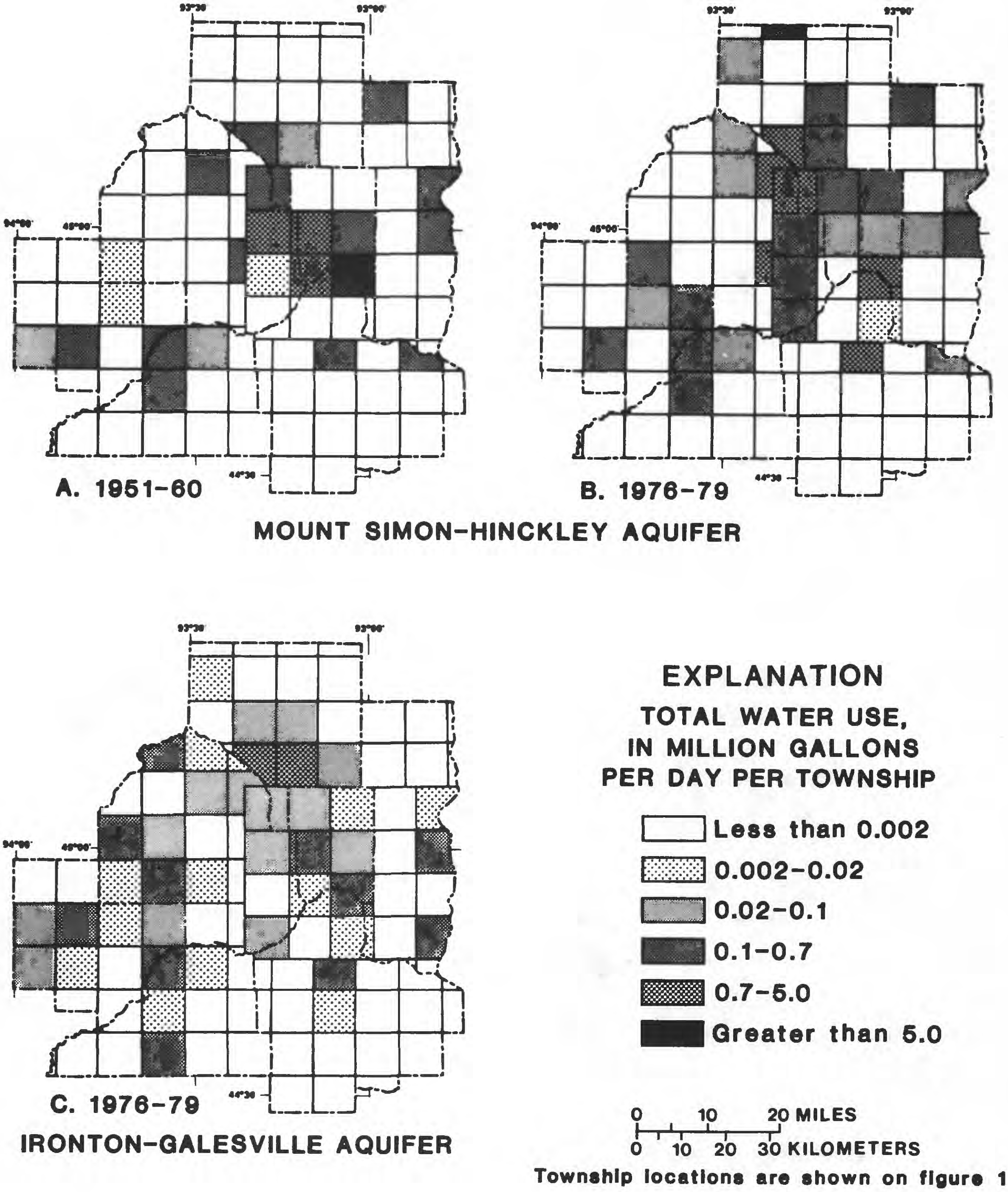


Figure 13.--Withdrawals by township from the Mount Simon-Hinckley and Ironton-Galesville aquifers

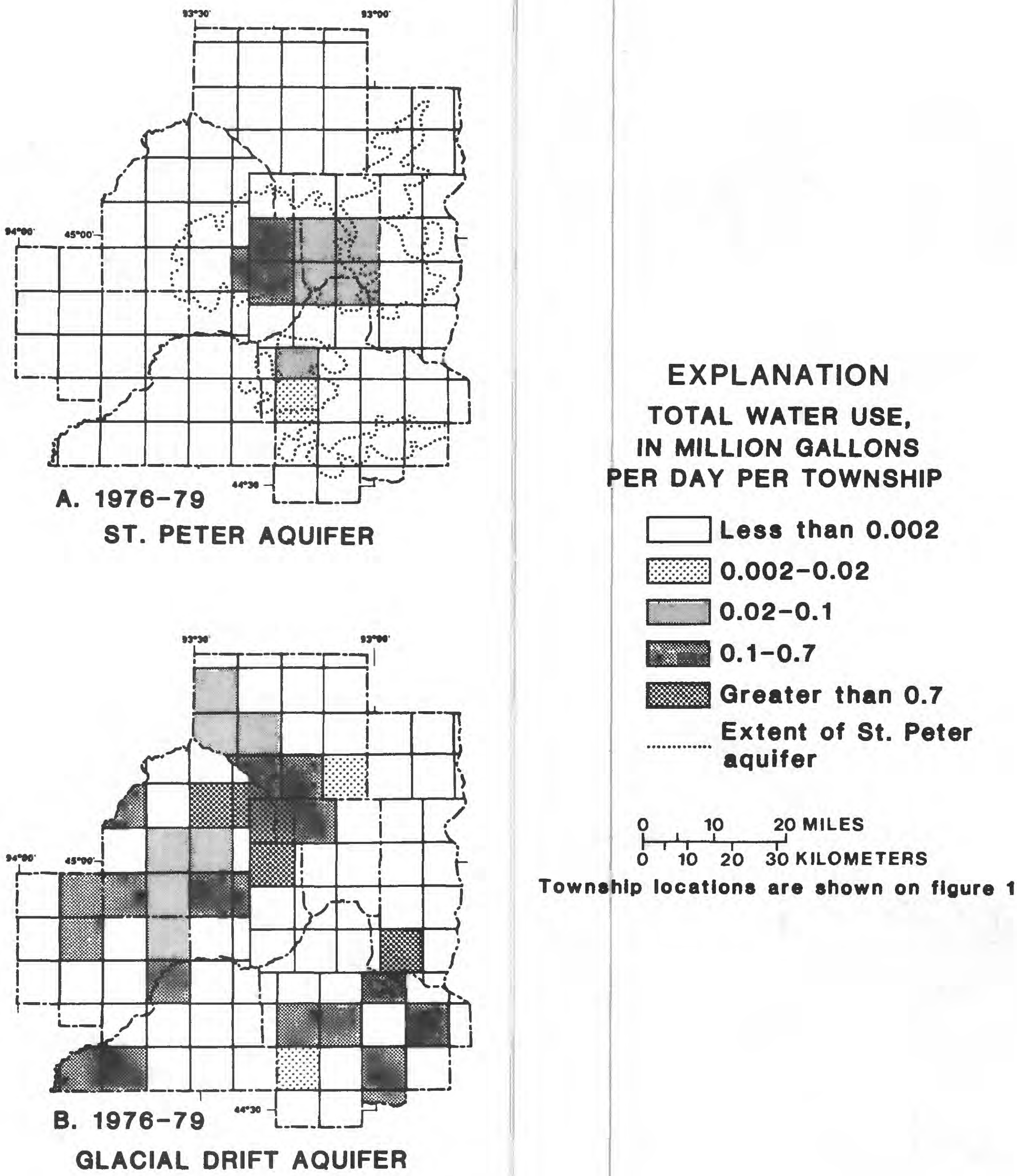


Figure 14.--Withdrawals by township from the St. Peter and glacial drift aquifers

Glacial Drift

Glacial drift was used as a source of water supply by the first settlements in the Twin Cities area. High-capacity wells were later developed in the drift beginning with the 1920's and use was 0.4 Mgal/d by the 1930's (fig. 12). Withdrawals from the drift aquifer increased continuously to the present. During the 1940's, 31 percent of the total withdrawal of 2.7 Mgal/d from the drift aquifer was for public supplies and 69 percent was for industrial use. Currently, 54 percent of the total withdrawals of 12.6 Mgal/d (fig. 12) is for public supplies and 46 percent is for industrial use.

Use of the drift aquifer is restricted to areas with substantial sand and gravel deposits. Most of the pumping is in areas where the drift is greater than 200 feet thick. The drift aquifer is especially important where the Prairie du Chien-Jordan aquifer is missing (fig. 9).

Summary of Withdrawals by Aquifer

The Prairie du Chien-Jordan is the major aquifer used in the Twin Cities metropolitan area. During the late 1970's, dependence on this aquifer increased to 80 percent of total ground water withdrawn (table 7). Earliest withdrawals were concentrated in the Minneapolis and St. Paul city limits. This was followed by expansion of pumping centers in the Minneapolis-St. Paul area suburbs. Most recently, withdrawals from the Prairie du Chien-Jordan have declined within the Minneapolis and St. Paul city limits, but continued to increase in the outlying suburban areas. The Mount Simon-Hinckley is the second-most-used aquifer, currently yielding about 10 percent of total withdrawals. The Mount Simon-Hinckley is used primarily in areas where the Prairie du Chien-Jordan is missing. As a result of the decrease in withdrawals in the Minneapolis and St. Paul downtown areas, water levels in the Mount Simon-Hinckley and Prairie du Chien-Jordan aquifers have recovered somewhat in these areas (Reeder, 1966; Norvitch and others, 1973; Schoenberg, 1983). Withdrawals from the Mount Simon-Hinckley declined by 3.5 Mgal/d from the early to the late 1970's, while withdrawals from the Prairie du Chien-Jordan increased slightly. The remaining aquifers, in order of significance, are the glacial drift, Ironton-Galesville, and St. Peter. The history of withdrawals from all aquifers is depicted in figure 15.

TRENDS IN SEASONAL WATER USE

The amount of water used in the Twin Cities area varies significantly throughout the year. To illustrate this, monthly pumpage data reported to the Department of Natural Resources were analyzed in detail for two years, (1976 and 1978). These two years were chosen because one was a drought year (1976) and one was a year with normal precipitation (1978). Two separate pumping seasons were identified: a summer season of May through September and a winter season of October through April (fig. 16).

In order to express this summer-winter variation quantitatively, a seasonal component of water use was defined as the difference between average summer and average winter use divided by the sum of average summer and average winter use. A lower number indicates less variation in pumpage between the summer and winter seasons. For example, in 1978 the average summer pumpage was 155 Mgal/m and the average winter pumpage was 88 Mgal/m, resulting in a seasonal component of (155-88)/(155 + 88) = 0.28.

Table 7.—Withdrawals by aquifer

[Mgal/d, million gallons per day]

Time period	Glacial drift		St. Peter		Prairie du Chien-Jordan		Ironton-Galesville		Mount Simon-Hinckley		Total	
	(Mgal/d)	(Percent of total)	(Mgal/d)	(Percent of total)	(Mgal/d)	(Percent of total)	(Mgal/d)	(Percent of total)	(Mgal/d)	(Percent of total)	(Mgal/d)	(Percent of total)
1880-1900	<0.1	—	0.1	1	0.6	90	<0.1	2	0.1	7	0.7	100
1901-10	<.1	—	.1	3	4.2	89	.1	2	.3	6	4.8	100
1911-20	<.1	—	.5	4	7.6	67	.7	6	2.6	23	11.4	100
1921-30	<.1	—	1.3	5	15.6	64	1.4	6	6.1	25	24.4	100
1931-40	.4	—	2.1	4	36.2	71	2.5	5	10.1	20	51.3	100
1941-50	2.7	4	1.7	2	49.6	70	3.5	5	13.9	19	71.4	100
1951-60	6.2	5	1.7	2	88.1	75	4.4	4	16.7	14	117.1	100
1961-65	8.1	6	1.4	1	107.9	76	4.4	3	20.8	15	142.6	100
1966-70	11.4	6	1.5	1	144.5	78	5.4	3	22.8	12	185.6	100
1971-75	12.5	6	1.4	1	155.3	78	7.0	4	22.7	11	198.9	100
1976-79	12.6	6	1.3	1	156.8	80	6.7	3	19.2	10	196.6	100

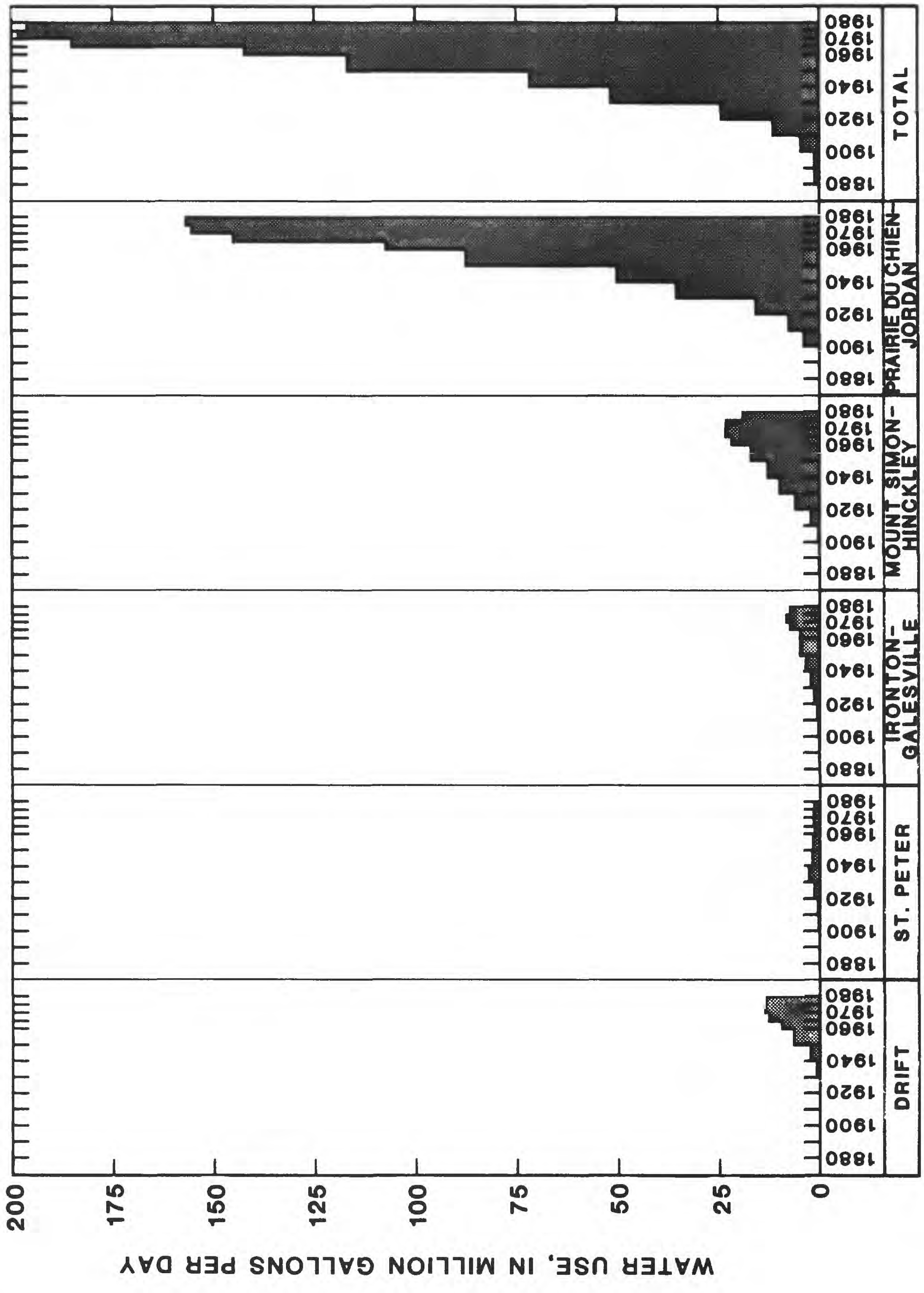


Figure 15.--Trends in total withdrawals from aquifers

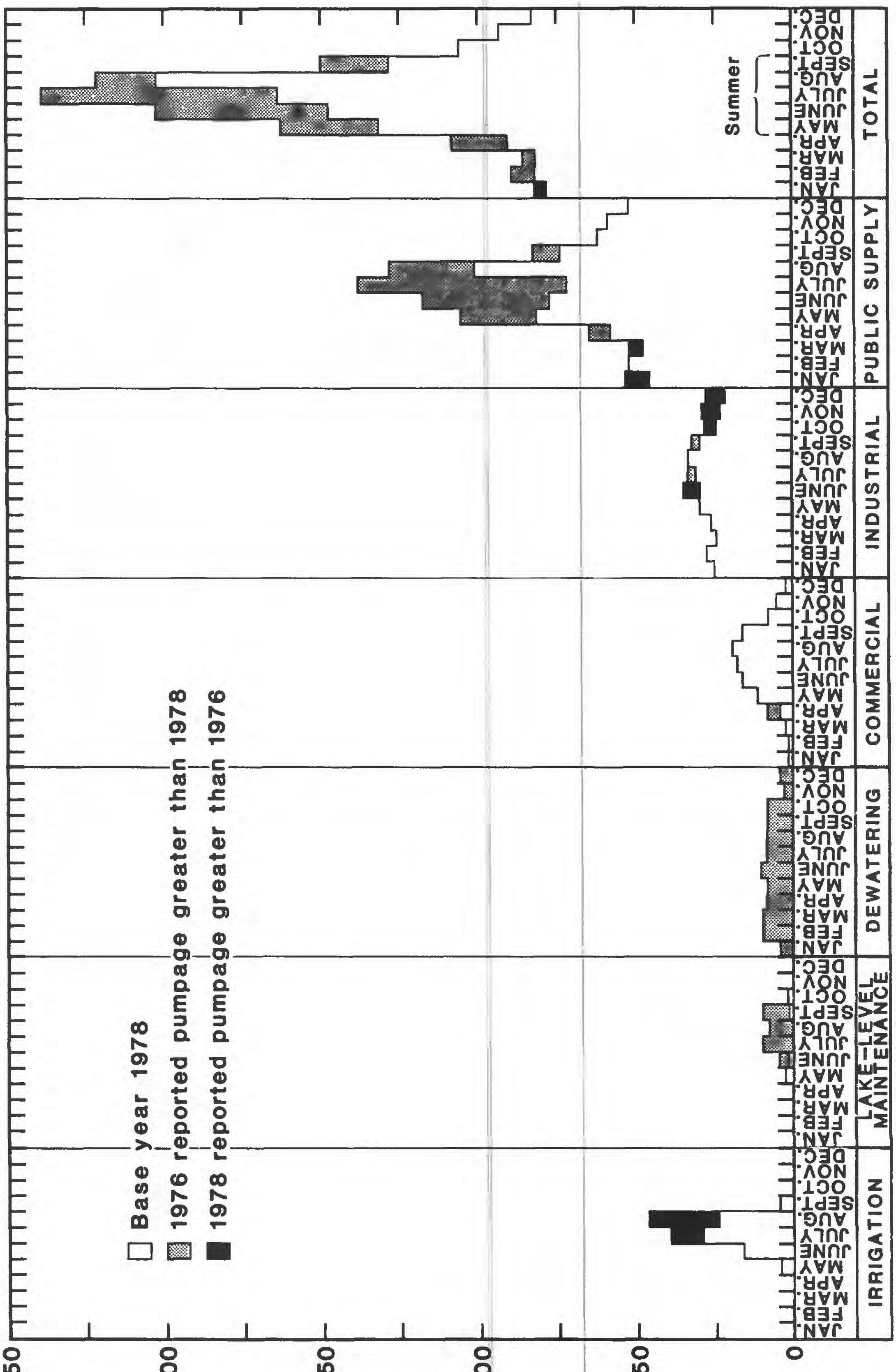


Figure 16.--Seasonal variation in ground-water withdrawals by use category

Seasonal data were further analyzed by use categories, each of which shows a distinctive pattern of seasonal use. Calculated seasonal components for the major-use categories for 1978 and 1976 are shown in table 8. Although the seasonal components for irrigation (1.00) and air conditioning (0.53) are high, they do not vary significantly during a drought year. The greatest increase in seasonal component was for municipal water use, which increased from 0.19 in 1978 to 0.35 in 1976. The seasonal component for all use increased from 0.28 in 1978 to 0.36 in 1976, indicating a greater demand for ground water during summer 1976 than during summer 1978. Seasonal components of water use are useful for comparison of characteristics of different use categories and for distinguishing long-term trends.

Table 8.—Seasonal variation in water use by use category

Use category	1978		1976	
	Seasonal component	Percentage of users represented	Seasonal component	Percentage of users represented
Public Supply	0.19	60	0.35	62
Industrial	.07	47	.14	50
Air conditioning.....	.53	47	.55	50
Irrigation	1.00	85	1.00	46
All users	.28	63	.36	55

The large volume of water used by municipalities has a significant effect on seasonal variations. Large municipalities will generally maintain uniform pumping rates with many wells year round, and use standby wells during summer for extra water. Although the seasonal component is only about 0.19, summer pumpage for public supply increases over winter pumpage (fig. 16) in the Twin Cities area by 15 to 50 Mgal during each of the summer months.

Self-supplied industrial use (minus air conditioning) has the smallest seasonal variation of all use categories. During 1971-79, a decrease of industrial ground-water withdrawals was accompanied by an increase in public supply and irrigation withdrawals. This caused an increase in seasonal pumpage because of the low seasonal component for industrial use and the high seasonal component for public supply and irrigation use. This trend is supported by unpublished data from the 1930's that indicate a seasonal component for all ground-water use of 0.16 in that time period. If the current trend of increasing public supply and irrigation use continues, the overall seasonal variation will also probably increase.

Seasonal variations are more pronounced in some aquifers. Summer-only use of municipal wells and decreased withdrawals for industrial use have caused strong seasonal variations in the Mount Simon-Hinckley. However, in the Prairie du Chien-Jordan aquifer, many public-supply and non-air-conditioning industrial wells are used uniformly throughout the year and mask the effects of large air-conditioning and irrigation withdrawals. As a result, seasonal water-level variations in the Prairie du Chien-Jordan are less pronounced than in the Mount Simon-Hinckley (Schoenberg, 1983).

SUMMARY AND CONCLUSIONS

Several major trends were observed in ground-water use in the Twin Cities between 1880 and 1979. Three distinct periods can be defined by combining several trends in use category, aquifer withdrawals, and seasonal variation.

At the beginning of this century, self-supplied industry was the primary user of ground water. This trend continued in the 1920's and 1930's as new plants were established in the cities of Minneapolis and St. Paul to process the State's agricultural produce. New industries developed in the 1940's, including paper, armament, and equipment manufacturing. Self-supplied industry then used 82 percent of all ground water withdrawn. Withdrawals from all aquifers were concentrated within the Minneapolis and St. Paul city limits. The Prairie du Chien-Jordan was the principal aquifer used, but the Mount Simon-Hinckley contributed from 19 to 25 percent of all ground water withdrawn during this time.

During the 1950's and 1960's, ground-water use continued to increase in the cities of Minneapolis and St. Paul, but ground-water use also began to expand rapidly in the surrounding suburban areas. Rapid growth in outlying suburban areas began in the 1950's as new plants and new types of industries, such as chemical processing, were established. Public-supply demand for ground water increased significantly because of population growth in the suburban areas and subsequent development of suburban municipal water works that used ground water for supply. Use of the Prairie du Chien-Jordan aquifer became more predominant in the 1960's. However, many new Mount Simon-Hinckley wells also were drilled in suburban areas for public supply, especially in areas where the Prairie du Chien-Jordan is missing. Dispersion of ground-water demands into the suburbs prevented pumpage in the downtown areas from increasing. Use of ground water for air conditioning increased throughout the Twin Cities metropolitan area.

The 1970's produced a decline in withdrawals from the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers within the Minneapolis and St. Paul city limits. Much of this decline was in self-supplied industrial water use because of water conservation and the closing of older industries. Continued growth in suburban areas resulted in an increase in ground-water use for public supply to 44 percent of total ground-water withdrawals for 1976-79. Irrigation became the third highest use of ground water and accounted for 9 percent of all ground-water withdrawals for 1976-79. The Prairie du Chien-Jordan remained the major aquifer used in the Twin Cities metropolitan area and dependence on it increased to 80 percent of all ground-water used. Withdrawals from the Mount Simon-Hinckley were approximately 10 percent of the total withdrawn. Withdrawals from the Prairie du Chien-Jordan increased only slightly while withdrawals from the Mount Simon-Hinckely declined by 3.5 Mgal/d during the late 1970's. Seasonal variation in water use was greatest for irrigation, air conditioning, and public supply. There is little seasonal variation in industrial use. Because withdrawals for irrigation, air conditioning, and public supply are increasing while industrial use is decreasing, seasonal variations in water use have become more pronounced. This trend will probably continue, and greater differences between summer and winter withdrawals are likely.

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