206

# WATER RESOURCES OUTLOOK FOR THE MINNEAPOLIS – SAINT PAUL METROPOLITAN AREA, MINNESOTA

by

R. F. Norvitch, T. G. Ross, and Alex Brietkrietz

United States Geological Survey

OFR 73-203

Prepared by the United States Geological Survey
in cooperation with the
Metropolitan Council of the Twin Cities Area

Approved by Director of USGS

Published by
Metropolitan Council of the Twin Cities Area

## ERRORS IN PRINTING

1. Township and range designations are left off Figures 3, 8-21, 41-45, 47, 48, and 56. These designations can be derived from Figures 23 and 54.
2. Headings "Present water use" and "Water available for development" in the text (p. 134 and 148, respectively) and in the table of contents (p. ii) should be of number 2 rather than number 3 rank. Subsequent headings under each of these should move up one rank, accordingly.
3. P. 20 - Figure 7 caption should read..."(Location of sections shown on Figure 45.)".
4. P. 87 - Figure 36, line patterns for the Minnesota and St. Croix Rivers are transposed.
5. P. 100 - Figure 44 caption should read..."(Location of sections shown on Figure 45.)".
6. P. 105 - Figure 44, also on p. 109, Section A-A' should be C-C'; B-B' should be D-D'; and so forth, to F-F' should be H-H'.
7. P. 107 - Figure 45, extent of subcrop area of Hinckley Sandstone and parts of all other bedrock formations are missing, inasmuch as the white part of the total study area as shown in Figure 1 has been cropped from all maps in this report. Open-file maps of all figures listed in item 1, above, can be seen in their entirety at the office of the Water Resources Division of the U.S. Geological Survey, Rm. 1033 Post Office Building, St. Paul, Minnesota 55101.
8. P. 111 - Second paragraph, 13th line; 140,000 should be 14,000.
9. P. 164 - First paragraph, 9th line; 616,000 should be 20,000.
10. P. 168 - Third paragraph, last sentence should read "(See discussion of timeliness of withdrawals on p. 111.)".

## TABLE OF CONTENTS

## TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

## TABLE OF CONTENTS (CONT.)

## LIST OF TABLES

## LIST OF TABLES (CONT.)

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS Continued

## LIST OF ILLUSTRATIONS Continued

## LIST OF ILLUSTRATIONS Continued

## ABSTRACT

The water resources were studied within an area whose natural ground-water flow is largely towards the center of the metropolitan area. This area coincides with the extent of the Hinckley Sandstone aquifer. Thus, the general geohydrology of the area bounded by the extent of the Hinckley Sandstone (about 6,000 square miles) as it relates to the hydrology of the Minneapolis-St. Paul metropolitan area is described. Greater emphasis is placed on the area underlain by the Prairie du Chien-Jordan aquifer (about 2,000 square miles), from which approximately 75 percent of the ground-water for the metropolitan area is pumped.

The study indicates that the surface-water resources of the Twin Cities metropolitan area are used to such an extent that a supply adequate for domestic and industrial needs as well as power plant and sanitary effluent assimilation will not be available during severe drought.

Ground-water is obtained primarily from two aquifer systems: The Prairie du Chien-Jordan and the Mount Simon-Hinckley. In 1970, these aquifers supplied about 90 percent (175 mgd) of the ground-water used in the metropolitan part of the study area. The probable level of development that can be sustained by these two aquifers in the metropolitan area is estimated to be 1,100 mgd; thus, substantial additional ground-water supplies could be developed. However, considerable management and planning would be needed to sustain this level of development.

Maps in this report can be used to select general well-field locations based on consideration of 1) aquifer, 2) depth needed for completion, 3) head availability, 4) location of natural recharge and discharge boundaries, and 5) distance from areas where over-development of ground-water resources is imminent. Because of complexities in the ground-water system, yield estimates, boundary effects, and effects of aquifer interaction may best be determined in a study incorporating the use of a hydrologic model.

Future detailed studies might include elaboration on some of the topics described in this report and the acquisition and interpretation of new data. Major items on which future work might focus are 1) data collection, 2) geohydrologic mapping, 3) hydraulic characteristics of subsurface geohydrologic units, 4) hydrology of lakes, and 5) hydrologic systems modeling.

# CHAPTER ONE: INTRODUCTION

Water use in the Twin Cities metropolitan area is steadily increasing, and the annual withdrawal of water through wells now exceeds the annual withdrawal of Mississippi River water used for public supply. Although there is presently no general plan for monitoring changes in the status of the total water resource nor for its optimum development, only through a thorough understanding of the hydrologic system can management plan for the best development and use of the area's water resources.

## PURPOSE AND SCOPE

The primary purposes of this report are to: 1) describe the physical occurrence and operation of the hydrologic system affecting the metropolitan area; 2) establish a hydrologic base upon which future comparisons can be made to evaluate changes; 3) identify areas where further study would better describe the hydrologic system; and 4) estimate the maximum water withdrawal the system can withstand before mining of ground water occurs.

The scope of this study is necessarily general because of the size of the area and the nature of the data collected. Studies of detailed scope will require new and controlled data collected within areas having definite boundaries.

## LOCATION AND EXTENT OF AREA

The Twin Cities (Minneapolis-St. Paul) metropolitan area, 2,968 square miles, includes 7 counties in east-central Minnesota. The major area of this study encompasses about 5,200 square miles in Minnesota and 1,000 square miles in Wisconsin (Figure 1). Political subdivision boundaries do not coincide with hydrologic boundaries, so the water resources were studied not only within the seven-county metropolitan area but also within an area whose natural ground-water flow is largely toward the center of the metropolitan area, the Twin Cities. About 11 percent of the seven-county area was excluded from the major area of this study because most of the ground-water flow in that part is away from the center, but the geohydrology of this excluded part is briefly discussed at the end of the report. (See Figure 1.) Thus, the boundary of the major study area, hereinafter also called the Minneapolis-St. Paul area, is based largely on the approximate areal extent of the Hinckley Sandstone, as it relates to the hydrology of the Twin Cities artesian basin. The northeastern, northern, and northwestern borders are the approximate geologic extent of the sandstone. The southern border, largely through Carver, Scott, and Dakota Counties, is based on an inferred potentiometric (pressure surface) high for water in the Hinckley Sandstone, even though the sandstone continues southward. In Wisconsin, the border is also based on an inferred potentiometric high. Because water from the Hinckley Sandstone probably discharges into the St. Croix River throughout most of the river's reach within the study area, the river constitutes a ground-water discharge boundary. Thus, for practical purposes, except for a sizeable ground-water contribution to flow in the St. Croix River, the area in Wisconsin might have been excluded from this study.

## NEED FOR STUDY

Since the beginning of the public water-supply systems in the Twin Cities, the sources and quantities of water available for future use have been in question. As early as 1910, Mille Lacs Lake (about 80 miles northwest of Twin Cities, outside of study area) was considered as a source of water for Minneapolis (Bass, Meyer, and Norling, 1932, p. 3) but was rejected as being insufficient. Another early source considered, and still favored by some as an ultimate supply, was Lake Superior (about 130 miles northeast of Twin Cities, outside of study area). Artesian wells offered an alternative to the continued use of the Mississippi River as a source of supply. The area grew and prospered, with the public water supplies of the Twin Cities remaining almost wholly dependent on the Mississippi River and most industrial, suburban municipal (excluding those connected to the Twin Cities systems), and suburban individual home sites dependent wholly on water from wells. The large in-

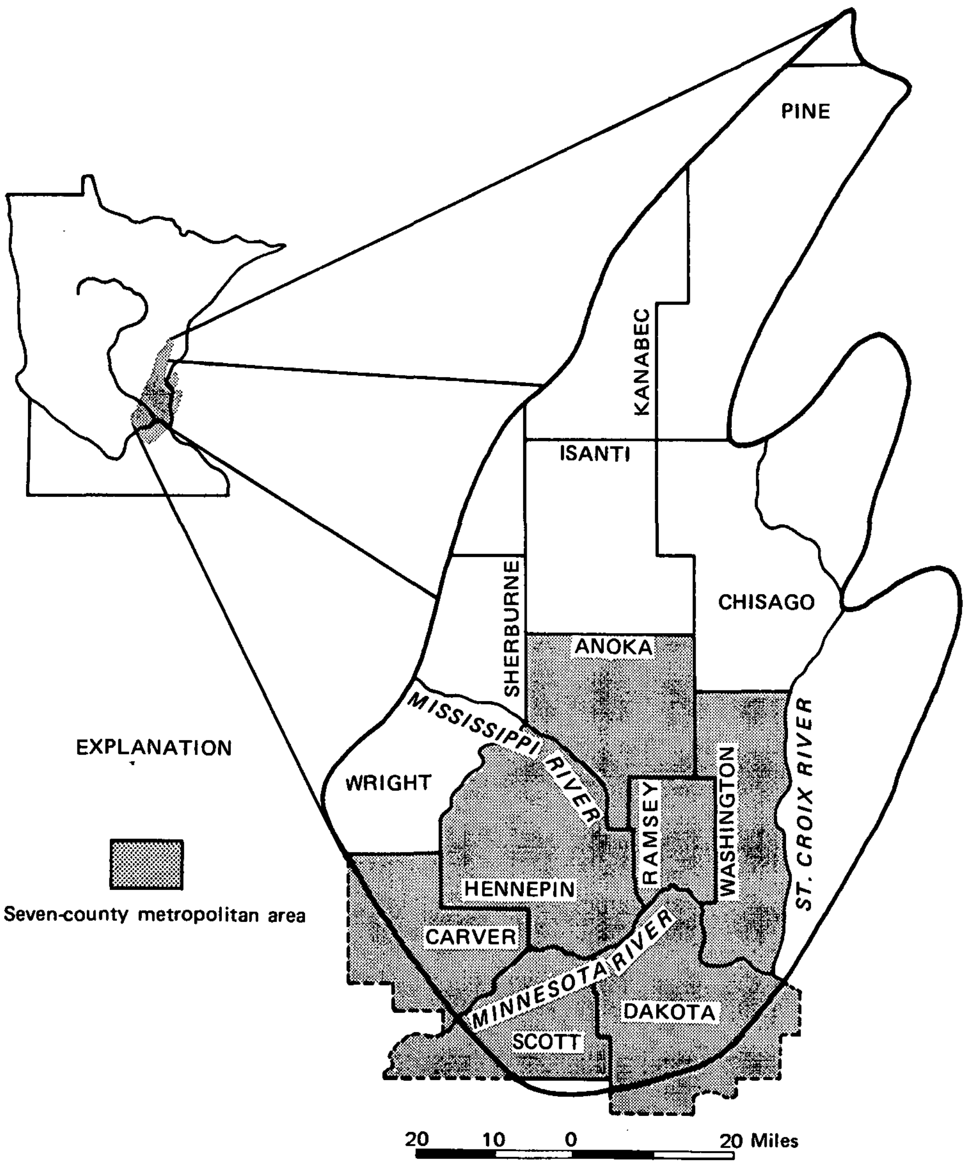



**Figure 1.— Map showing total area of study described by this report.**

crease in water use (excluding thermoelectric and hydroelectric power uses) in the metropolitan area from 1900 to 1970 is shown in Figure 2. It was not known what effect this increased use would have on the overall water resources in the area and if it would be necessary to go far afield to develop a larger water supply.

The increase in water use has locally created some immediate problems and some grave concern for the future. Before this study the magnitude of these problems was largely surmised. In 1961, the Minnesota Division of Waters predicted that an ultimate supply of ground water of about 250 mgd could be developed without serious lowering of artesian pressure in the aquifers. Present (1970) total ground-water withdrawal is about 194 mgd. The past predictions of water availability may or may not have been accurate. An up-to-date evaluation was needed.

One major concern is the effect of ground-water withdrawals on lake levels. Many believe that the lowering of the water table caused by pumping is responsible for leakage through lake bottoms. The metropolitan area is conscious of the esthetic value of its lakes. Thus, large volumes of water diverted from streams or pumped from wells are fed into some lakes to maintain levels.

Another major concern is the apparent decline in water levels in the major aquifers. In some places, the declines are real and may pose serious problems. The impact of these declines on the overall ground-water resources in the metropolitan area is not known. Nor is it known how much of the resource has been depleted or how much remains. There may not be enough observation wells in representative places within the aquifers to monitor important changes in the ground-water system effectively.

Surface-water use for public supplies has increased 37 percent in the last decade to an average of about 133 mgd, while the peak daily use (1970) has approached 300 mgd. Minimum flow requirements in the Mississippi River for sanitary effluent assimilation at the time of peak demand is estimated at 2,300 – 2,500 mgd (Water Resources Coordinating Committee, 1970). If a drought similar to that of the 1930's occurs, river flows may be insufficient to meet the demands for public supplies, sanitary effluent assimilation, power plant operations, and navigation. Some curtailment in the functioning of these facilities may be imminent.

In short, the status of the present water-resources system, how it operates, and how much it can be expected to supply in the future is not fully understood. This understanding can only be obtained through detailed hydrologic studies. Although somewhat generalized, this study offers answers, or at least a means to arrive at first approximations for answers, to many questions that have arisen concerning the water resources of the metropolitan area.

No matter how proficient the investigation nor how large the expenditure in time and money, the hydrologic system defies totally accurate long-term prediction of its responses to stress; only approximations can be made because of the extreme complexity and size of the natural system and the difficulty of predicting probable future stresses. A base for future comparison is thus necessary so that planning for the future can be facilitated. Potentiometric-surface maps of water of the major artesian aquifers are included in Bulletin No. 11 (Minnesota Division of Waters, 1961) and in Reeder (1966). Although these maps afford some generalized comparison of historical water-level changes, they are not directly comparable because different observation wells were used to draw the different maps, the areas mapped were not entirely coincident, and the scale of the base maps on which the potentiometric surfaces were plotted were not the same. Thus, it was necessary to select and catalog a large number of wells whose water levels were and are representative of those in the different aquifers and which could be measured repeatedly in the future, so as to establish a dependable base for future comparisons. Also, it was necessary to use a stable and suitable map scale so that all future comparisons could be made directly. The Minnesota Geological Survey has adopted the scale of 1:250,000 for their geologic maps. The U.S. Geological Survey also is mapping hydrology at this same scale in this area. Because the study of geology and hydrology of any area are inseparable, the benefits that can be derived from the mapping practice adopted by these two agencies are great.

Thus, the new water-level data generated in this study are largely repeatable and are plotted on maps that will enable ease of comparison as future changes occur.

## PREVIOUS WORK

Both the Minneapolis and St. Paul public water-supply systems were begun in the later part of the 19th century. Since their beginnings much work has been done toward an evaluation of the water resources available to the city supplies. (See Appendix A.) Because hydrology and hydrogeology then were relatively new sciences, most of the earlier work was done by engineers and geologists little trained in the quantitative aspects of the hydrosciences. Not until the 1930's did the mathematics of ground-water flow begin to flourish in this country. The early mathematics were focused on flow around individual wells and well fields. Later mathematics focused on regional flow. The present state of the science has advanced to where ground-water flow can be evaluated quantitatively, provided that all tools available for study are used. These tools are related to the advance of computer technology. Concomitant with the growth of ground-water hydrology was the growth of the statistics of surface-water hydrology. Combining the advances made in these two disciplines, together with those made in the field of climatology, enables a rather complete evaluation of the water resources in any region accessible to data collection. An annotated chronological list of reports related to water resources in the general area of this study is included in Appendix A.

**Figure 2. — Population growth and average daily water pumpage in the metropolitan area.**

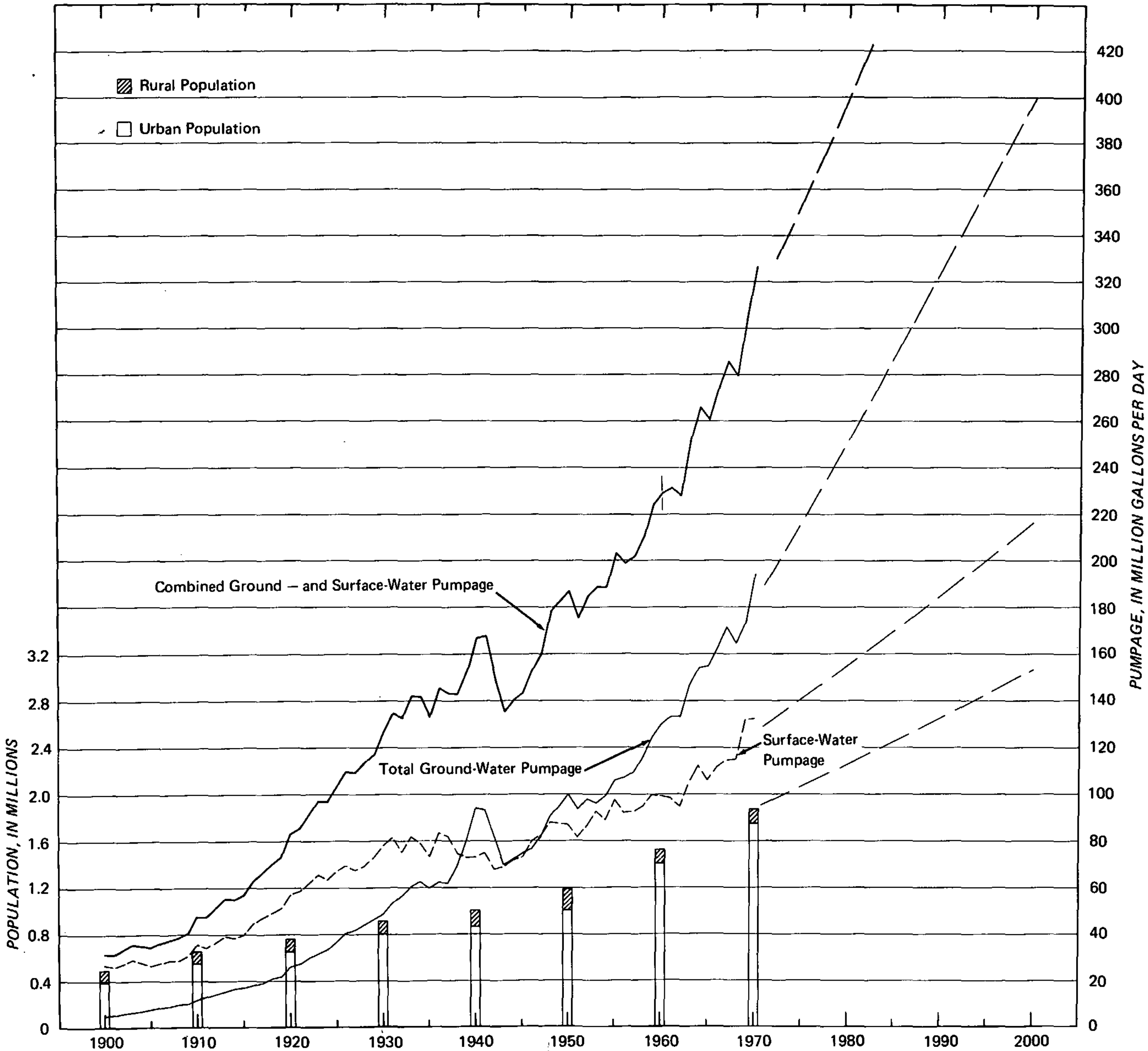



**Figure 2. — Population growth and average daily water pumpage in the Metropolitan Area.**

# CHAPTER TWO: GEOGRAPHIC SETTING

## TOPOGRAPHY

Physiographically, the larger part of the area is in the Central Lowland Province of the Western Lakes Section (Fenneman, 1938, pl. 1). The northeastern and smaller part is in the Superior Upland Province. Most of the area is characterized by a young glaciated plain of moraines, lakes, and lake plains. The entire area was glaciated; thus, the configuration of the land surface is due to glacial and post-glacial deposition and erosion.

Maximum land-surface relief is about 600 feet, ranging from less than 700 feet above mean sea level along the flood plains of the Minnesota, Mississippi, and St. Croix Rivers in the southern part of the area to more than 1,250 feet atop the morainic hills in the extreme northeastern part. Most of the surface is gently undulating upland and lies between altitudes of 850 to 1,050 feet. The lowest water-surface altitude is about 675 feet, where the Mississippi River flows out of the area to the southeast.

The most striking land-surface features are the band of morainic hills that border the more densely populated parts of the metropolitan area on the east, south, and west; the relatively deeply incised valleys of the major streams; and the broad, fan-shaped Anoka sand plain in the north-central part of the metropolitan area. The band of morainic hills are characterized by knob and kettle topography, with small ponds occupying many of the kettles. These hills are generally wooded, and their natural beauty makes them desirable for home-sites. Lake Minnetonka lies within this morainic splendor. The incised valleys of the Minnesota, Mississippi, and St. Croix Rivers are generally wooded and expose bedrock sections in places. The Anoka sand plain, resulting as a diversion of the Mississippi River from and back to its original channel in late glacial time, is flat and hummocky and contains many lakes and swamps. Sand dunes occur in places near its southern margins.

Water covers 147 square miles, or about 5 percent of the land surface, within the metropolitan area.

## DRAINAGE

The study area occupies 13 percent of the Upper Mississippi River drainage basin above the stream-gaging station at Prescott, Wisconsin. All drainage flows past the Prescott gage except that from the Vermillion River and that from a small part of the Cannon River basin (Figure 3). The three major streams are the Minnesota, St. Croix, and Mississippi Rivers, with 44, 85, and 83 miles, respectively, of channel within the study area.

The Minnesota River flows northeastward and joins the Mississippi River at the southwest border of St. Paul. It is an underfit stream, flowing in a valley formerly carved by Glacial River Warren, the southern outlet for Glacial Lake Agassiz to the west (Leverett, 1932, p. 123-126). The average gradient of the river is only 0.3 foot per mile, dropping from an altitude of about 700 feet, where it enters the area, to 687 feet at its confluence with the Mississippi River. The upland part of its basin is dotted with numerous lakes, which occupy depressions left after the retreat of the Des Moines lobe glaciation. The valley flood plain is poorly drained, containing many flood-plain lakes and swamps, especially in its lowermost reach.

The St. Croix River flows southward and joins the Mississippi River near Prescott. Its average gradient is 1.3 feet per mile in the northeast part of the area, entering at an altitude of about 800 feet and dropping to an altitude of 755 feet above Taylors Falls. Below Taylors Falls, the gradient is 1.3 feet per mile to about 1 mile north of where the Polk County line meets the river, from whence the gradient is only 0.5 foot per mile, in the next 11 miles to the inlet of Lake St. Croix. There the channel broadens considerably, and the water-surface altitude remains at about 675 feet in the 24 miles to the Mississippi River at Prescott. Between Taylors Falls and Lake St. Croix, the stream channel is highly braided, giving rise to many flood-plain ponds and lakes. The upland part of the basin, especially north of the Washington County line, contains many lakes and swamps and is poorly drained, largely because of the flatness of the terrain.

The Mississippi River flows southeastward, diagonally across the central part of the area, entering at an altitude of about 910 feet and leaving at an altitude of 675 feet under controlled conditions. The natural gradient of the stream is altered by five dams. Of the 235 feet of drop in water-surface altitude within the area, 143 feet occurs at the dams. Thus, although the average gradient is little changed from natural conditions, its distribution has been appreciably altered by man's activities, with the possible exclusion of Upper St. Anthony Falls Lock and Dam, which is situated at a natural waterfall. The river flows in a narrow gorge between Upper St. Anthony Falls Lock and Dam to its confluence with the Minnesota River where, like the Minnesota River, it now flows in a broad valley that was originally carved by the Glacial River Warren. Preglacial and glacial patterns in the drainage of the Mississippi River are described by Schwartz (1936, p. 72).

The study area as a whole is poorly drained, particularly in its northern part, with the Snake, Sunrise, and Rum Rivers having 43, 47, and 37 percent, respectively, of the drainage areas above the gaging stations occupied by lakes, ponds, and swamps (Mann and Collier, 1970, Table 5). Stream gradients are generally low, and frozen ground and water conditions reduce land drainage drastically during the winter.

## CLIMATE

The study area is close to the geographical center of the continent; thus, the climate is predominantly the continental type, characterized by generally mild, subhumid summers and relatively long, severe winters. All climatic features tend to extremes. Temperature at St. Paul ranged from -34°F in January 1936 and January 1970 to 108° in July 1936. Monthly precipitation ranged from a trace in December 1943 to 8.03 inches in May 1962. Abrupt changes in temperature and precipitation are common and are caused by the pressure systems that cross from west to east. Because relief is low, topographic influence on climatic patterns is insignificant. Similarly, the water bodies are too small to have any noticeable modifying influences on the passing air-masses.

Normal monthly temperature and precipitation graphs for three stations in the area are shown in Figure 4. The temperatures at these stations are almost coincident and show a close correlation with latitude, Mora being the northern-most station. The precipitation is more variable, being lowest at the Minneapolis-St. Paul station. Rainfall is greatest during the summer, when it is most favorable for crop growth. The average growing season is 166 days. About 55 percent of the annual precipitation is during May through August.

The seasonal areal distribution of precipitation is shown in Figure 5. The average annual precipitation over the study area was computed to be 28.3 inches, by the Thiessen method of polygonal distribution and weighted averages (Thiessen, 1911). Records from 31 stations, 11 outside the area and 20 inside, were used in the computation.

Potential evapotranspiration, PE, and actual evapotranspiration, AE, highly dependent on climate, are important factors in the water resources of an area. Actual evaporation from standard evaporation pans is recorded for selected stations in the climatological data of the U.S. Department of Commerce, Weather Bureau; but studies discussed in Sellers (1965, p. 165) show that pan evaporation is consistently high compared with various methods for determining evaporation from soils. To obtain evapotranspiration values for use in a water budget for this area, two methods were used, the Thornthwaite (Thornthwaite and Mather, 1957) and the energy balance. The relative merits and discussion of the Thornthwaite method are given in Sellers (1965) and Cruff and Thompson (1967). Figure 6 shows Thornthwaite diagrams for three different stations in the study area, Farmington, Cambridge, and Mora. The diagrams depict generalized soil-moisture conditions on an average annual basis. The computations used to draw the diagrams show AE to be 23.4, 22.0, and 23.1 inches, respectively, and PE to be 25.3, 23.8, and 23.9 inches, respectively, for the station records analyzed and mentioned above.

Figure 3. – Data collection sites in the metropolitan area.

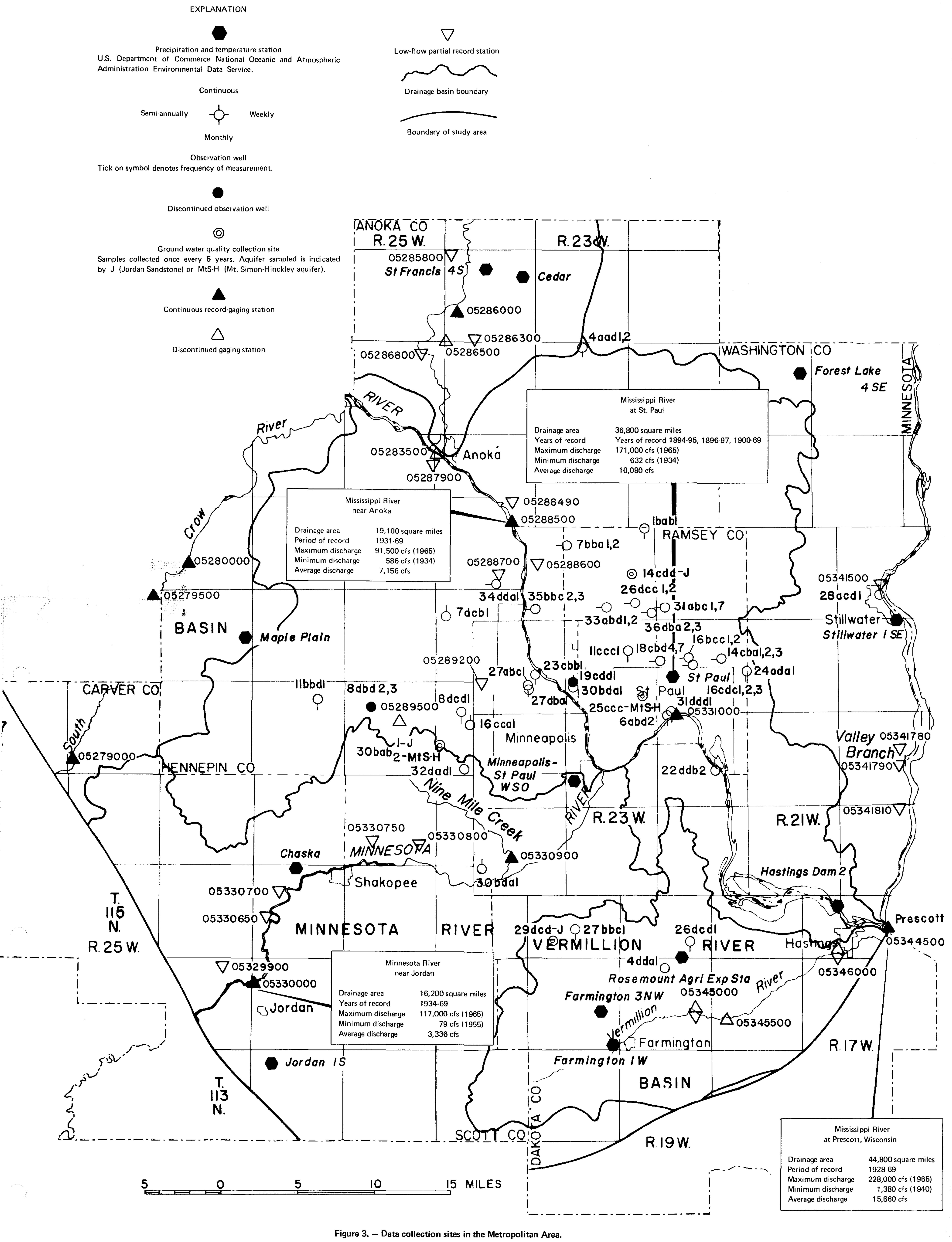



Figure 3. — Data collection sites in the Metropolitan Area.

The energy-balance method for determining evapotranspiration is applicable only where net radiation data are available. Blad and Baker (1971) made a 3-year study of net radiation at St. Paul (Table 1) and, thus, made it possible to use the method here. According to Tanner (1960), evapotranspiration in humid areas (such as eastern Minnesota) is approximately equal to net radiation. Evapotranspiration, then, can be determined from the ratio $R_o/L$, where $R_o$ is the net radiation, in langleys, and L is the latent heat required to evaporate water, in calories per cubic centimeter. The unit for langleys is calories per square centimeter. L is equal to about 600 calories per cubic centimeter. Thus, from Table 1, the average net radiation during April 15 to September 15, an approximate growing season, is 34,336 langleys. Dividing this by L and then by 2.54 (centimeters in an inch), gives an average annual total evaporation rate of 22.5 inches, a rather close approximation to the Thornthwaite determinations.

Table 1.—Measured average daily and annual net radiation totals (in langleys) at St. Paul, Minn., for each month from April 1964–March 1967. (From Blad and Baker, 1971.)

| Period | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | Jan. | Feb. | Mar. | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1964-65 | 162 | 246 | 255 | 266 | 201 | 119 | 51 | −14 | −57 | −65 | −20 | −56 | 33,266 |
| 1965-66 | 127 | 214 | 295 | 278 | 229 | 95 | 49 | −27 | −45 | −58 | −13 | 74 | 37,307 |
| 1966-67 | 137 | 239 | 263 | 290 | 200 | 131 | 21 | − 3 | −44 | −40 | −34 | 35 | 38,169 |
| Average | 142 | 233 | 271 | 278 | 210 | 115 | 40 | −15 | −49 | −54 | −22 | 18 | 36,247 |

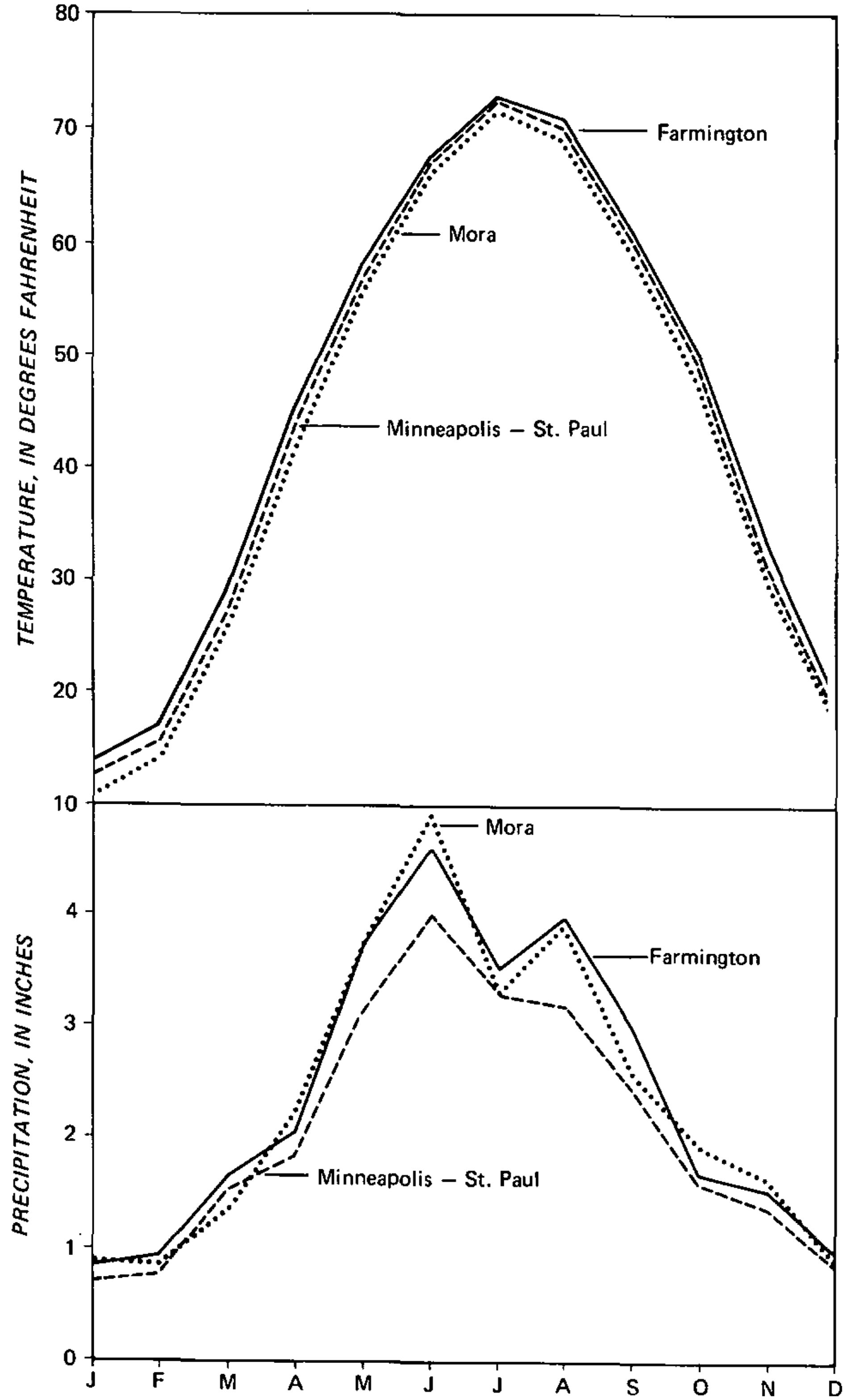



**Figure 4. — Normal monthly temperature and precipitation at selected sites. (From National Oceanic and Atmospheric Administration climatological data.)**

**Figure 5. — Seasonal distribution of precipitation, in inches, in the study area. (Baker and others, 1967)**

**Figure 6. — Thornthwaite diagram depicting generalized soil moisture conditions on an average annual basis (period 1931-1969).**

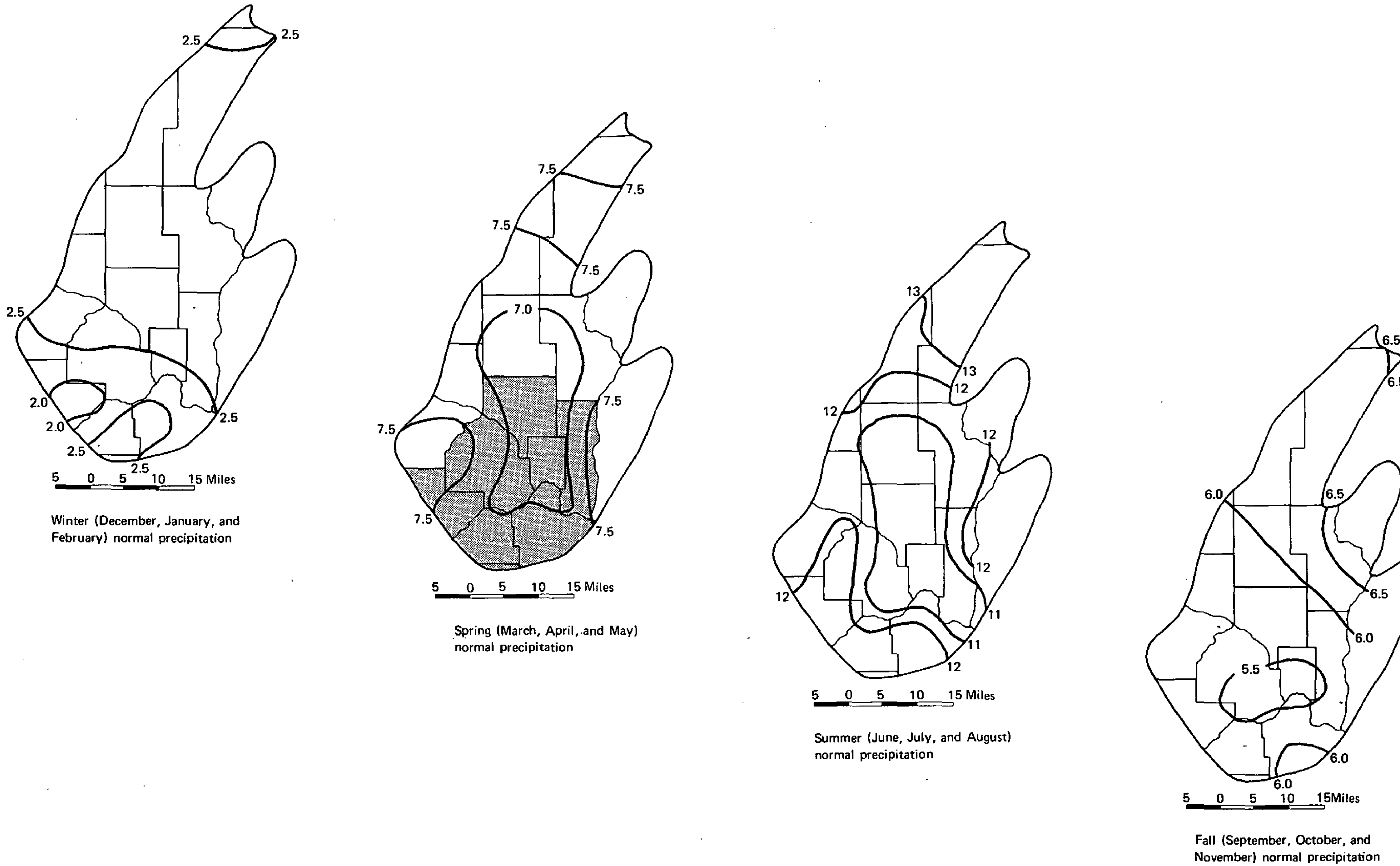



**Figure 5. — Seasonal distribution of precipitation, in inches, in the study area. (Baker and others, 1967)**

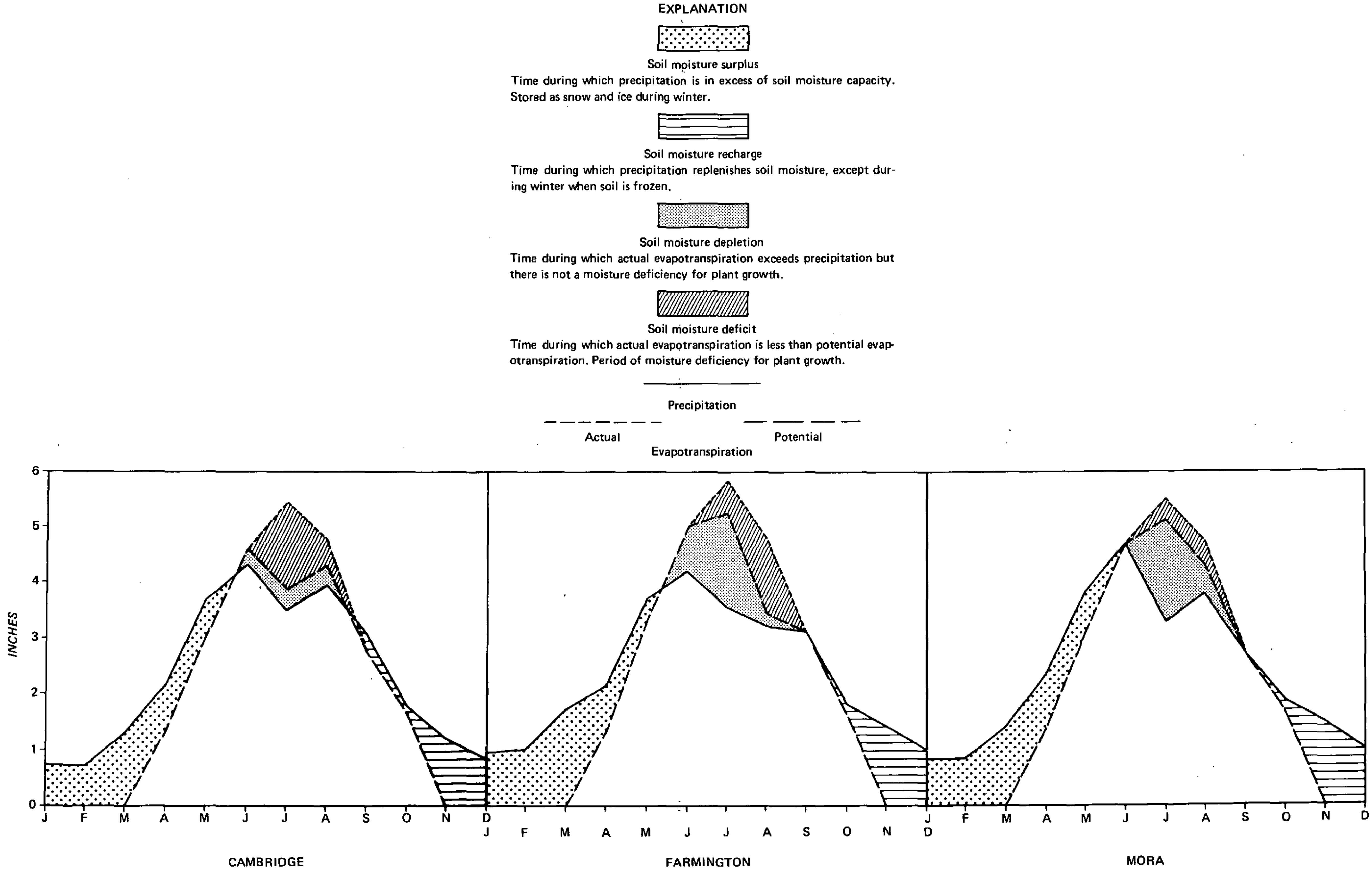



**Figure 6. — Thornthwaite diagram depicting generalized soil moisture conditions on an average annual basis (period 1931-1969).**

# CHAPTER THREE: GEOLOGY

The abundant ground-water resources in the metropolitan area result from a distinctive geologic structure, commonly called the Twin Cities artesian basin. The overall configuration of this basin is depicted on the geologic cross sections shown in Figure 7. The Precambrian and Cambrian and Ordovician rock formations constituting the basin (Table 2) were deposited in a trough in the Precambrian rock surface. The longitudinal axis of the trough is nearly north-south, plunging slightly to the south. The shape of the basin can be likened to that of a large soup spoon whose handle is tilted upward to the north and whose lip spills to the south. The deepest part of the spoon would lie almost directly beneath the Twin Cities.

The sedimentary rocks in the basin, exclusive of the Hinckley Sandstone, were deposited in Cambrian and Ordovician seas. Transgression resulted in deep water filling the basin and consequent deposition of fine-grained limestone and shale sediments. Regression resulted in shallow water in the basin and consequent deposition of more coarse-grained siltstone and sandstone sediments. The rock record is absent from the middle Ordovician to Quaternary time. Description of the bedrock units and their position in the geologic column is shown in Table 2.

During the Pleistocene Epoch four continental glaciers traversed the area, blanketing the bedrock surface with drift. The present land surface is largely composed of drift from the Wisconsin glaciation of the Pleistocene. Two major ice lobes invaded the area, the Superior lobe from the northeast, and the Des Moines lobe, with its attendant Grantsburg sublobe, from the southwest. The Superior lobe traversed terrain composed largely of Precambrian crystalline rocks, and the Des Moines lobe traversed terrain composed largely of limestone and clay; thus, the materials deposited from the two sources are considerably different in composition, the former being more coarse and permeable. (For a generalized glacial history of Minnesota, see Wright and Ruhe, 1965.)

The bedrock surface is dissected by deep valleys that were carved either during the pre-Quaternary hiatus mentioned above or during the interglacial periods. The bedrock surface was further dissected by tunnelling streams beneath the glacier ice (Lindholm and others, 1972). The locations of these tunnel valleys were derived from the drift-thickness map (Figure 8). The approximate trends for the valleys in parts of the metropolitan area are shown on bedrock structure-contour maps (Figures 10, 12, and 14). The valleys are significant to the hydraulic continuity between the bedrock formations and the surficial deposits. Post glacial erosion of the bedrock surface is restricted largely to the surface valleys of the Mississippi, Minnesota, and St. Croix Rivers.

The surficial geology is shown on the map in Figure 9. The most prominent glacial deposits, in order of areal extent, are till, outwash, valley-train and lake deposits. Till of the Superior lobe ice is mostly reddish brown to brown and sandy and gravelly, in contrast to till of the Des Moines lobe, which is yellowish brown to gray and clayey. Large apronlike deposits of outwash sand and gravel fanned out in front of the two ice sheets during both their advancing and retreating stages. The Grantsburg sublobe of the Des Moines lobe, in part, overrode the deposits of the Superior lobe, thus, in the southeast part of the area where outwash from the two different sources abut each other sand and gravel is thicker, as is inferred by the drift-thickness map in Figure 8. The largest expanse of outwash is that of the Anoka sand plain, north of the Twin Cities. This deposit was formed as a result of the diversion of the Mississippi River from its pre- or inter-glacial course to around the front of the Grantsburg ice. The sand was deposited upon wasting of the ice and the return of the river to its present channel through the cities. (See Farnham, 1956, for a more detailed geology of the Anoka sand plain.)

Table 2. – Geologic units and their water-bearing characteristics (modified from Stone, 1965).

| System | Geologic Unit | Approx. Range In Thickness (in feet) | Description | Water-Bearing Characteristics |
|---|---|---|---|---|
| Quaternary | Undifferentiated glacial drift | 0-400+ | Glacial till, outwash sand and gravel, valley-train sand and gravel, lake deposits, and alluvium of several ages and several provenances; vertical and horizontal distribution of units is complex. | Distribution of aquifers and relatively impermeable confining beds is poorly known, especially in subsurface. Where saturated, stratified well-sorted deposits of sand and gravel (alluvium, valley train, outwash, some lake and ice-contact deposits) yield moderate to large supplies of water to wells. Records of 24 large diameter wells completed in sand and gravel show yields ranging from 240 to 2,000 gpm (gallons per minute) with from 2 to 69 feet of drawdown. Des Moines Lobe till is non-water bearing; Superior Lobe till is sandy and may yield small supplies suitable for domestic or farm use. |
| | | | Unconformity | |
| Ordovician | Decorah Shale | 0-95 | Shale, bluish-green to bluish-gray; blocky; thin, discontinuous beds of fossiliferous limestone throughout formation. | Only about 25 square miles in extent in area of study. Confining bed. |
| Ordovician | Platteville Limestone | 0-35 | Dolomitic limestone and dolomite, dark-gray, hard, thin-bedded to medium-bedded; some shale partings; can be divided into five members. | Only about 200 square miles in extent in area of study. Where saturated, fractures and solution cavities in rock generally yield small supplies to wells. Records of 23 wells show an average yield of 23 gpm. Water is generally under artesian pressure where overlain by Decorah Shale. Not considered to be an important source of water in area of study. |
| Ordovician | Glenwood Shale | 0-18 | Shale, bluish-gray to bluish-green; generally soft but becomes dolomitic and harder to the east. | Confining bed; locally, some springs issue from the Glenwood-Platteville contact in the river bluffs. |
| Ordovician | St. Peter Sandstone | 0-150+ | Sandstone, white, fine- to medium-grained, well-sorted, quartzose; locally iron-stained and well cemented; rounding and frosting of grains is common; 5-50 feet of siltstone and shale near bottom of formation. | About 650 square miles in extent in Minnesota part of study area; not fully saturated throughout area. Most wells completed in the sandstone are of small diameter and used for domestic supply. They yield 9 to 100 gpm with 1 to 21 feet of drawdown. Two wells known to be used for public supply have been pumped at 600 and 1,250 gpm. Water occurs under both confined and unconfined conditions. Confining bed near bottom of formation seems extensive and hydraulically separates sandstone from underlying Prairie du Chien-Jordan aquifer. Not considered to be an important source for public supplies in area of study, but is suitable source for domestic supplies. |
| Ordovician | Prairie du Chien Group: Shakopee Dolomite | 0-250+ | Dolomite, light-brown to buff, thinly to thickly bedded, cherty; shale partings; commonly sandy and oolitic. | About 2,000 square miles in extent in Minnesota part of study area. Together, the Prairie du Chien dolomite and Jordan Sandstone constitute the major aquifer unit in the area. The two are hydraulically connected throughout most of the area, but locally some small head differences may exist owing to intervening low-permeable confining beds of limited extent.<br>Prairie du Chien: Permeability is due to fractures, joints and solution cavities in the rock. Yields small to large supplies of water to wells. Pumping rates of up to 1,800 gpm have been obtained.<br>Prairie du Chien-Jordan aquifer: Supplies about 75 percent of ground water pumped in the metropolitan area. Yields of 115 wells (3-24 inch diameter casings), open to both rocks, ranged from 85 to 2,765 gpm with 3 to 133 feet of drawdown. Higher obtainable yields seem to reflect closeness to the Mississippi and Minnesota Rivers or to places where the aquifer is overlain directly by glacial deposits particularly where drift-filled valleys penetrate.<br>Jordan: Permeability is mostly intergranular but may be due to joint partings in cemented parts. Main source of water for public supply in metropolitan area. Almost all wells completed in the sandstone are of large diameter. Recorded yields are from 36 to over 2,400 gpm with 2 to 155 feet of drawdown. |
| Ordovician | Prairie du Chien Group: New Richmond Sandstone | | Sandstone and sandy dolomite, buff; often missing. | |
| Ordovician | Prairie du Chien Group: Oneota Dolomite | | Dolomite, light-brownish-gray to buff; thinly to thickly bedded, vuggy. | |
| Cambrian | Jordan Sandstone | 0-100+ | Sandstone, white to yellowish, fine- to coarse-grained, massive to bedded, cross-bedded in places, quartzose; commonly iron-stained; loosely to well cemented. | |
| Cambrian | St. Lawrence Formation | 0-65 | Dolomitic siltstone and fine-grained dolomitic sandstone; glauconitic, in part. | Confining bed. No wells are known to obtain water from this formation. |
| Cambrian | Franconia Sandstone | 0-200+ | Sandstone, very fine grained; moderately to highly glauconitic; worm-bored in places.<br>Interbedded very fine grained sandstone and shale; mica flakes common.<br>Glauconitic fine-grained sandstone and orange to buff silty fine-grained sandstone (often worm-bored). | Small amounts of water may be obtainable from the medium- to coarse-grained members of the formation, very little water from the fine-grained members. Not considered to be an important water source in the area of study. Records of wells completed only in the Franconia Formation are lacking. |
| Cambrian | Ironton Sandstone | 0-80+ | Sandstone, white, medium- to fine-grained, poorly sorted and silty. | About 3,000 square miles in extent in area of study. An important aquifer beyond the limits of the Prairie du Chien-Jordan aquifer. Yields of wells range from 40 to 400 gpm with 4 to 110 feet of drawdown. |
| Cambrian | Galesville Sandstone | | Sandstone, yellow to white, medium- to coarse-grained, poorly cemented. | |
| Cambrian | Eau Claire Sandstone | 0-150 | Sandstone, siltstone, and shale, gray to reddish-brown, fossiliferous. | Confining bed. Sandstone beds may yield small quantities of water to wells for domestic use. Shale of very low permeability and apparent large areal extent constitutes the main confining bed for water in the underlying aquifer. |
| Cambrian | Mt. Simon Sandstone | As much as 200 | Sandstone, gray to pink, medium- to coarse-grained. Some pebble zones and thin, shalely beds. | Secondary major aquifer in the area of study. Supplies about 15 percent of ground water pumped in the metropolitan area. Recorded yields of 27 municipal and industrial wells ranged from 125 to 2,000 gpm with 20 to 209 feet of drawdown. Major source of artesian water in northern half of study area. |
| | | | Unconformity | |
| Precambrian | Hinckley Sandstone | As much as 200 | Sandstone, buff to red, medium- to coarse-grained, well sorted and cemented. | |
| | | | Unconformity | |
| Precambrian | Red clastics | As much as 4,000 | Silty feldspathic sandstone and lithic sandstone, fine-grained; probably included red shale. | Aquifer of local interest in Chisago County, T. 35 M., R. 21 W. Wells have yields from 15 to 120 gpm with 41 to 150 feet of drawdown. Data are lacking in metropolitan and other parts of area. |
| | | | Unconformity | |
| Precambrian | Volcanic rocks | As much as 20,000 | Mostly mafic lava flows, but includes thin interlayers of tuff and breccia. | Rock is at and near the surface at Taylors Falls and north of boundary of study area. Weathered or fractured zones provide small quantities of water for domestic needs. Deeply buried in metropolitan area and no data available. |

**Figure 7. – Generalized cross sections of the Twin Cities artesian basin. (Location of sections shown on Figure 44.)**

**Figure 8. – Thickness of the glacial drift overlying bedrock formations in the Metropolitan Area.**

**Figure 9. – Generalized surficial geology in the Metropolitan Area.**

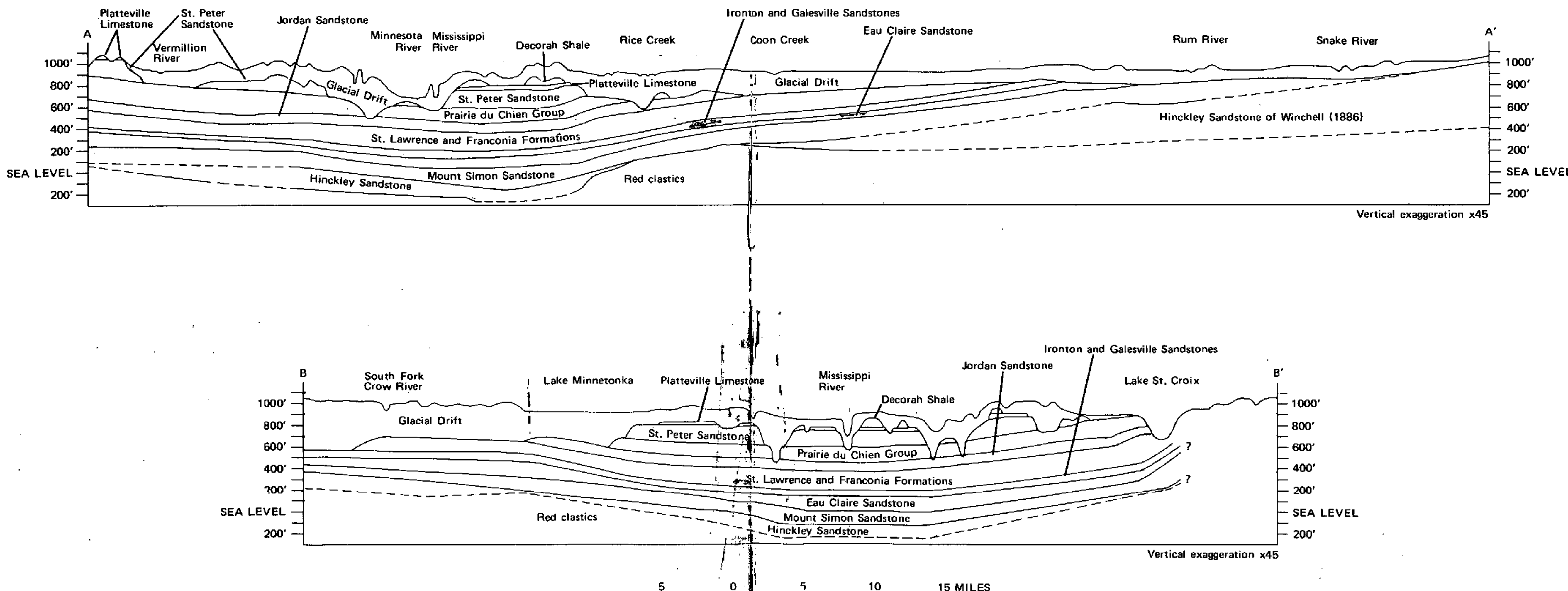



**Figure 7. — Generalized cross sections of the Metropolitan Area artesian basin. (Location of sections shown on Figure 45.)**

EXPLANATION

150 — ?

Contours of equal thickness of glacial drift
Dashed where approximately located, queried where unknown.

●

Well or test hole used for control outside of Hennepin and Ramsey

Boundary of study area

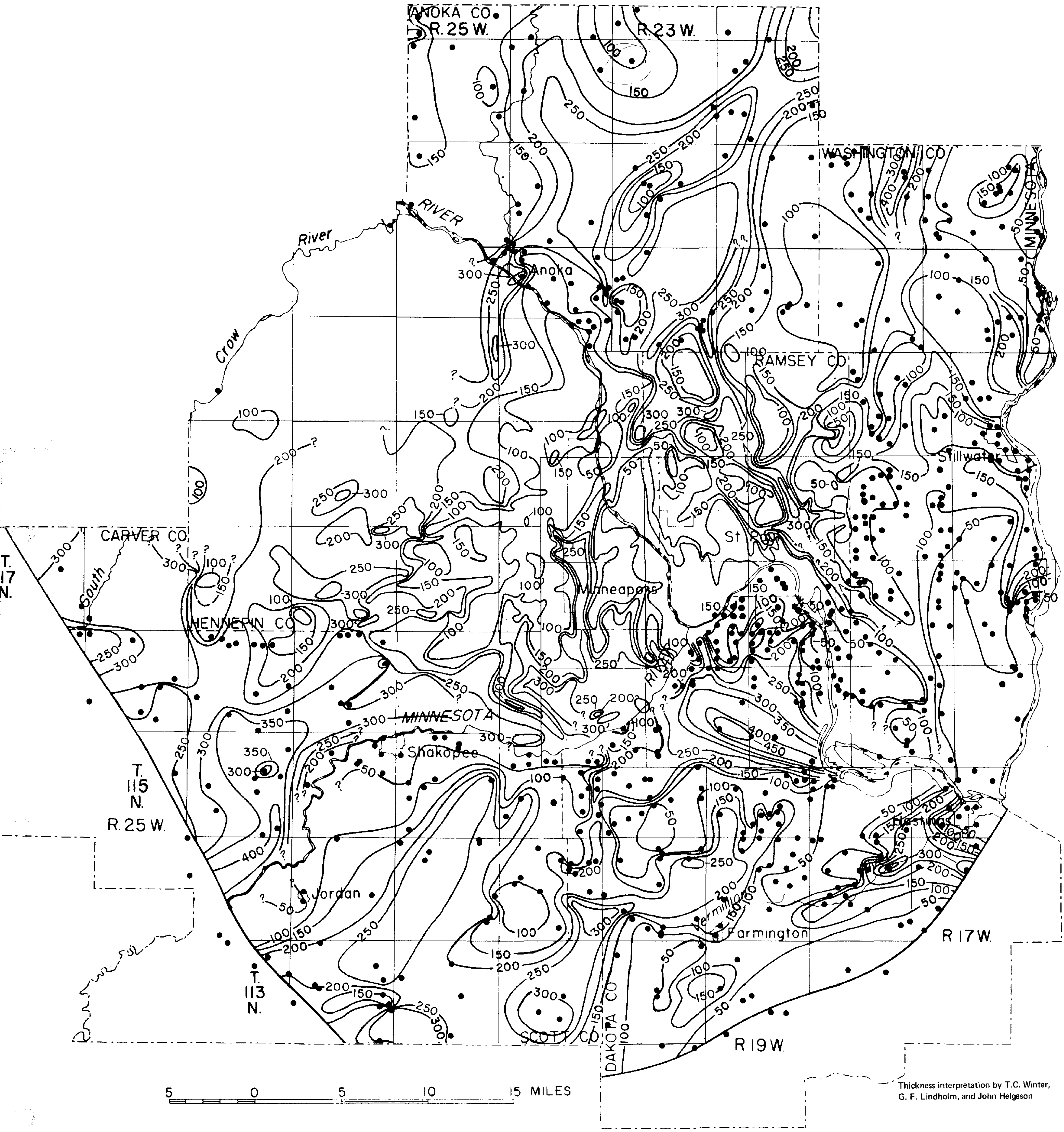



**Figure 8. — Thickness of the glacial drift overlying bedrock formations in the Metropolitan Area.**

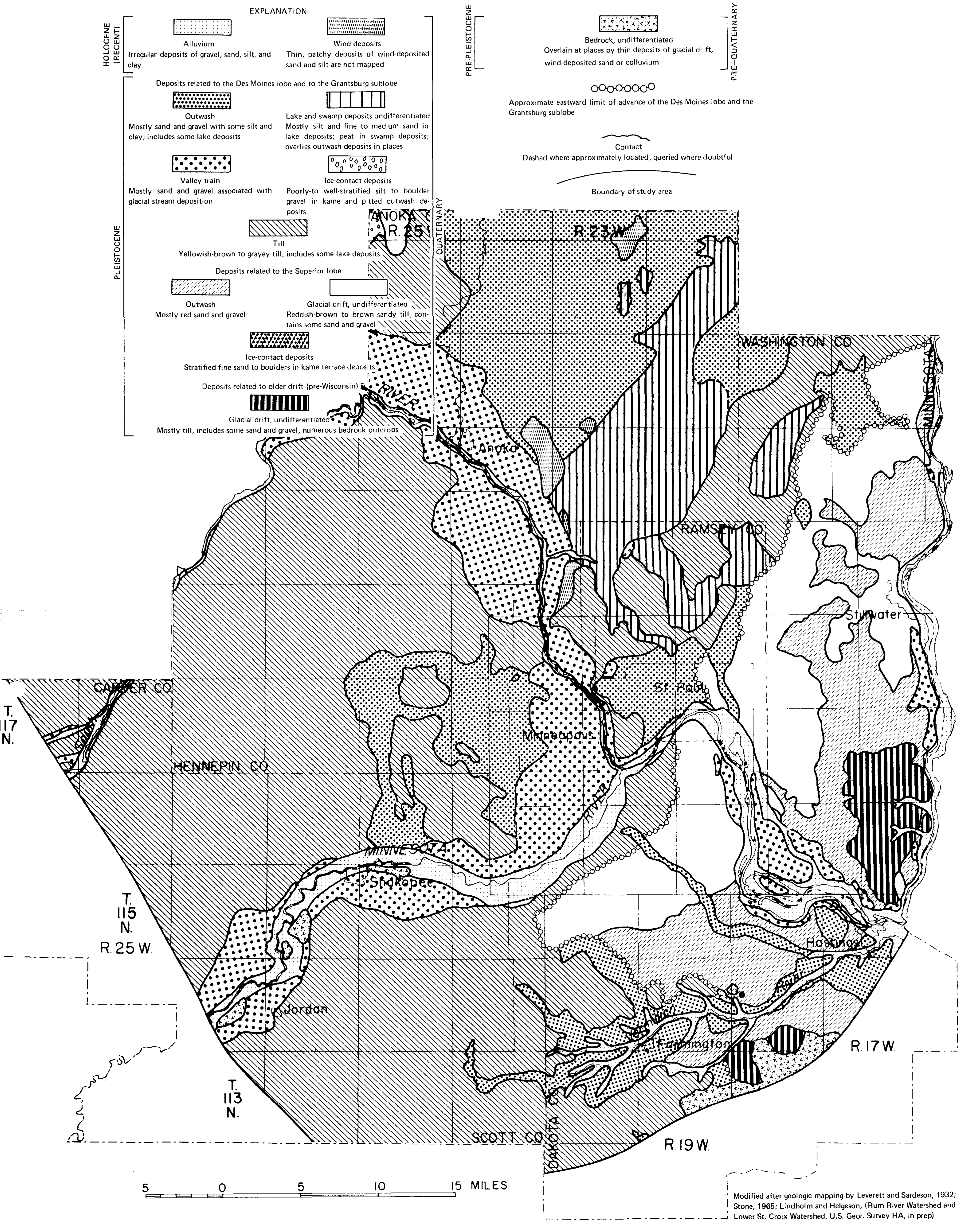



**Figure 9. — Generalized surficial geology in the Metropolitan Area.**

Generally broad remnants of valley-train sand and gravel occur along the valleys of the major streams. These sediments were deposited when the valleys were brimfull with glacial meltwater. As the sources of water waned with the wasting ice sheets, a succession of terraces were formed along the stream courses, down to the level of the present stream development. Minneapolis is built largely on valley-train sand and gravel deposited at the confluence of the glacial Mississippi and Minnesota Rivers.

A rather extensive deposit of lake sand and silt occurs north of the Twin Cities at the south end of the Anoka sand plain (Stone, 1965). Other lake deposits were formed at the margins of the ice sheets and in depressions left by the retreating ice. The lake deposits are fine grained, poorly drained, and generally boggy throughout.

The ice-contact deposits are similar to the outwash except in their mode of deposition, and they are generally more poorly sorted in part. The wind deposits (sand dunes) were probably formed by strong winds blowing off the ice sheets during their waning stages.

Long and, in places, wide ribbons of alluvium make up the surface of the flood plains of most of the streams. These deposits largely overlie glacial valley-fill deposits, and, together, they are thick in places. Their occurrence, in contact with the major streams and incised in the bedrock formations, makes them significant to the hydrology and availability of water.

## GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS

The rocks underlying the surface in the Twin Cities artesian basin area are probably as wide in variety and as hydrologically complex as any other sequence of rocks in the country. They range in age from Precambrian to Holocene; in origin from igneous to sedimentary (marine, glacial, fluvial, and lake); in texture from subcrystalline to granular, consolidated to nonconsolidated, and massively to thinly bedded; in permeability from near impervious to highly pervious; in type of permeability from intergranular to fracture, solution cavity, and joint; in permeability continuity from homogeneous to nonhomogeneous and from isotropic to anisotropic; and in hydraulic condition from artesian to water table. The description of the geologic units and their water-bearing characteristics is shown in Table 2.

In order of use and development, the major bedrock aquifers are the 1) Prairie du Chien – Jordan, 2) Mount Simon – Hinckley, 3) Ironton – Galesville, 4) St. Peter, and 5) Platteville. Water obtained from any of the other bedrock strata is probably insignificant. The combination of the adjacent rock strata into unit aquifers is made because of the hydraulic connection between the different beds; that is, a well completed in one of either of the combined strata should have nearly the same static water level as a well open to both. Also, pumping from only one of the strata should result in a combined lowering of hydrostatic pressures in the aquifer unit. Locally, confining beds of small extent, especially between the Prairie du Chien and Jordan strata, may cause different static water levels in wells in the same general location. Pumping from one, however, will affect the water level in the other to the extent that, for all practical purposes, the two strata can be considered to be a hydrologic unit.

Major aquifers in the surficial deposits are composed of sand and gravel valley fill in the valleys of the larger streams and sand and gravel outwash deposits at and below the surface (generally underlying till sheets) within the glacial drift. The surficial extent of many of these potential aquifers are mapped (Figure 9), but their subsurface configuration and the position of the water table are so variable and complex that it was not possible to delimit or to fully evaluate these aquifers. In comparison with the bedrock aquifers, drift aquifers are little used in the metropolitan area and are not fully developed.

Well-log data were used to draw structure-contour and thickness maps of the major bedrock aquifers. These maps are shown in Figures 10-18. Water-level data were used to draw potentiometric-surface (water-level) maps for the St. Peter, Prairie du Chien – Jordan, and Mount Simon – Hinckley aquifers. These maps are shown in Figures 19-21. The detail of each map is commensurate with the amount of available data for each aquifer. Because the Prairie du Chien – Jordan aquifer is the major aquifer, it is mapped in greatest detail. The accuracy of these maps and, hence, their usability can be enhanced greatly as more data become available.

Both artesian (confined) and water-table (unconfined) conditions occur in the St. Peter aquifer. Data are not sufficient to determine which condition prevails at each well site, thus, some contours actually may represent the surface of the water table instead of the artesian surface. However, head differences between the two surfaces are not great, so no great error is introduced in combining the two surfaces.

One practical use of the maps is for selecting locations and predicting depths of wells to be drilled in the different aquifers. This application may best be described by a hypothetical case. Suppose a well is to be completed in the Jordan Sandstone in the NW1/4NW1/4 section 6, T.27N., R.24W. Inspection of a U.S. Geological-Survey 7 1/2-minute topographic map of the Bloomington quadrangle shows the altitude here to be about 825 feet. Figure 14, the structure-contour map of the top of the Jordan Sandstone, shows the bedrock surface altitude to be about 525 feet, and Figure 15, the thickness map of the Jordan Sandstone, shows the sandstone to be about 80 feet thick. In addition, Figure 20 shows that the water level (in December 1970) in a well completed in the Prairie du Chien – Jordan aquifer at this site should rise to an altitude of about 805 feet. Therefore, the proposed well will penetrate the sandstone at about 300 feet below the land surface and will have to be drilled about 80 feet more to obtain full penetration, or a total of about 380 feet. The static water level in late December should be about 20 feet below the land surface under the present level of ground-water development.

Further inspection of the similar bedrock maps show that the St. Peter Sandstone (Figure 10) in this well should be about 125 feet below the land surface and 50 feet thick (Figure 11), and the Prairie du Chien Group (Figure 12) should be about 175 feet below the land surface and about 125 feet thick (Figure 13).

Care should be exercised when interpreting the maps at places such as this, however, because of the nearness of the bedrock valley immediately west of the proposed well site. There are many such valleys penetrating the uppermost bedrock strata throughout the area, and these valleys are only approximately delimited. At this particular site, the uppermost bedrock strata may be partly or wholly eroded and replaced by glacial drift. But, because the Jordan Sandstone is relatively deep, it may not have been affected by erosion.

The accuracy and usability of these maps can be improved considerably if well drillers would report map inconsistencies to the U.S. Geological Survey, St. Paul, Minn., so that corrections can be made.

**Figure 10. – Structure contours at the top of the St. Peter Sandstone in the metropolitan area.**

**Figure 11. – Thickness of the St. Peter Sandstone in the metropolitan area.**

**Figure 12. – Structure contours at the top of the Prairie du Chien group in the metropolitan area.**

**Figure 13. – Thickness of the Prairie du Chien group in the metropolitan area.**

**Figure 14. – Structure contours at the top of the Jordan Sandstone in the metropolitan area.**

**Figure 15. – Thickness of the Jordan Sandstone in the metropolitan area.**

**Figure 16. – Structure contours at the top of the Ironton and Galesville Sandstones in the metropolitan area.**

**Figure 17. – Thickness of the Ironton-Galesville aquifer in the metropolitan area.**

**Figure 18. – Structure contours at the top of the Mount Simon Sandstone and Hinckley Sandstone in the metropolitan area.**

**Figure 19. – Potentiometric surface of water in the St. Peter aquifer in Winter 1970-71 in the metropolitan area.**

**Figure 20. – Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in Winter 1970-71 in the metropolitan area.**

**Figure 21. – Potentiometric surface of water in the Mount Simon-Hinckley aquifer in Winter 1970-71 in the metropolitan area.**

EXPLANATION

750 —?—

Structure contour

Altitude of top of St. Peter Sandstone. Dashed where approximately located, queried where doubtful.

●

Well or test hole used for control

Locations not plotted in Hennepin and Ramsey Counties because of density of points.

— — — — — — — —

Boundary of St. Peter Sandstone

Modified after Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966) and Stillwater Sheet (unpublished advance version).

••••••••••••••••••••••••••

Axis of buried channel, approximately located

Cut into or through St. Peter Sandstone by glacial stream erosion; extents are partial; inferred at most places from reported glacial drift thickness data.

Boundary of study area

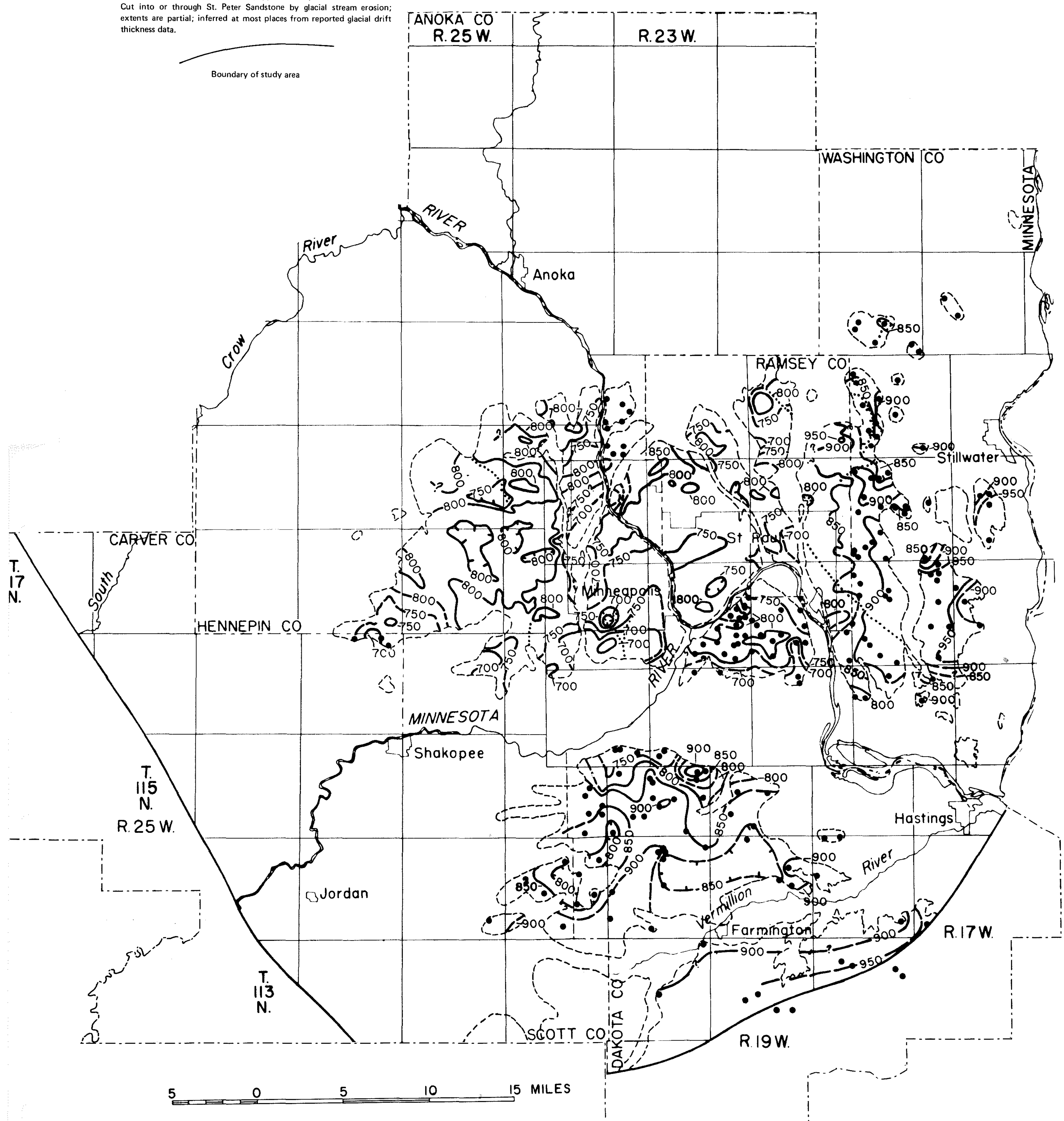



Figure 10. — Structure contours at the top of the St. Peter Sandstone in the Metropolitan Area.

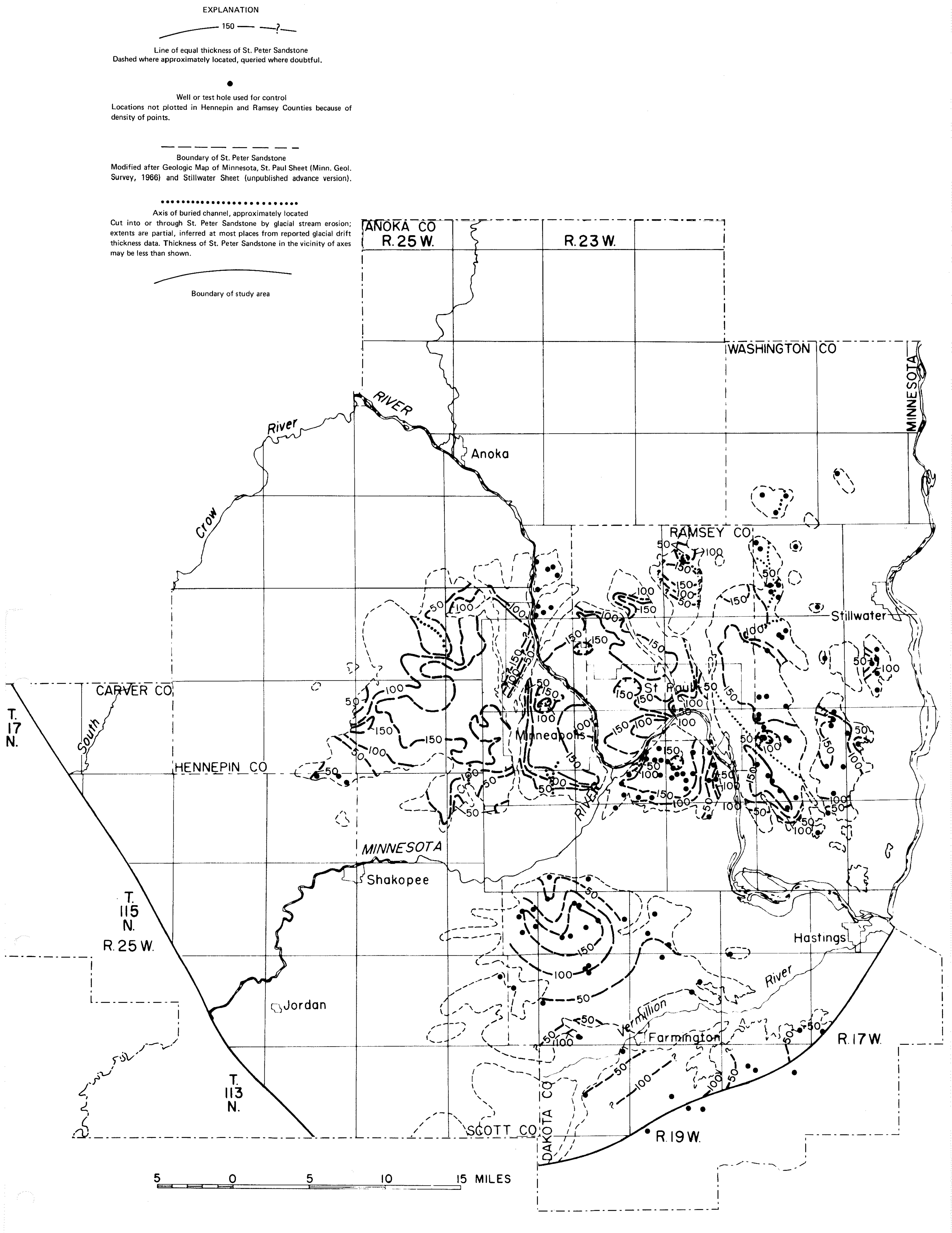



Figure 11. — Thickness of the St. Peter Sandstone in the Metropolitan Area.

EXPLANATION

800

Structure contour
Shows altitude of top of Prairie du Chien Group. Dashed where approximately located.

Well or test hole used for control
Locations not plotted in Hennepin and Ramsey Counties because of density of points.

Geologic contact
Modified after Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966) and Stillwater Sheet (unpublished advance version). Con-

Fault
From Geologic Map of Minnesota, St. Paul Sheet, 1966.

Axis of buried channel, approximately located
Cut into and through the Prairie du Chien Group by glacial stream erosion, extents are partial, inferred at most places from reported glacial drift thickness data.

Boundary of study area

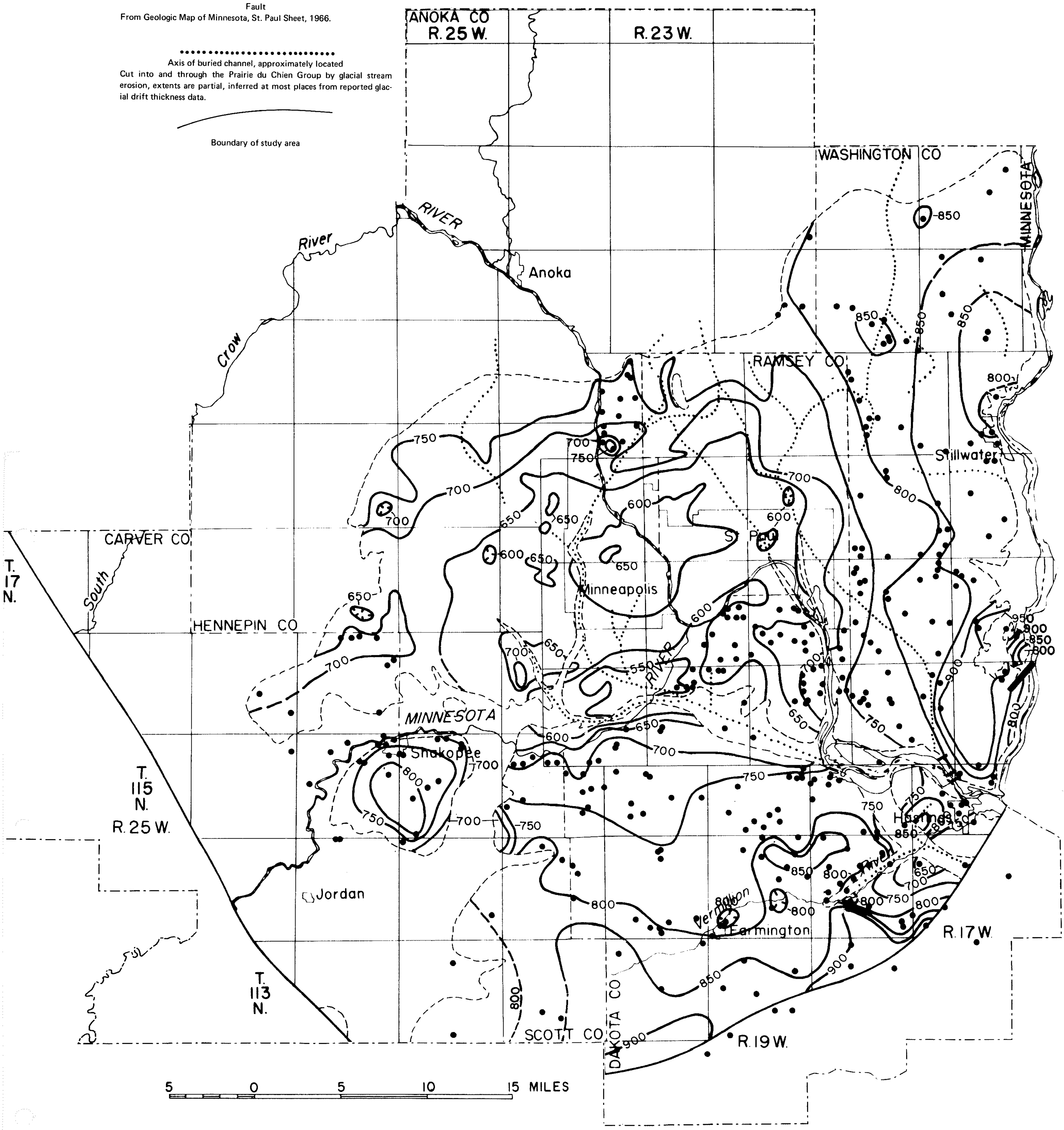



Figure 12. – Structure contours at the top of the Prairie du Chien group in the Metropolitan Area.

EXPLANATION

150 — ?

Line of equal thickness of Prairie du Chien Group
Dashed where approximately located, queried where unknown.

Well or test hole used for control
Locations not plotted in Hennepin and Ramsey Counties because of density of points.

Point of inferred thickness used for control
Thickness and location derived at intersection of structure contours drawn on the surfaces of the Jordan Sandstone and Prairie du Chien Group.

Geologic contact
Modified after Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966) and Stillwater Sheet (unpublished advance version).

Fault
From Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966)

Axis of buried channel, approximately located
Cut into or through the Prairie du Chien Group by glacial stream erosion; extents are partial; inferred at most places from reported glacial drift thickness data. Thickness of the Prairie du Chien Group in the vicinity of axes may be less than shown.

Boundary of study area

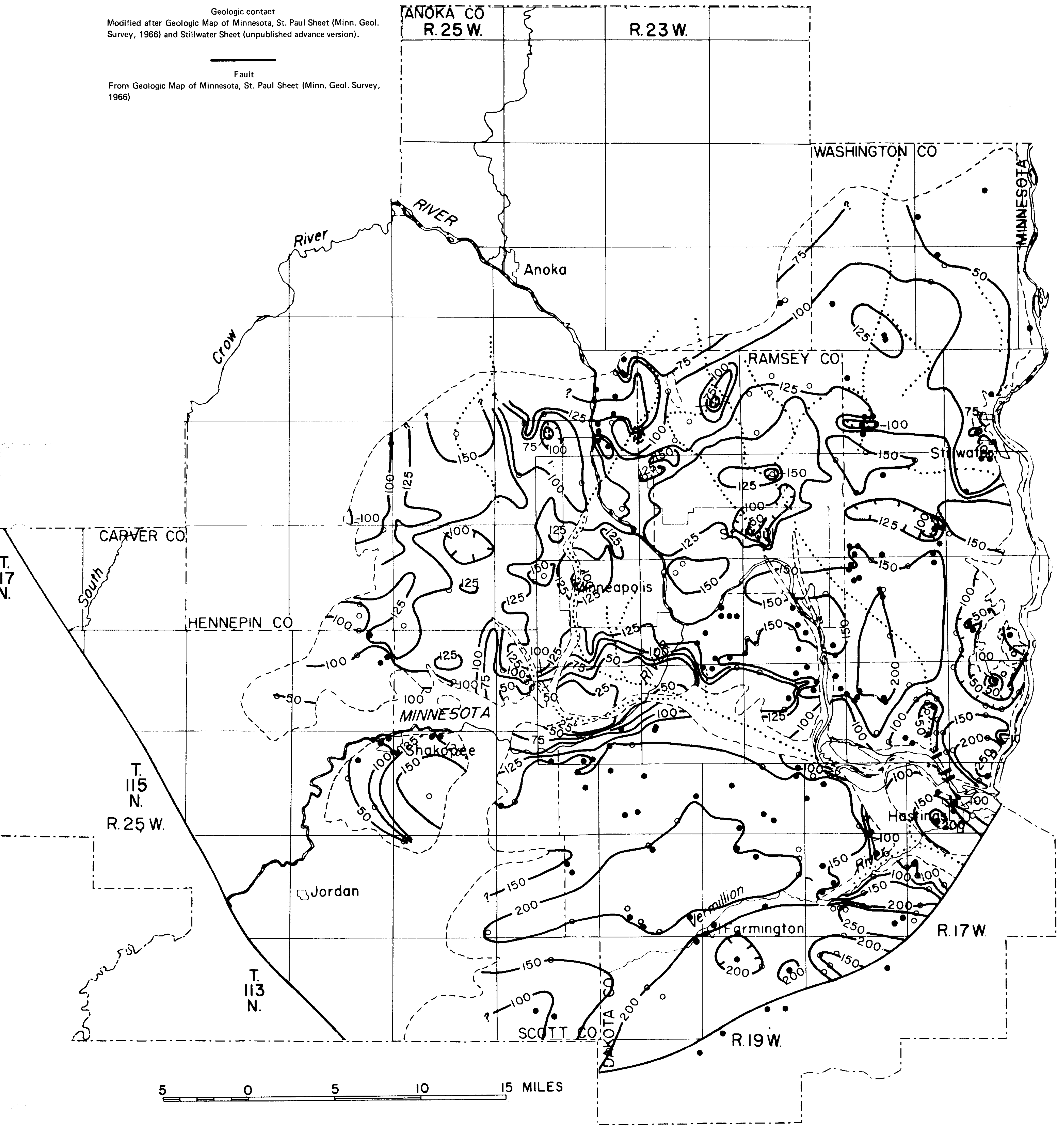



Figure 13. — Thickness of the Prairie du Chien group in the Metropolitan Area.

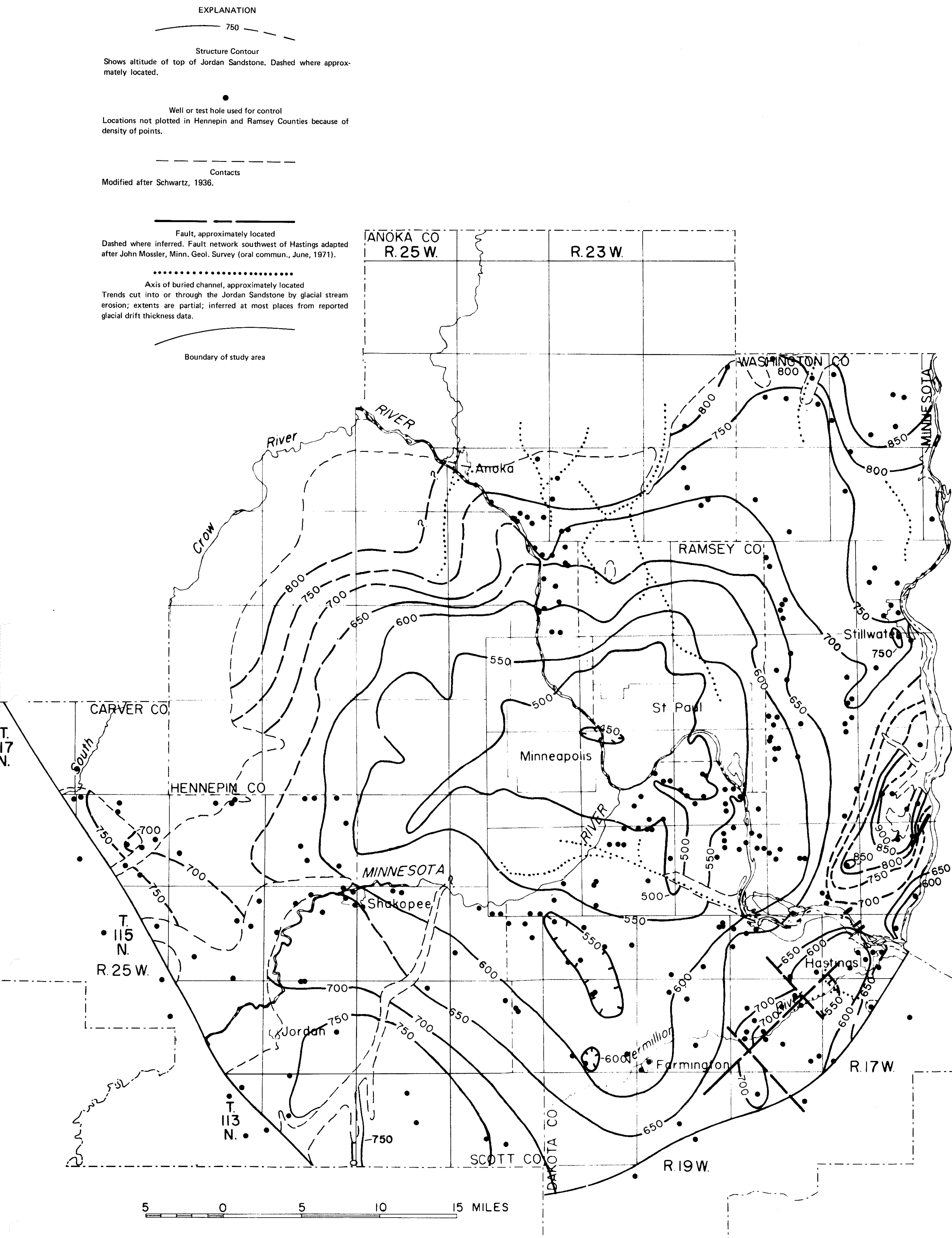



Figure 14. — Structure contours at the top of the Jordan Sandstone in the Metropolitan Area.

EXPLANATION

90 ?

Line of equal thickness of Jordan Sandstone
Dashed where approximately located, queried where doubtful.

●

Well or test hole used for control
Locations not plotted in Hennepin and Ramsey Counties because of density of points.

Contact
Modified after Schwartz, 1936.

Fault, approximately located
Dashed where inferred. Fault network southwest of Hastings adapted after John Mossler, Minn. Geol. Survey (oral commun., June,1971).

Axis of buried channel, approximately located
Trends cut into Jordan Sandstone by glacial stream erosion, extents are partial; locations inferred at most places from reported drift thickness data. Thickness of the Jordan aquifer in the vicinity of the axes may be less than shown.

Boundary of study area

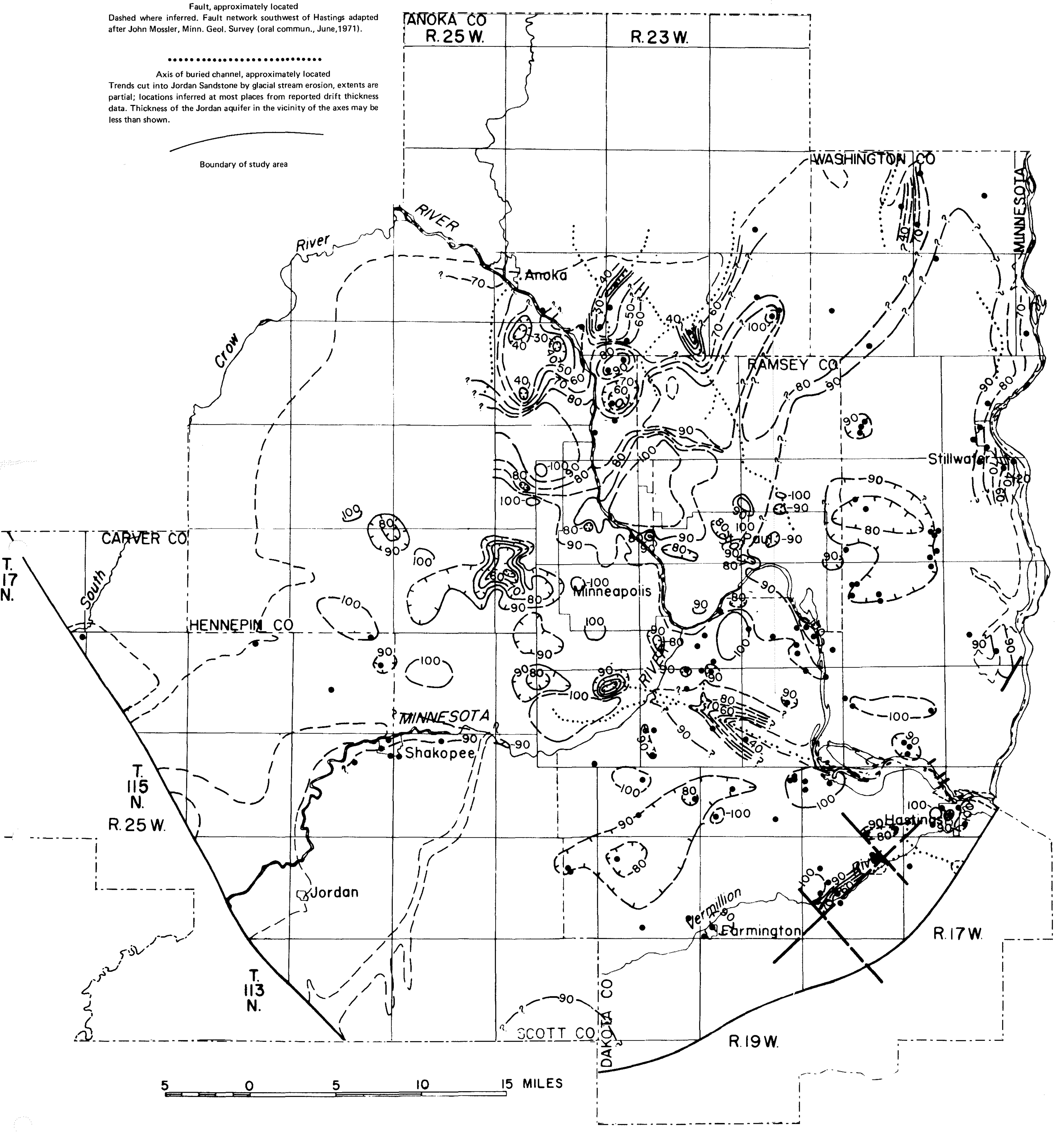



Figure 15. — Thickness of the Jordan Sandstone in the Metropolitan Area.

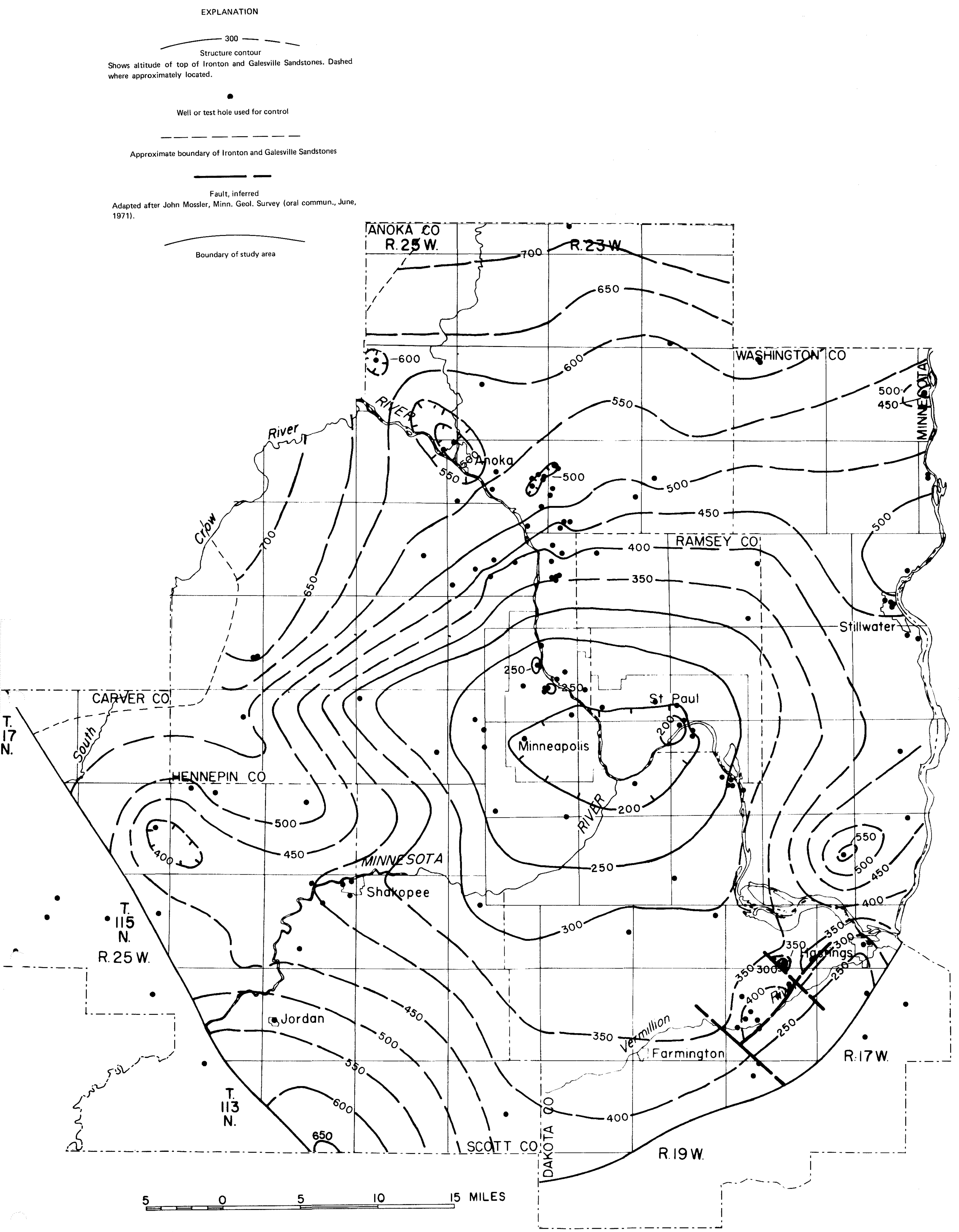



Figure 16. — Structure contours at the top of the Ironton and Galesville Sandstones in the Metropolitan Area.

EXPLANATION

60 — ? —

Line of equal thickness of Ironton and Galesville Sandstones
Dashed where approximately located, queried where doubtful.

Well or test hole used for control

Approximate boundary of Ironton and Galesville Sandstones

Fault, inferred
Adapted after John Mossler, Minn. Geol. Survey (oral commun., June, 1971).

Boundary of study area

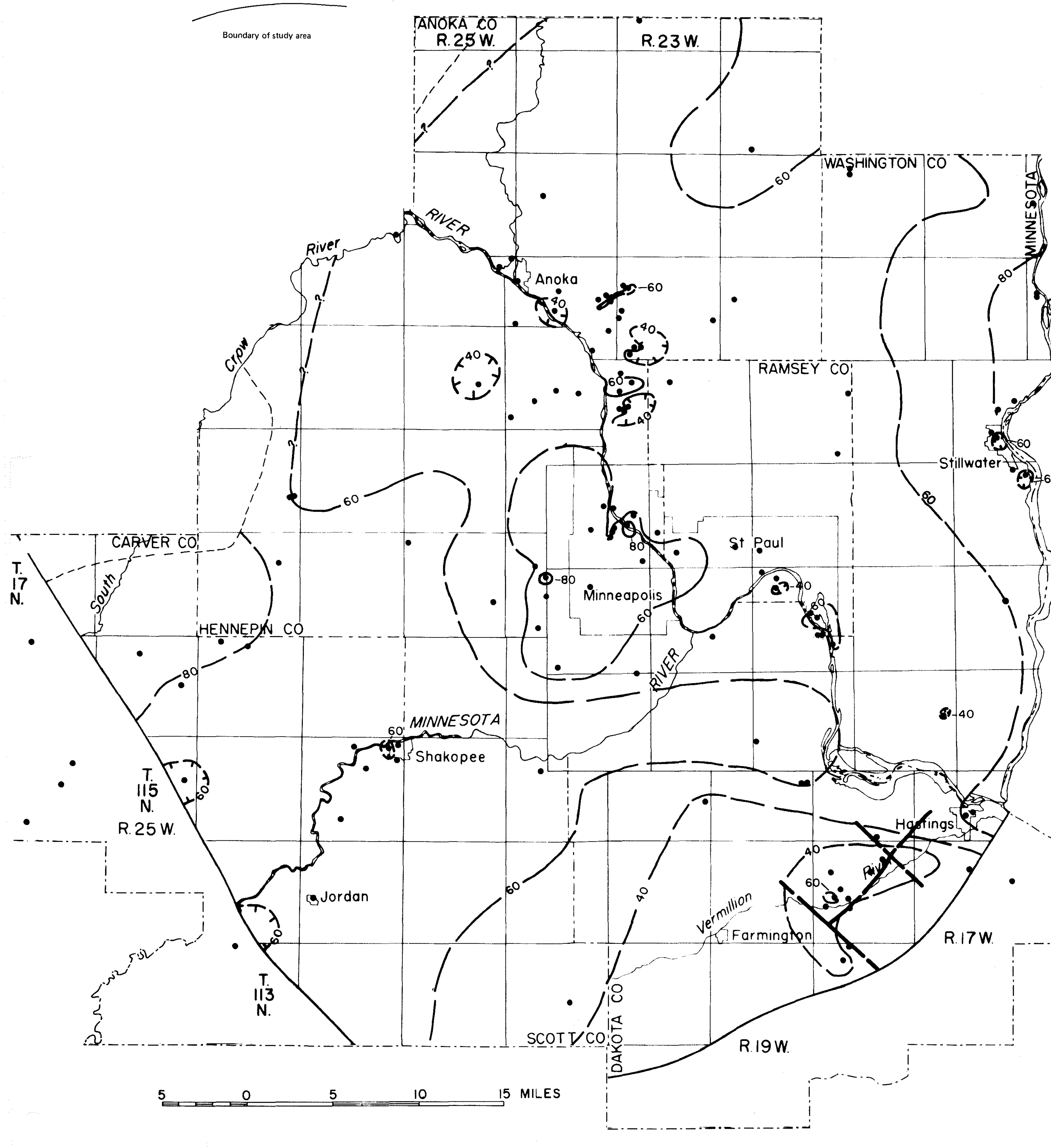



Figure 17. — Thickness of the Ironton-Galesville aquifer in the Metropolitan Area.

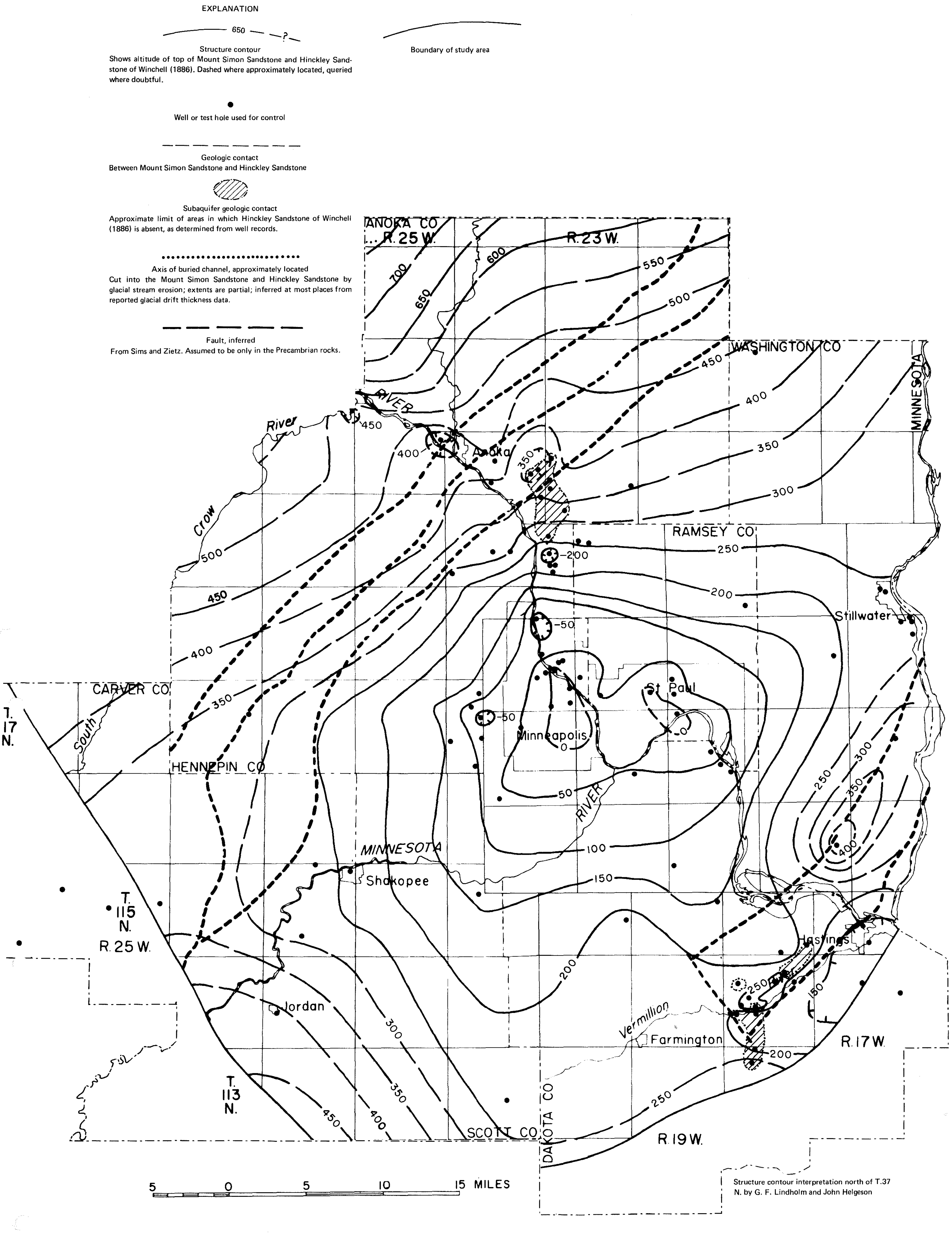



Figure 18. — Structure contours at the top of the Mount Simon Sandstone and Hinckley Sandstone in the Metropolitan Area.

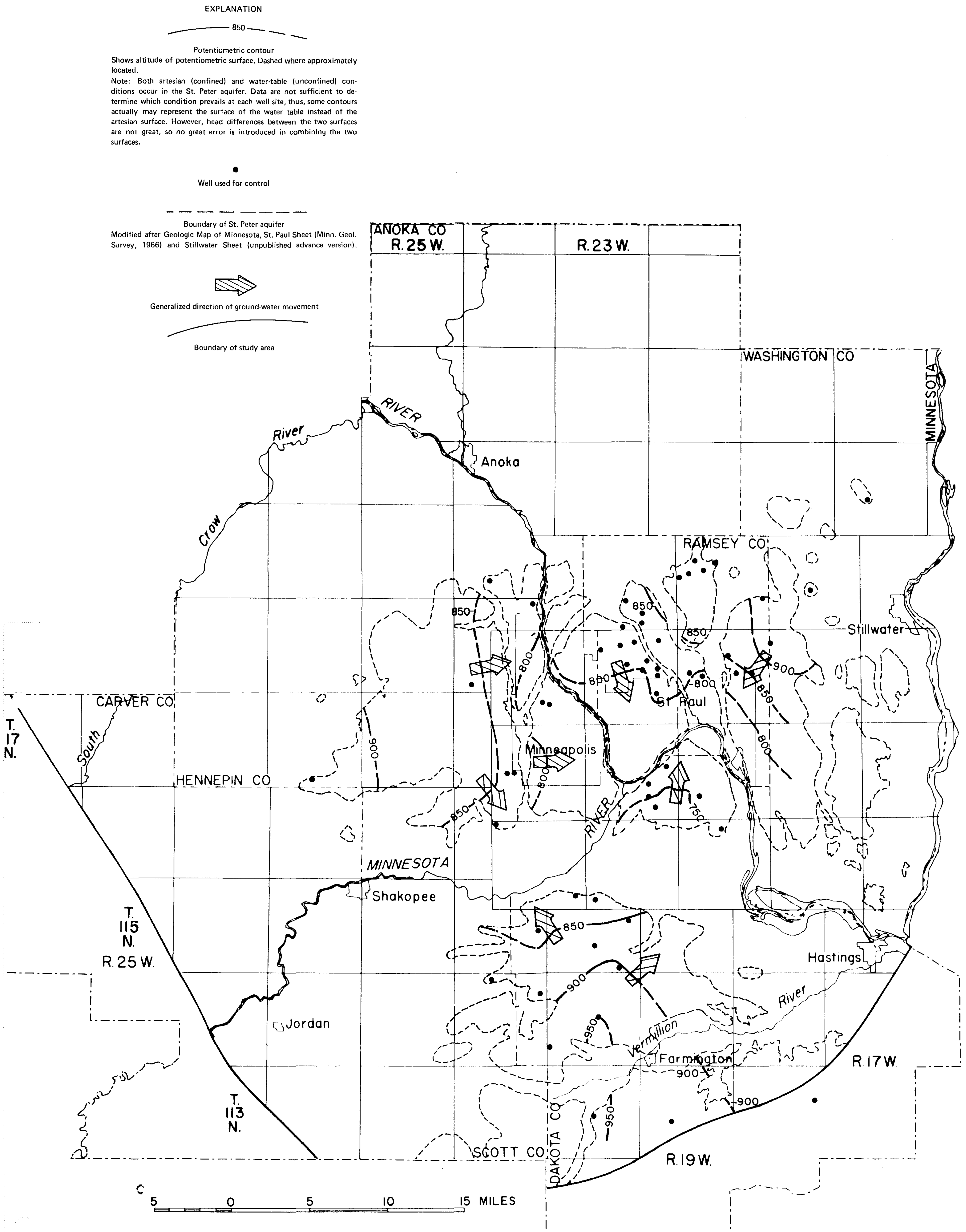



Figure 19. — Potentiometric surface of water in the St. Peter aquifer in Winter 1970-71 in the Metropolitan Area.

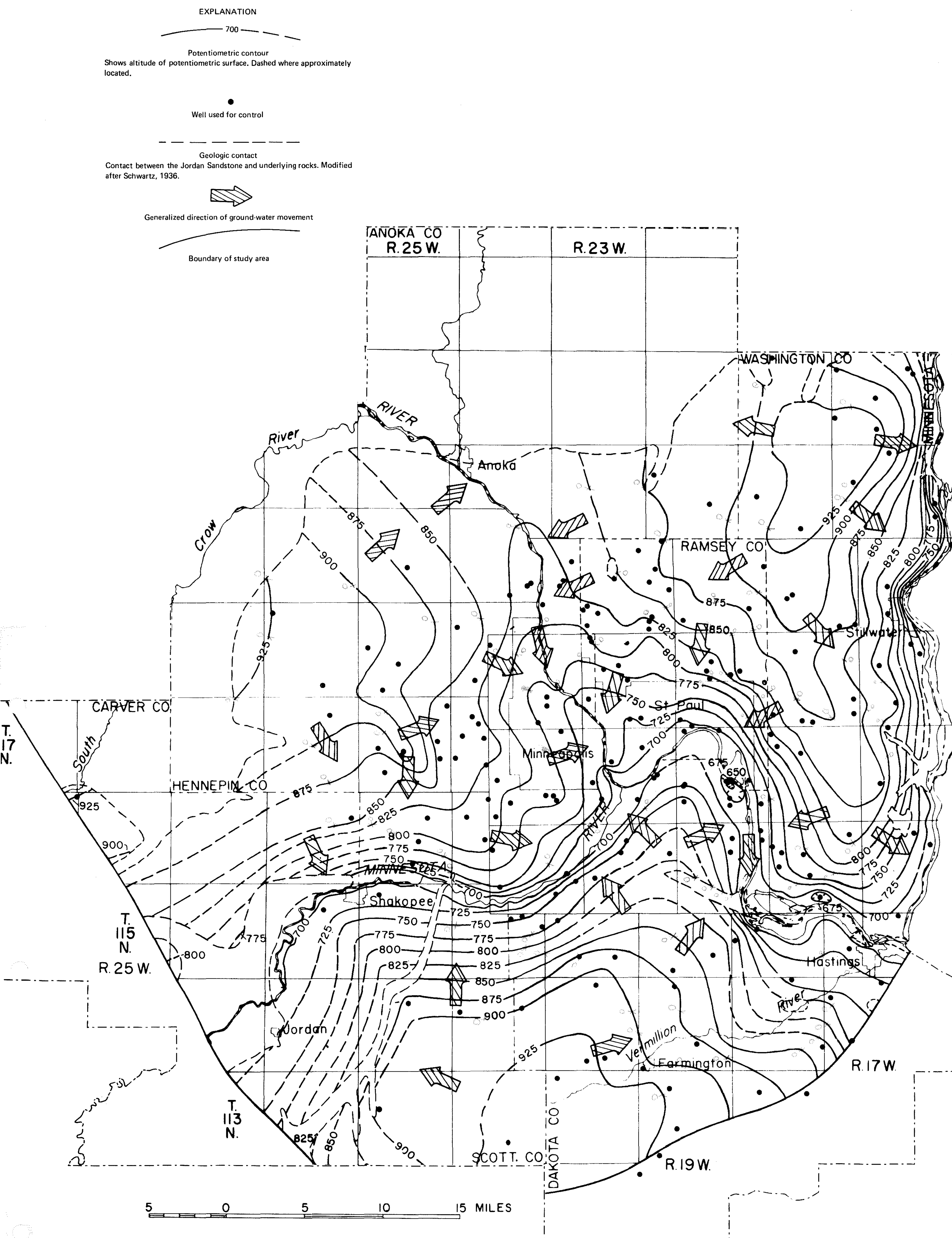



Figure 20. — Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in Winter 1970-71 in the Metropolitan Area.

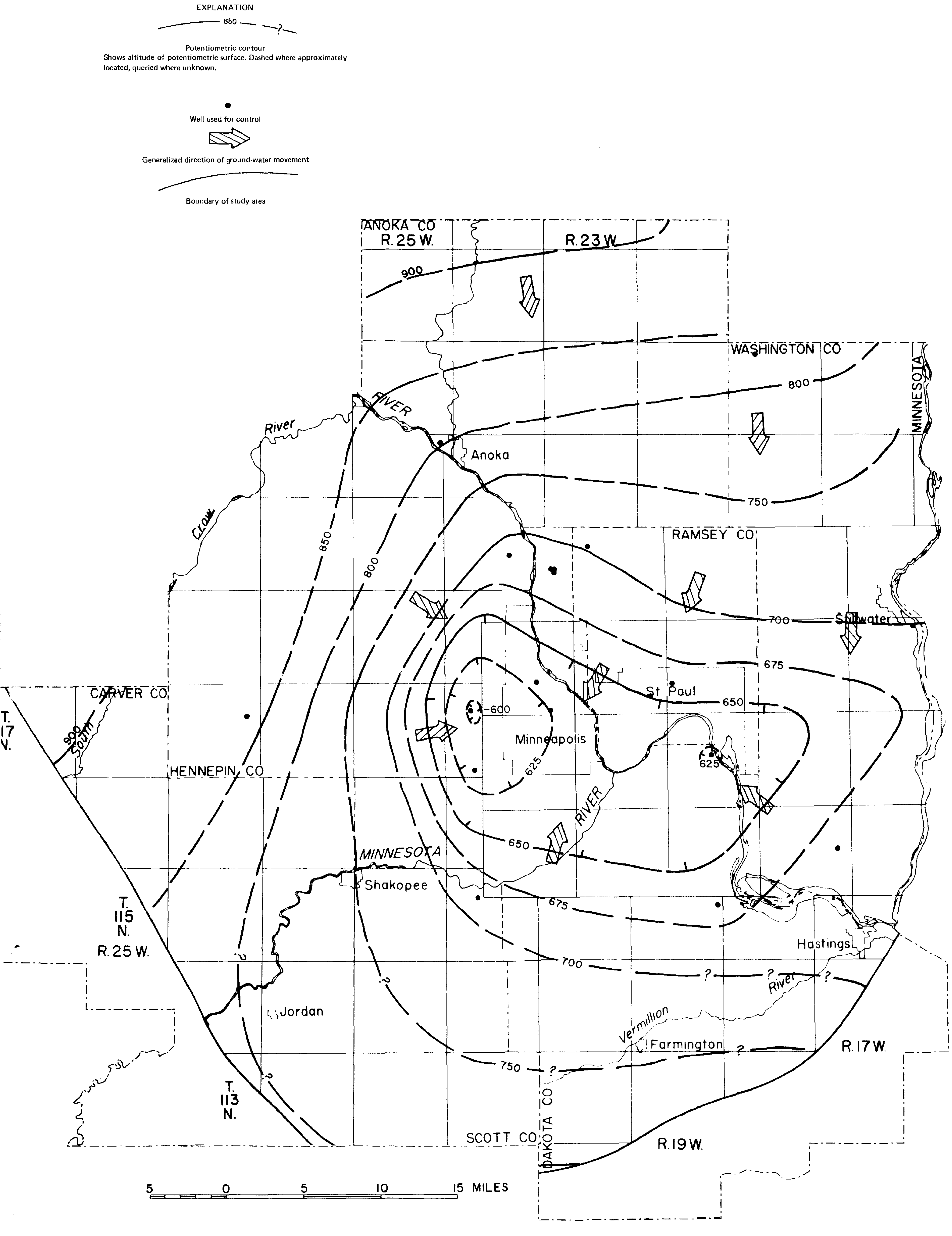



Figure 21. — Potentiometric surface of water in the Mount Simon-Hinckley aquifer in Winter 1970-71 in the Metropolitan Area.

# CHAPTER FOUR: STATUS OF DATA COLLECTION

Sites of recurring hydrologic and climatologic data collection within and near the study area are shown on the map in Figure 3. Names, types of record collected, period of record, and quality-of-water data available for each surface-water gaging station are listed in Table 3. Fourteen continuous-record gaging stations are presently in operation within the study area. Two of these stations, St. Croix River at St. Croix Falls and Apple River near Somerset, Wisconsin, are maintained by the Geological Survey in cooperation with various State and other Federal agencies in Wisconsin. The remaining 12 continuous-record, the 46 low-flow partial record, and 3 miscellaneous-record stations are operated by the Geological Survey in cooperation with the Minnesota Department of Natural Resources. The primary purposes for continuous-record stations are for water management and for planning and design, in addition to streamflow correlation. The low-flow partial-record stations are part of a Statewide program to define the low-flow characteristics of streams. Ten miscellaneous-record stations were maintained in cooperation with the Metropolitan Council to gather information on streamflow characteristics in the metropolitan area. Data on discharge measurements for all the stations listed in Table 3 are published. The earlier data (1892 – September 1950) are contained in Water-Supply Paper 1308 (U.S. Geological Survey, 1959). Subsequent records are contained in Water-Supply Paper 1728 and 1914 (U.S. Geological Survey, 1964 and 1971, respectively) and in a series of annual reports of the U.S. Geological Survey, since 1965, titled Water Resources Data for Minnesota (or Water Resources Data for Wisconsin for the two stations in Wisconsin).

Fifty-six observation wells are presently measured in the entire study area shown in Figure 3. Forty eight of these are in the metropolitan area. Six of the wells are equipped with continuous water-level recorders, and water levels in the others are measured periodically, either weekly, monthly, or semiannually. Twenty-five of these wells monitor water levels in the glacial drift, 3 in the St. Peter, 20 in the Prairie du Chien-Jordan, 1 in the Ironton-Galesville, 3 in the Mount Simon-Hinckley, and 4 in multiaquifers.

The observation-well program is in a general state of flux. Wells are usually chosen for monitoring either as a part of an ongoing cooperative ground-water network program between the Geological Survey and the Minnesota Department of Natural Resources or as a part of special projects. Data collection terminates at the close of the projects, and the records obtained are of relatively short duration. The present budget allowed ($33,910 for fiscal year 1972) for the State is not enough to maintain a growing observation-well program. When the monitoring network was established, the availability of an unused well suitable for measurement sometimes governed the selection of a collection site more than the need for information concerning the aquifer being monitored. As time passed, some of the earlier wells in the network were dropped, as better wells completed in more important aquifers became available. However, as the use of ground water increases and monitoring of water levels becomes more critical, the budget for the network program remains little changed. Periodic evaluation and revision of the program would help to insure its effectiveness as a warning system against critical water-level declines.

Hydrographs of some selected wells included in the ground-water network are shown in Figure 22. Hydrographs of past records of other wells in the study area and in other parts of the State are included in Straka and Schneider (1957), Straka and Miller (1963), and Miller and Straka (1969).

Thousands of well records were collected and compiled as a part of this study. Most were obtained from files of the Minnesota Department of Natural Resources and the Geological Survey. Municipalities were visited, and records of their wells were obtained. Where part of the municipal records were missing, additional data were obtained from consulting firms. Some additional data were obtained from well-drilling companies.

The validity of some, but not all, of the reported well locations was checked in the field. The Survey locates wells to the nearest 10-acre tract. Some of the

Table 3. – Continuous-record, low-flow partial-record and miscellaneous gaging stations in the study area

| Station number | Station name | Type of record | Period of record (water years) | Water quality data available |
|---|---|---|---|---|
| | UPPER MISSISSIPPI RIVER BASIN | | | |
| | Mississippi River: | | | |
| | ELK RIVER BASIN | | | |
| | Elk River: | | | |
| 05274480 | Snake River near Big Lake, Minn. | L | 1969 | C |
| 05274500 | Elk River above St. Francis River near Big Lake, Minn. | C | 1929-30* | |
| 05274800 | Battle Brook near Zimmerman, Minn. | M | 1962, 1964-69 | |
| 05274900 | St. Francis River near Big Lake, Minn. | C | 1965-70* | A |
| 05275000 | Elk River near Big Lake, Minn. | C | 1911-17*, 1931-* | A |
| 05275500 | Mississippi River at Elk River, Minn. | C | 1915-57* | |
| | CROW RIVER BASIN | | | |
| | Crow River: | | | |
| 05278340 | North Fork Crow River near Delano, Minn. | L | 1969- | A, C |
| 05279000 | South Fork Crow River near Mayer, Minn. | C | 1934-* | A |
| 05279500 | South Fork Crow River near Rockford, Minn. | C | 1909-12* | |
| 05280000 | Crow River at Rockford, Minn. | C | 1906-* | A, B, S |
| 05283500 | Mississippi River at Anoka, Minn. | C | 1897-1914* | |
| | RUM RIVER BASIN | | | |
| | Rum River: | | | |
| 05284710 | West Branch Rum River at Princeton, Minn. | L | 1961, 1965, 1968- | A, C |
| 05284750 | Rum River at Spencer Brook, Minn. | C | 1960-64* | |
| 05284810 | Green Lake Brook at West Point, Minn. | L | 1965, 1968- | |
| 05284950 | Stanchfield Creek at Springvale, Minn. | L | 1965, 1968- | A, C |
| 05284970 | Lower Stanchfield Creek near Grandy, Minn. | L | 1969 | C |
| 05285000 | Rum River at Cambridge, Minn. | C, M | 1909-14*, 1965, 1969 | A, C |
| 05285300 | Long Lake outlet near Isanti, Minn. | L | 1965, 1969 | C |
| 05285800 | Seeley Creek near St. Francis, Minn. | L | 1965, 1969- | A, C |
| 05286000 | Rum River near St. Francis, Minn. | C | 1929-* | A, C |
| 05286300 | Cedar Creek near Anoka, Minn. | L | 1965, 1968- | A, C |
| 05286500 | Rum River near Anoka, Minn. | C | 1905-06*, 1909-10* | |
| 05286800 | Trout Brook near Nowthen, Minn. | L | 1965, 1969- | A, C |

Table 3. – Continuous-record, low-flow partial-record and miscellaneous gaging station in the study area. – Continued

| Station number | Station name | Type of record | Period of record (water years) | Water quality Data available |
|---|---|---|---|---|
| | Mississippi River – Continued | | | |
| | ELM CREEK BASIN | | | |
| 05287900 | Elm Creek near Champlin, Minn. * | M | 1969- | C |
| | COON CREEK BASIN | | | |
| 05288490 | Coon Creek at Coon Rapids, Minn. * | M | 1956, 1969- | C |
| 05288500 | Mississippi River near Anoka, Minn. | C | 1931-* | A |
| | RICE CREEK BASIN | | | |
| 05288600 | Rice Creek at Fridley, Minn.* | M | 1969- | |
| | SHINGLE CREEK BASIN | | | |
| 05288700 | Shingle Creek at Brooklyn Center, Minn. * | M | 1969- | C |
| | BASSETT CREEK BASIN | | | |
| 05289200 | Bassett Creek at Fruen Mill, at Minneapolis, Minn. | M | 1952, 1954-55, 1963 | |
| | MINNEHAHA CREEK BASIN | | | |
| 05289500 | Minnehaha Creek at Minnetonka Mills, Minn. | C | 1953-64* | |
| | MINNESOTA RIVER BASIN | | | |
| | Minnesota River: | | | |
| 05329900 | Bevens Creek at East Union, Minn. | L | 1969- | A, C |
| 05330000 | Minnesota River near Jordan, Minn. | C | 1935- | A |
| 05330650 | Carver Creek near Carver, Minn. * | M | 1969 | C |
| 05330700 | Chaska Creek at Chaska, Minn. | L | 1967 | C |
| 05330750 | Riley Creek at Eden Prairie, Minn. * | M | 1969 | |
| 05330800 | Purgatory Creek at Eden Prairie, Minn. * | M | 1968- | C |
| 05330900 | Nine Mile Creek at Bloomington, Minn. | C | 1963-* | |
| 05331000 | Mississippi River at St. Paul, Minn. | C | 1892-* | A, T |
| | ST. CROIX RIVER BASIN | | | |
| | St. Croix River: | | | |
| 05335500 | Clam River near Webster, Wis. | C | 1941-42 | A |
| 05336240 | Kettle River near Sturgeon Lake, Minn. | L | 1965-69 | A |
| 05336320 | Moose River at Sturgeon Lake, Minn. | L | 1965-69 | A |
| 05336380 | Willow River at Willow River, Minn. | L | 1943, 1947, 1950, 1967 | A |
| 05336480 | Pine River at Rutledge, Minn. | L | 1967 | |

Table 3. – Continuous-record, low-flow partial-record and miscellaneous gaging stations in the study area. -- Continued

| Station number | Station name | Type of record | Period of record (water years) | Water quality data available |
|---|---|---|---|---|
| | Mississippi River – Continued | | | |
| | ST. CROIX RIVER BASIN – Continued | | | |
| | St. Croix River – Continued | | | |
| 05336500 | Kettle River near Sandstone, Minn. | C | 1909-17* | |
| 05336700 | Kettle River below Sandstone, Minn. | C | 1968- | A |
| | Grindstone River: | | | |
| 05336900 | North Branch Grindstone River near Hinckley, Minn. | L | 1967, 1970 | |
| 05336990 | South Branch Grindstone River near Hinckley, Minn. | L | 1967, 1970 | |
| 05337010 | Grindstone River near Hinckley, Minn. | L | 1967, 1970 | |
| 05337200 | Snake River near Warman, Minn. | L | 1967, 1969- | C |
| 05337220 | Snowshoe Brook near Warman, Minn. | L | 1967, 1970 | |
| 05337400 | Knife River near Mora, Minn. | L | 1966- | A |
| 05337500 | Snake River at Mora, Minn. | C, L | 1909-13*, 1966-69 | A, C |
| 05337550 | Ann River near Mora, Minn. | L | 1967, 1970 | |
| 05337600 | Groundhouse River near Ogilvie, Minn. | L | 1967, 1969- | C |
| 05337650 | South Fork Groundhouse River near Ogilvie, Minn. | L | 1967, 1969- | C |
| 05337700 | Groundhouse River at Brunswick, Minn. | L | 1966- | A, C |
| 05337790 | Mud Creek at Quamba, Minn. | L | 1967, 1970 | |
| 05337900 | Snake River at Grasston, Minn. | L | 1967, 1969- | C |
| 05338500 | Snake River near Pine City, Minn. | C | 1913-17*, 1951-* | A |
| | Wood River: | | | |
| 05338950 | North Fork Wood River near Grantsburg, Wis. | L | 1964, 1967 | |
| 05339000 | Wood River near Grantsburg, Wis. | C | 1939-40* | |
| 0039490 | Rock Creek near Rush City, Minn. | L | 1967-69 | A |
| 05339500 | St. Croix River near Rush City, Minn. | C | 1923-60* | |
| 05339720 | Rush Creek near Rush City, Minn. | L | 1967-69 | A |
| 05339750 | Goose Creek near Harris, Minn. | L | 1967, 1969 | C |
| 05339800 | Sunrise River near Wyoming, Minn. | L | 1967, 1969- | C |
| 05339950 | West Branch Sunrise River at Stacy, Minn. | L | 1967, 1969- | C |
| 05340000 | Sunrise River near Stacy, Minn. | C | 1949-1965* | |

Table 3. – Continuous-record, low-flow partial-record and miscellaneous gaging stations in the study area. – Continued

| Station number | Station name | Type of record | Period of record (water years) | Water quality data available |
|---|---|---|---|---|
| | Mississippi River – Continued | | | |
| | ST. CROIX RIVER BASIN – Continued | | | |
| | St. Croix River – Continued | | | |
| 05340050 | Sunrise River near Lindstrom, Minn. | C | 1965-* | A |
| 05340060 | Sunrise River tributary near Lindstrom, Minn. | L | 1969 | C |
| | North Branch Sunrise River: | | | |
| 05340100 | North Branch Sunrise River tributary near Weber, Minn. | L | 1969- | |
| 05340110 | North Branch Sunrise River near Weber, Minn. | L | 1969- | A, C |
| 05340130 | North Branch Sunrise River at North Branch, Minn. | L | 1969 | C |
| 05340170 | North Branch Sunrise River near North Branch, Minn. | L | 1967- | C |
| 05340400 | Wolf Creek near St. Croix Falls, Wis. | L | 1964, 1967 | |
| 05340500 | St. Croix River at St. Croix Falls, Wis. | C | 1902-* | A, C |
| 05340550 | Lawrence Creek at Franconia, Minn. | L | 1969- | C |
| | Apple River: | | | |
| | Cedar Creek: | | | |
| 05341450 | Horse Creek near Star Prairie, Wis. | L | 1963-64, 1966-67 | |
| 05341500 | Apple River near Somerset, Wis. | C | 1901-* | A |
| 05341550 | Browns Creek at Stillwater, Minn. | L | 1969 | C |
| 05341780 | Valley Branch at Afton, Minn. * | M | 1967, 1969- | C |
| 05341790 | St. Croix River tributary at Afton, Minn. | L | 1969 | C |
| 05341810 | Trout Brook near Afton, Minn. | L | 1969 | C |
| 05342000 | Kinnickinnic River near River Falls, Wis. | C | 1917-21 | A |
| 05344500 | Mississippi River at Prescott, Wis. | C | 1928-* | A |
| | VERMILLION RIVER BASIN | | | |
| 05345000 | Vermillion River near Empire City, Minn. * | C, M | 1942-45*, 1969- | C |
| 05345500 | Vermillion River at Empire City, Minn. | C | 1942-44* | |
| 05346000 | Vermillion River at Hastings, Minn. * | C, M | 1935-38, 1940-41, 1942-47*, 1949, 1952, 1965- | A, C |

Table 3. – Continuous-record, low-flow partial-record and miscellaneous gaging stations in the study area. – Continued

**Type of record**

C – Continuous record gaging station
L – Low-flow partial-record station
M – Miscellaneous measurement station

**Period of record** means water years discharges published, or, years measurements made at partial-record and miscellaneous measurement sites.

* – Indicates some water years incomplete at continuous-record gaging stations
† – When dual symbols (C, L, or C, M or vice versa) are used, indicates period of operation as continuous record station

**Quality of water data**

A – Chemical analysis(es) available
B – Particle size analysis(es) of bed material available
C – Specific conductances(s) available (other than in A)
S – Suspended sediment measurement(s) available
T – Daily maximum and minimum temperatures available

Figure 22. – Long-term hydrographs of selected wells in the Metropolitan Area.

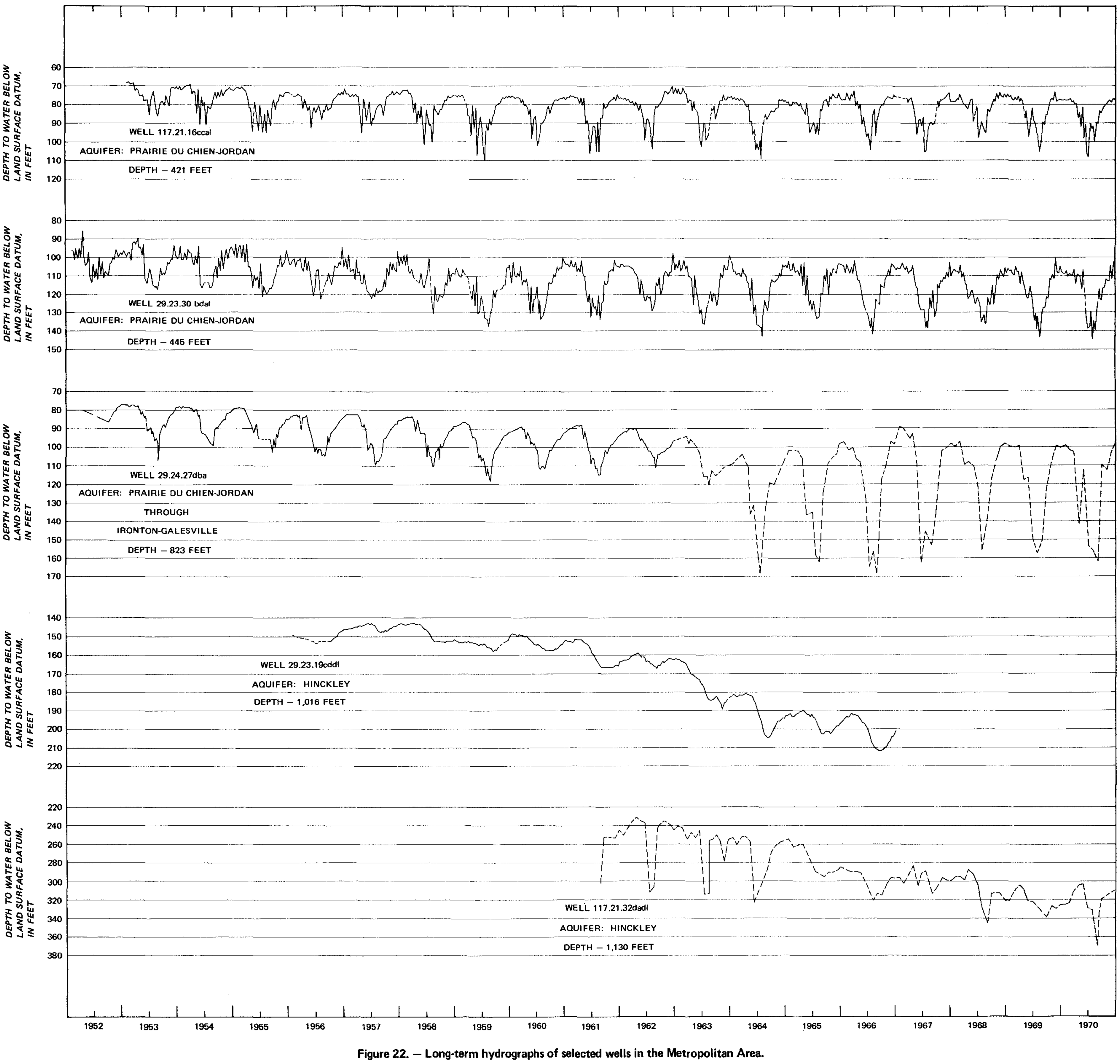



**Figure 22. — Long-term hydrographs of selected wells in the Metropolitan Area.**

wells were found to be mislocated, and location numbers were corrected. Several of the wells could not be found from the reported locations. Thus precise location (within 10 acres) of all wells cannot be expected. The well-record-collection phase was, in essence, finished as of June 1970. However, water-level data were collected as late as August 1971. Mass water-level measurements were made in about a 2-week period in 404 wells for the purpose of drawing potentiometric-surface maps (Figures 19-21) and evaluating water-level changes. Twenty-six wells were completed in the glacial drift, 87 in the St. Peter, 192 in the Prairie du Chien-Jordan, 6 in the Ironton-Galesville, 46 in the Mount Simon-Hinckley, and 47 in multiaquifers. These records are on file for future evaluations of water-level changes.

New wells are being drilled at a fairly rapid rate in the metropolitan area, but new records are not being compiled or coded for storage and retrieval by ADP (automatic data processing). Coding was done for many of the records collected in this study, as explained under a following section.

## WELL-NUMBERING SYSTEM

The system of numbering wells (and test holes) is based on the U.S. Bureau of Land Management's system of subdivision of the public lands. The report area is in the fourth- and fifth-principal-meridian and base-line system. The first segment of a well number indicates the township north of the base line; the second, the range west of the principal meridian; and the third, the section in which the well is situated. The lowercase letters a, b, c, and d, following the section number, indicate the location within the section. The first letter denotes the 160-acre tract, the second the 40-acre tract, and the third the 10-acre tract. The letters are assigned in a counterclockwise direction, beginning in the northeast quarter. Within one 10-acre tract, consecutive numbers, beginning with one, are added as suffixes.

Figure 23, part a, illustrates the method of numbering a well. Thus, the number 33.22.8ddbl identifies the first well located in the NW1/4SE1/4SE1/4 sec. 8, T.33 N., R.22 W.

The Mississippi River is the dividing line between the 4th and 5th principal meridians except for a block of townships extending west of the river in the Twin Cities area. The displacement of the dividing line away from the river boundary is shown in Figure 23, part b. Ranges north of the dividing line are read along the top of the map; ranges south of the line are read along the bottom of the map. The townships are read to the right and left sides of the map, respectively.

## AUTOMATIC DATA PROCESSING (ADP)

### Records of Wells

The Geological Survey adopted a punch-card system for storage, retrieval, and facilitation of statistical analysis of ground-water data in 1967. The cards use the latitude-longitude system of locating and coding wells, which is usable nationwide and which is adaptable for worldwide application. Instructions for using this system are presented in a report by Lang and Leonard (1967).

As a part of this study, 3,159 well records were punched and coded on cards, so that the ADP system could be used. These wells, in about 1,000 square miles of the metropolitan area, are within Anoka, Dakota, Hennepin, Ramsey, and Washington Counties. Records were not punched and coded for the entire study area. Computer print-out sheets were obtained for the records. The sheet headings list the following information, where available, for each well record:

location (lat., long.)
local well number
driller (name)
ownership (type of)
water use
well use
log available (type of)
well depth
casing depth
casing diameter
well finish
method drilled

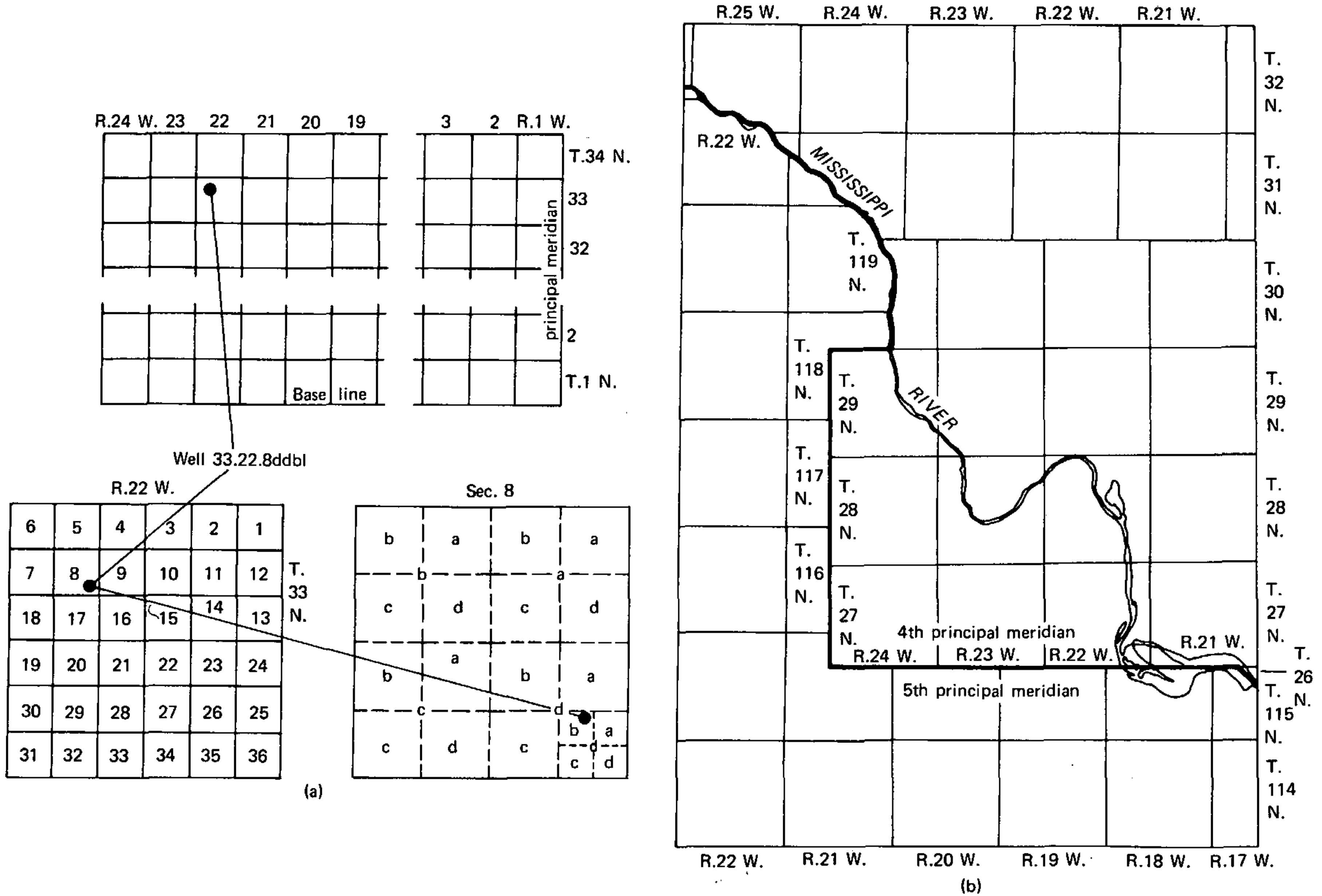



**Figure 23. — Well-numbering system.**

date drilled
type lift (pump)
power
altitude of land surface datum
water level
water level/date measured
yield
drawdown
temperature
drainage basin

Digital-computer manipulation of the data includes well information for each county and total number of wells and total wells with yields reported for each of the following headings:

all wells
wells privately owned
wells owned by industry
wells owned by government
wells used for air conditioning
wells used for municipal supply
wells used for industrial supply
wells used for domestic supply
wells finished in sandstone
wells finished in dolomite and limestone
wells finished in drift

By obtaining reliable well information and by keeping well records current, the ADP program offers rapid tabulation of well information and evaluation of water use and water-resource data in the urban and suburban areas, where wells are too numerous for slower methods.

### Well Logs

The Minnesota Geological Survey maintains a central file of geologic information for the State and presently has coded and entered on punch cards lithologic data for more than 3,000 wells in and around the metropolitan area. The coding system and digital-computer program for this system was adapted for use in Minnesota from a program developed by J. M. McNellis and C. O. Morgan (1967). Instructions for using the Minnesota system are given in a report by John Mossler and others (1971).

Computer printouts of the well and lithologic data entered in the system are now available. The printout headings include the following well information, where it is available:

well-location number
county
well number (unique)
latitude, longitude
latitude, longitude accuracy
owner
date drilled
method of drilling
surface elevation
well depth
well-bottom elevation
elevation accuracy
cased depth
casing-bottom elevation
well finish (sand point, screen, etc.)
depth of well below casing (open hole)
logs available
open-interval midpoint elevation

The lithologic-log data of the strata penetrated included with the above well information comes under the following headings:

geologic name
lithologic description
thickness
depth
water level (if reported)

Various programs can be written to retrieve different parts of the stored well-log data. For example, it would be possible to obtain printouts for only those wells that tap the Prairie du Chien-Jordan aquifer and to obtain altitudes of the top of and thicknesses of that aquifer. Similar data could be retrieved for any other lithologic unit in the geologic section underlying the metropolitan area. This capability was not available for making the structure-contour and thickness maps (Figures 8, 10-18) included in this report; therefore, the needed data was obtained by scanning each well log. Now, the task would take only a fraction of the time. Any revisions or additional mapping of bedrock units in the future will be greatly facilitated through use of the ADP program.

## THE WATER BUDGET

The water budget defines the total amount of water available to an area. In essence, it shows that over a long period of time and under natural conditions inflow (precipitation, stream and ground water inflow) is equal to outflow (evapotranspiration, stream discharge and ground water outflow). In most places the budget is in balance, but in highly urbanized areas, where man's use of water can exceed natural inflow, the water budget may come into balance only through a long-term reduction of water in natural storage or a long-term reduction in natural outflow. The result might be a critical lowering of local ground-water levels on the one hand or a reduction of the base flow of streams and drying up of swampy areas on the other.

In its simplest form, the basic water budget under equilibrium conditions states that total inflow equals total outflow. In a more expanded form, the budget equation is:

$$P - ET + I - \phi \pm \Delta S = 0 \text{ (zero)}$$

where P equals precipitation, ET equals evapotranspiration, I equals stream inflow, $\phi$ equals stream discharge and $\Delta S$ equals a change in surface-and ground-water storage. The plus (+) items in the equation are inflow and the minus (-) items are outflow.

### Gross Water Budget

Although the boundaries of the total study area (Figure 1) do not define a closed hydrologic system, the average annual water budget during 1935-69 can be approximated. Three assumptions are made in order to compute the budget: 1) water storage remains constant and underflow into and out of the area is in balance; 2) data used to compute average annual precipitation by the Thiessen method are representative for 1935-69; and 3) evapotranspiration, as derived from energy data gathered by Blad and Baker (1971) at St. Paul, is representative for the whole area and for the long term.

The period 1935-69 was chosen for computation for the following reasons: 1) streamflow records at the gaging station on the Minnesota River near Jordan (Figure 3 – 05330000), a major inflow site, began in October 1934; 2) 1935 marks the end of a major drought and, consequently, a return to more normal climatic conditions; and 3) streamflow records at two major gaging stations, Mississippi River at St. Paul (05331000) and St. Croix River at St. Croix Falls, Wisconsin (05340500), show that average annual discharge for their entire periods of record through 1969 are exceeded by their average annual discharges for 1935-69 by only 8.5 and 12.5 percent, respectively. Because the complete records include periods of excessive precipitation as well as part of the prolonged drought, the 1935-69 period is assumed to be representative.

Given values for the average annual precipitation (28.3 inches over entire study area) and the average annual evapotranspiration (22.5 inches) and assuming no change in storage or underflow, then streamflow is the only other item that needs to be considered. Streams cross the boundary of the study area at about 60 places. Most inflows and outflows at these places cancel each other or are considered negligible because of the total quantity of water involved. Of the significant remaining items, 21 are inflows and 6 outflows. Flow at three stream stations account for 87.9 percent of the inflow. They are Mississippi River at Elk River (05275500), St. Croix River near Rush City (05339500), and Minnesota River near Jordan (05330000) (see Figure 3). Stream-correlation techniques were used on records from the first two stations above to fill out the missing record for the 1935-69 period. The gaging station, Mississippi River at Prescott, Wisconsin (05344500), accounts for 92.6 percent of the outflow. Of the remaining inflows and outflows, 12.1 and 7.4 percent of total flows, respectively, some are at, or near, continuous-record or low-flow partial-record gaging stations (Table 3), and others are estimated from miscellaneous measurements at or near the points needed, or on nearby streams.

The average annual water budget, assuming no change in storage and stated in cubic feet per second is then:

$$12{,}977(P)-10{,}033(ET)+15{,}455(I)-18{,}399(\phi)=0$$

Thus, the yield, 2944 cts of runoff, of the study area is equivalent to 6.43 inches spread over the entire 6,200 square miles which is about 1,900 mgd.

The budget was balanced by adjusting the ET value, probably the least certain of the four parameters in the equation. As previously stated, the ET for the growing season was estimated at 22.5 inches, but, in order to balance the equation, ET was changed to 21.87 inches, a reduction of only 3 percent.

The unit yield of the study area is 0.47 cfsm (2,944 cfs/6,200 sq. mi.) which is higher than most of the unit yields for 1935-69 of some of the drainage basins that are in part of and surrounding the study area, as listed in Table 4.

Table 4.—Unit yield of selected drainage basins

| Gaging station | Unit yield, cfsm |
|---|---|
| Mississippi River at Elk River, Minn. (05275500) | 0.43 |
| Minnesota River near Jordan, Minn. (05330000) | .21 |
| Mississippi River at St. Paul, Minn. (05331000) | .29 |
| St. Croix River near Rush City, Minn. (05339500) | .79 |
| Mississippi River at Prescott, Wis. (05344500) | .38 |

One plausible reason for part of the apparently high yield is caused by the Twin Cities artesian basin, which occupies the southern one-third of the area. Here ground water collects from surrounding areas and discharges, as base flow, to the major streams. As a result the underflow into the study area may be greater than the underflow out of the area. Another reason is the high-yielding characteristics of the St. Croix basin, which makes a sizeable contribution to streamflow in the study area. Also the study area is not a closed system which may lead to small errors in the water balance computations.

The surface-water budget for that part of the metropolitan area underlain by the Prairie du Chien-Jordan aquifer is approximated below. Further definition of this budget is attempted by separating yield, represented by stream outflow, into its component parts, base flow and overland runoff. When this is done, the naturally sustained potential availability of ground water in the metropolitan area can be estimated. It should be understood that the results obtained are only approximations of the volumes of water flowing through the system because the part of the system analyzed is not a closed basin. The same is true of the budget determination for the entire area of study.

**Surface-Water Budget**

The Twin Cities area, for the purposes of this budget analysis, includes about 2,330 square miles within the metropolitan area and is larger than but roughly overlies the subsurface extent of the Prairie du Chien-Jordan aquifer (2,000 sq. mi.) within the major area of study. Five gaging stations account for 97.4 percent of the inflow in this area: Mississippi River at Elk River (05275500), Crow River at Rockford (0528000), Rum River near St. Francis (05286000), Minnesota River near Jordan (05330000), and St. Croix River at St. Croix Falls, Wisconsin (05340500). The gaging station, Mississippi River at Prescott, Wisconsin (05344500), accounts for 99.6 percent of the outflow.

The inflow-outflow balance, in cubic feet per second, is computed as:

17,109(ϕ)-15,784(I)=1,325

This represents a gain in yield equal to 45 percent of the yield in the whole study area, and it occurs in just 37.6 percent of the area (2,330 sq. mi./6,200 sq. mi.). The unit yield then is 0.57 cfsm.

*Separation of Streamflow Components*

In order to analyze streamflow in the study area as a whole, especially in the Twin Cities area, an attempt was made to separate the streamflow hydrograph into its components. A brief explanation of the method used to make this separation follows.

Many methods have been devised for streamflow-component separation; most of them are complex and not easy to apply uniformly. For consistency and relative ease of computation, a graphic method developed by Kunkle (1962) is used herein. Briefly, the method involves the plotting of the daily discharge hydrograph and separating it into three components: direct surface runoff, bank-storage discharge, and basin-storage discharge. Bank- and basin-storage discharge are usually lumped and called base flow. These components of streamflow vary greatly in character due to their different derivations, and, thus, the characteristic recession curves of bank- and basin-storage discharge make these elements of total runoff the same slope for the same gaging station regardless of year or period of year, whereas, the slope of the basin-storage discharge recession curve is flat in comparison.

The Kunkle method was used on records at five stream-gaging stations: Mississippi River at Elk River, Rum River near St. Francis, Minnesota River near Jordan, St. Croix River near Rush City, and Mississippi River at Prescott, Wisconsin. St. Croix River near Rush City was used in place of St. Croix River at St. Croix Falls, Wisconsin, because flow at the latter station is regulated. The period of 1935-69 was scanned in order to select 1 year each of high, average, and low flow. The highest and lowest years were excluded from consideration in order to avoid undue bias, and care was taken to choose a year for which the preceding and following years of record were of the same character.

After the hydrographs were drawn and components separated, the percentage of each component in terms of the total runoff was determined. The number of years of high, average, and low flow were used to weight the percentages obtained, so that the average during 1935-69 could be used. The factors thus derived were applied to the gaging station records from which they were taken and also to the remaining inflow and outflow sites for which hydrograph separation was not done. Hydrogeologic characteristics were the determinant in deciding which factor to apply to the unanalyzed areas.

After direct surface runoff is removed from the Twin Cities area surface-water budget, the balance, in cubic feet per second, is:

10,529(ϕ)-9.368(I)=1,161

For comparison, a computation of the "base-flow" balance was made using the 60 percent duration point on the streamflow duration curve, which is a commonly accepted rough guide to base flow in streams. The balance here, in cubic feet per second, is:

8,381(ϕ)-7,205(I)=1,176

Although the outflow and inflow quantities above are not the same as those in the preceding computation, the net result is close and is a seeming check of the rationale of Kunkle's method.

Separating the base flow into bank storage discharge and basin-storage discharge, the basin storage discharge in cubic feet per second, becomes:

7,944(ϕ)7,042(I)=902

The same type of computations were made for the entire study area, so that the different component quantities could be compared. Table 5 summarizes the findings.

It seems that the area underlain by the Prairie du Chien-Jordan aquifer (metropolitan area) yields much more water, for its size, than the rest of the study area. As shown in the breakdown in Table 5, only a small part of the total runoff appears as direct surface runoff in this area. In fact, the Twin Cities area (38 percent of the study area) yields only about 27 percent of the direct surface runoff of the study area.

Table 5. – Differentation of streamflow gain into components

| Units | Baseflow | | | Direct surface runoff | Total flow |
|---|---|---|---|---|---|
| | Bank storage discharge | Basin storage discharge | Total | | |
| | | Entire area (6,200 sq mi) | | | |
| Inches | .89 | 4.23 | 5.12 | 1.31 | 6.43 |
| Cfs | 408 | 1,935 | 2,343 | 601 | 2,944 |
| Mgd | 280 | 1,250 | 1,530 | 370 | 1,900 |
| Cfsm | .07 | .31 | .38 | .10 | .48 |
| Mgd/sq mi | .05 | .20 | .25 | .06 | .31 |
| Percent | 13.9 | 65.7 | 79.6 | 20.4 | 100 |
| | | Twin Cities area (2,330 sq mi) | | | |
| Inches | 1.51 | 5.24 | 6.75 | .96 | 7.71 |
| Cfs | 259 | 902 | 1,161 | 164 | 1,325 |
| Mgd | 170 | 580 | 750 | 110 | 860 |
| Cfsm | .11 | .39 | .50 | .07 | .57 |
| Mgd/sq mi | .07 | .25 | .32 | .05 | .37 |
| Percent | 19.5 | 68.1 | 87.6 | 12.4 | 100 |

The direct-surface-runoff value of the Twin Cities area may be low when compared with that determined for small drainage basins within the area. This is because of a lack of bank or channel storage in the small basin compared to that in the overall basin.

*Areal Differences of Yield*

Much of the basin-storage discharge (true ground-water discharge) occurs in that part of the artesian basin east of the Twin Cities through which the St. Croix River and its tributaries flow. This is partly because the Prairie du Chien-Jordan aquifer forms the valley walls of the St. Croix River and some of its tributaries, thus contributing its ground-water discharge directly into the streams. In addition, the Ironton-Galesville and Mount Simon-Hinckley aquifers contribute base flow to the St. Croix River above the Prescott gage.

Valley Branch (drainage area, 13.0 sq. mi.), a small tributary, enters the St. Croix River at Afton. Much of the area north and northwest of the headwaters of Valley Branch is comprised of small closed depressions with no surface-water outlets, Lake Edith. Lake Edith overflows only during high spring runoff and contributes very little direct surface runoff to average yearly flows of Valley Branch. Thus, for most of the year, the stream owes its discharge to springs in the channel and valley wells. Discharge measurements made on Valley Branch on State Highway 95 in Afton (just upstream from the mouth) were correlated with daily discharges at the gaging station on Nine Mile Creek at Bloomington (05330900). The line of relation is flat (Figure 24) making small any error introduced by overestimating or underestimating the average discharge for Nine Mile Creek. From the line of relation, the average discharge for Valley Branch was determined to be 9.6 cfs. Using 9.6 cfs for the average discharge gives a runoff of 10.03 inches, or 0.74 cfsm, from the drainage area of Valley Branch, which approximates the runoff from the drainage area for the St. Croix River near Rush City. The average discharge for Nine Mile Creek (period of record Jan. 1963 to 1969) was adjusted to be representative of long-term discharge by correlation with Elk River near Big Lake (period of record 1911-17, 1935 to 1969).

Similar calculations for Bassett Creek at Fruen Mill (05289200) in Minneapolis (drainage area 41.6 sq. mi.) show a unit yield of 0.28 cfsm after adjustment for the short period of record (Figure 24). Computing the average discharge for Vermillion River at Hastings (05346000) as 68 cfs (drainage area 195 sq. mi.), the runoff is 4.73 inches, or 0.34 cfsm. Thus, it is concluded that the yield of the area northeast and east of the Twin Cities is greater than that of the area to the north, west, and south.

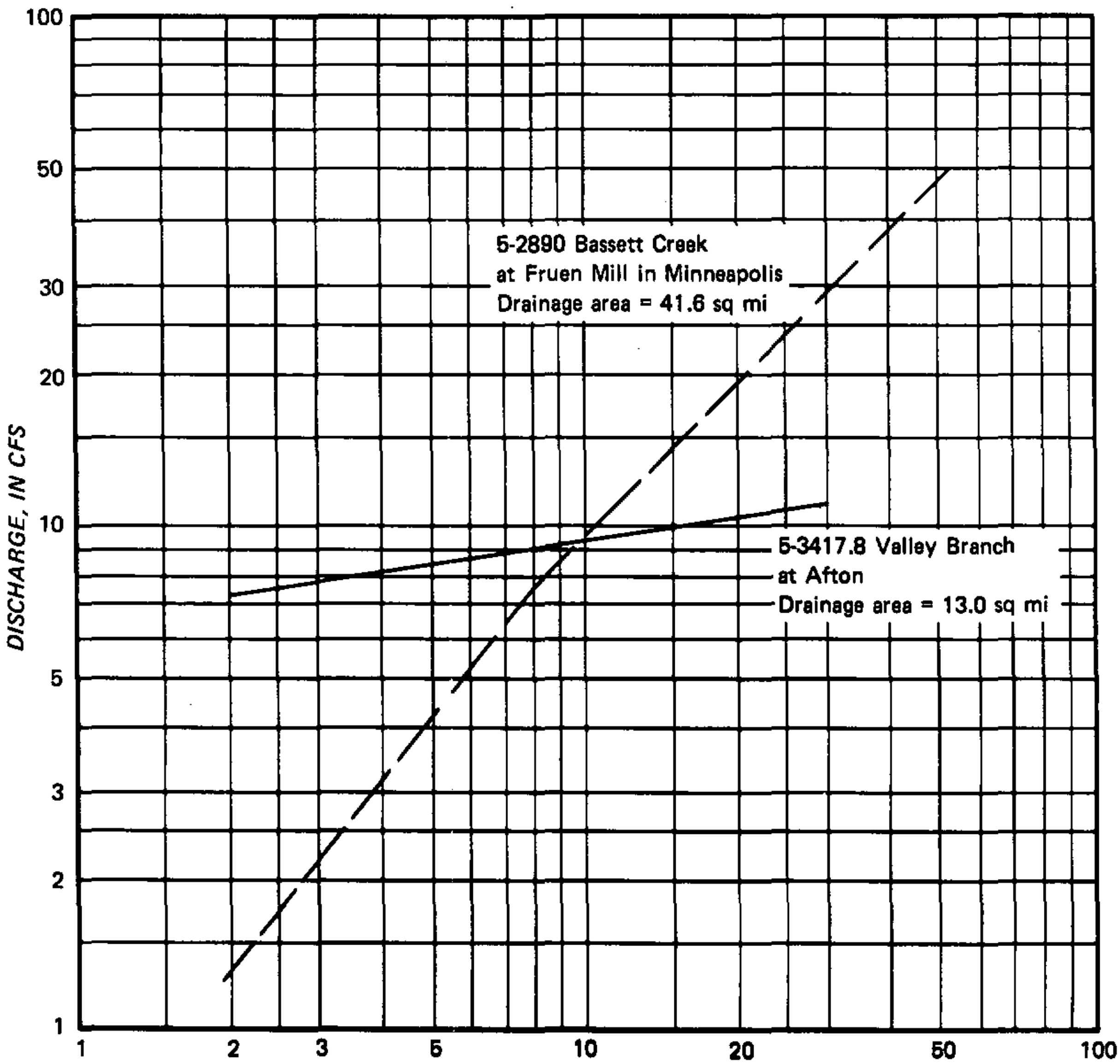



**Figure 24. — Low-flow relation for Bassett Creek and Valley Branch.**

## SURFACE WATER

The data (Table 6) from records at long-term presently gaged stations on the major streams give an overall synopsis of the large volumes of streamflow in the area.

Table 6.—Average discharge for major drainage basins

| Stream and gaging-station location | Approximate drainage area (sq mi) | Average discharge (cfs) |
|---|---|---|
| Mississippi River | | |
| near Anoka, Minn. | 19,100 | 7,156 |
| at St. Paul, Minn. | 36,800 | 10,080 |
| at Prescott, Wis. | 44,800 | 15,660 |
| Minnesota River | | |
| neat Jordan, Minn. | 16,200 | 3,336 |
| St. Croix River | | |
| at St. Croix Falls, Wis. | 5,930 | 4,098 |

The average discharges seem to indicate that, if runoff were evenly distributed, enough water would be available from surface-water sources to satisfy all uses in the Twin Cities metropolitan area. However, flows fluctuate too greatly to guarantee this.

### Seasonal Aspects of Streamflow

Although major annual runoff occurs in the spring (usually in April, sometimes in late March or early May), precipitation is greater May through August than during the rest of the year. However, runoff generally decreases from May to August owing to increased evapotranspiration. (See Figure 25.) In calendar years 1935-69 on the Mississippi River near Anoka, only 6.6 percent of the average annual runoff was produced in August, while August and September combined produced only 12.6 percent. For the same period on the Minnesota River near Jordan, only 6.1 percent of the average annual runoff occurred in August, with a combined August-September contribution of only 10.2 percent. Thus, at the time of year when water needs are great, water reserves and streamflow are at a minimum.

As shown in Figure 25, there is wide variation between the median discharge and the maximum and minimum discharges for each month. The lowest monthly median discharges are in the winter, but the lowest minimum monthly discharges are in the summer, with the exception of the Minnesota River near Jordan, where the minimum monthly discharge occurs in January. This is because of the quantity of water locked up in ice storage at all stations in January; the quantity at Jordan represents a larger percentage of the flow, thus resulting in the low minimum discharge.

The dashed line on the graph (Figure 25) for the Minnesota River near Jordan is the mean monthly flow for the Minnesota River at the mouth at Mendota (unpublished data) for the 1934 water year. It shows that, for all times except November through February, the mean monthly flows at Mendota in 1934 were lower than the minimum mean monthly flows over the long term at the Jordan gage, which is fully 40 miles upstream. This occurs despite a minimum gain of 60 cfs between Jordan and the mouth, as indicated by discharge measurements made in 1934. Here then, is afforded an insight as to the extreme effects the severe drought of the early 1930's had on streamflow and what might be expected from similar droughts in the future, when demands on water supply will be greater than now.

The data presented above indicate a cyclic character to monthly streamflow, that is, streamflow decreases from its high in April through August, increases in September, generally decreases again in October through February, and then begins to increase again in March, with the moderation in temperature. This cycle repeats itself annually – magnitudes vary, but, with the exception of relatively unusual runoff-producing conditions, the cycle persists.

### Long-Term Trends

Five-year moving averages of streamflow at major gaging sites in the area are shown in Figure 26. These averages are used to smooth out normal yearly fluctuations and to show only trends. The 5-year average is plotted in the 5th year, which means that a rising or falling trend reversal is due to the discharge of the year in which it occurs. Annual discharges in the Mississippi River at St. Paul and in the Minnesota River near Jordan seem to have reached historical highs and are now trending downward. The Mississippi River near Anoka and at Prescott, Wisconsin, and the St. Croix River at St. Croix Falls, Wisconsin, are trending downward from highs that are lower than the historical highs. The long-term cycle is irregular and unpredictable. If the magnitude and time of occurrence of lows and highs in streamflow could be predicted, one of man's major problems in water management could be solved. At present, these data can be used as an illustration of past trends in streamflow and as a rough measure of the severity of what could happen in the future. The graphs show that the system reached a historical low in the 1930's and has not come anywhere near that low since.

### Statistics of Streamflow

Although it is not possible to predict the year of occurrence of a streamflow event, it is possible to calculate its probability of occurrence by statistical methods, such as low-flow frequency and flow-duration curves. Low-flow-frequency curves relate the magnitude and frequence of annual minimum flows and provide an estimate of the probability of flow being less than a given amount in any year, whereas, the flow-duration curve shows the long-term distribution of daily flows but not the probability within individual year.

#### *Magnitude and Frequency of Low Flows*

Low-flow-frequency curves are the primary tools used to determine availibility of streamflow for man's use. Curves of this type are derived by determining the lowest average flow for periods ranging from 1 to 365 consecutive days in a given year. These data are compiled for each year of record and then analyzed to determine the frequency of various magnitudes of flow.

Low-flow curves for periods of 1, 7, 30, 60, 90, and 365 days (annual) at nine gaging stations are shown in Figures 27-35. These curves were derived from data collected through the 1967 climatic year (April 1 to March 31), which includes all complete climatic years for which daily flow data are available. Computer-derived curves (Log-Pearson) were compared with those obtained by use of the formula, $T = \frac{n + 1}{m}$ (where T = recurrence interval in years, n = number of years of record, and m = magnitude, the lowest flow value being assigned a magnitude of 1, the highest a magnitude of n). Because the two sets of differently derived curves compared favorably, those presented herein are basically the ones obtained by computer analysis, with slight modifications necessitated by the known severity of the drought of the 1930's. The number of days for each curve are consecutive, and the discharge is the average for the indicated number of days. A recurrence interval of 50 years means that the low flow will be equal to or less than the indicated value at intervals averaging 50 years, or that there is a 2 percent chance that the discharge will be less than the indicated value in any one year. The 1- through 90-day curves shown in Figure 27 for the Elk River near Big Lake are not characteristic of the rest of the low-flow-frequency curves – they are convex rather than concave. No

**Figure 25. – Maximum, median and minimum monthly discharges at five gaging stations in the study area. (Dashed line on lower part of Minnesota River near Jordan graph is monthly mean discharge for 1934 for Minnesota River at the mouth, at Mendota.)**

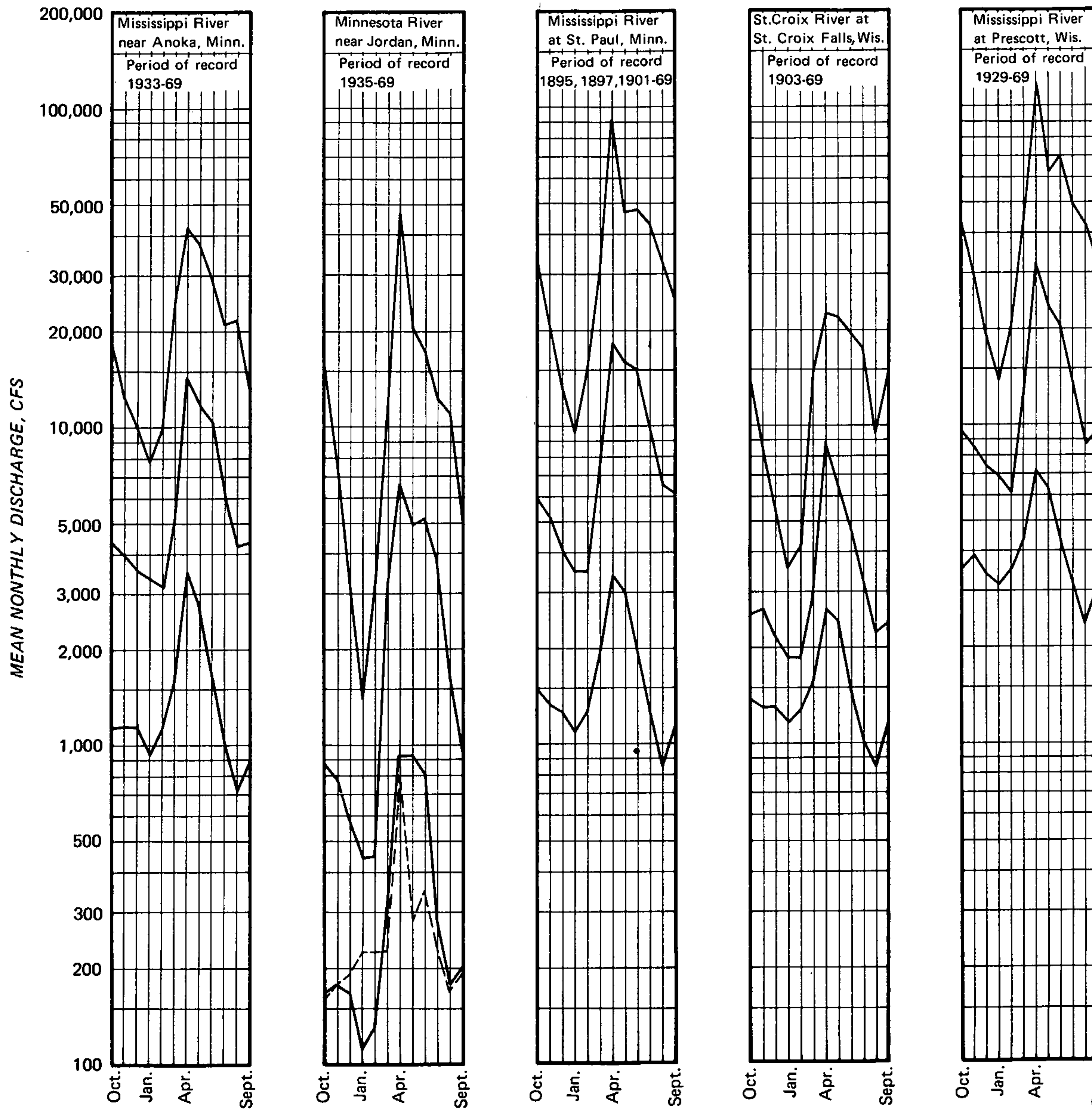



**Figure 25. — Maximum, median and minimum monthly discharges at five gaging stations in the study area. (Dashed line on lower part of Minnesota River near Jordan graph is monthly mean discharge for 1934 for Minnesota River at the mouth, at Mendota.)**

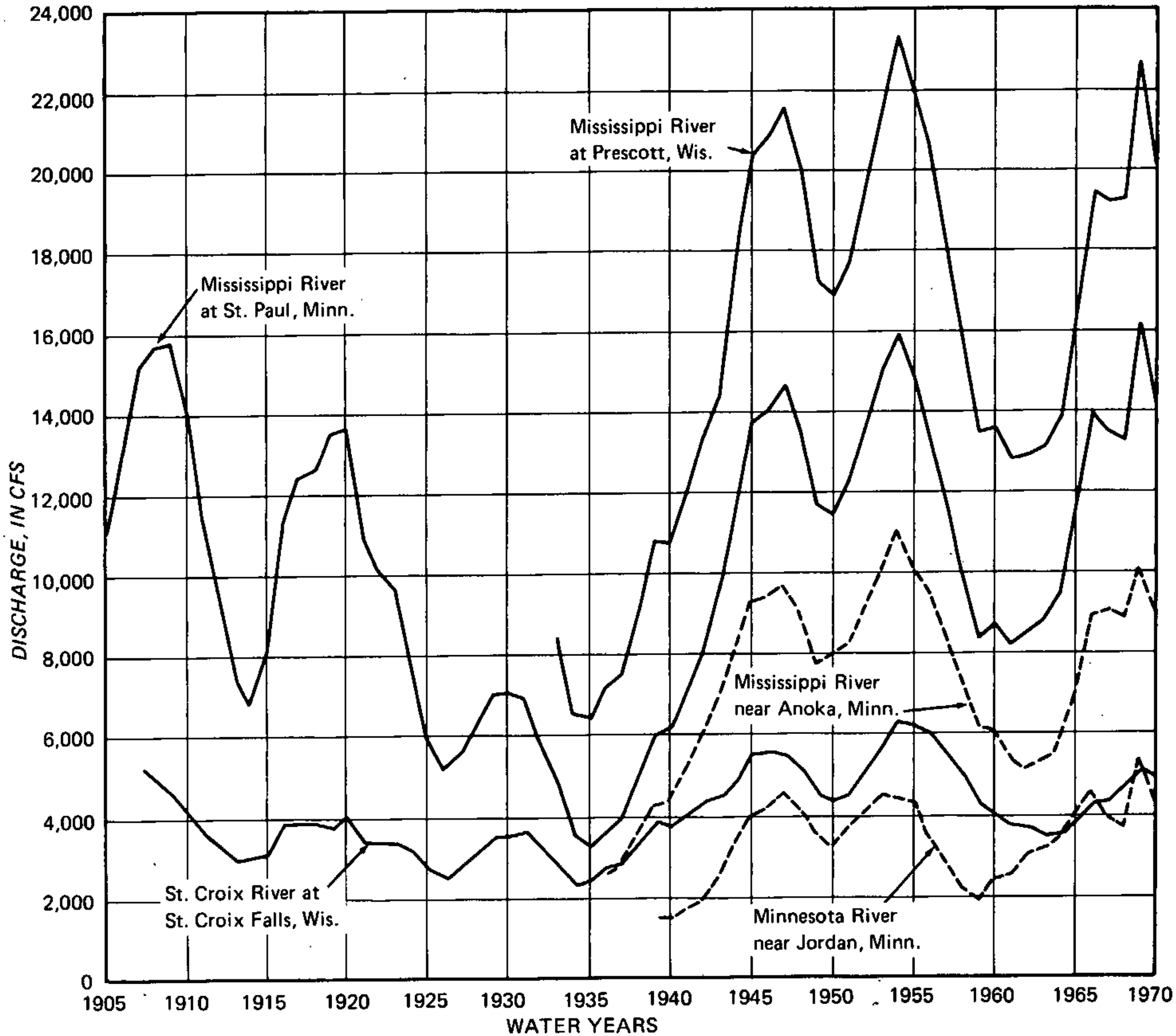



Figure 26. — Five-year moving average of annual discharge at major stream gaging stations.

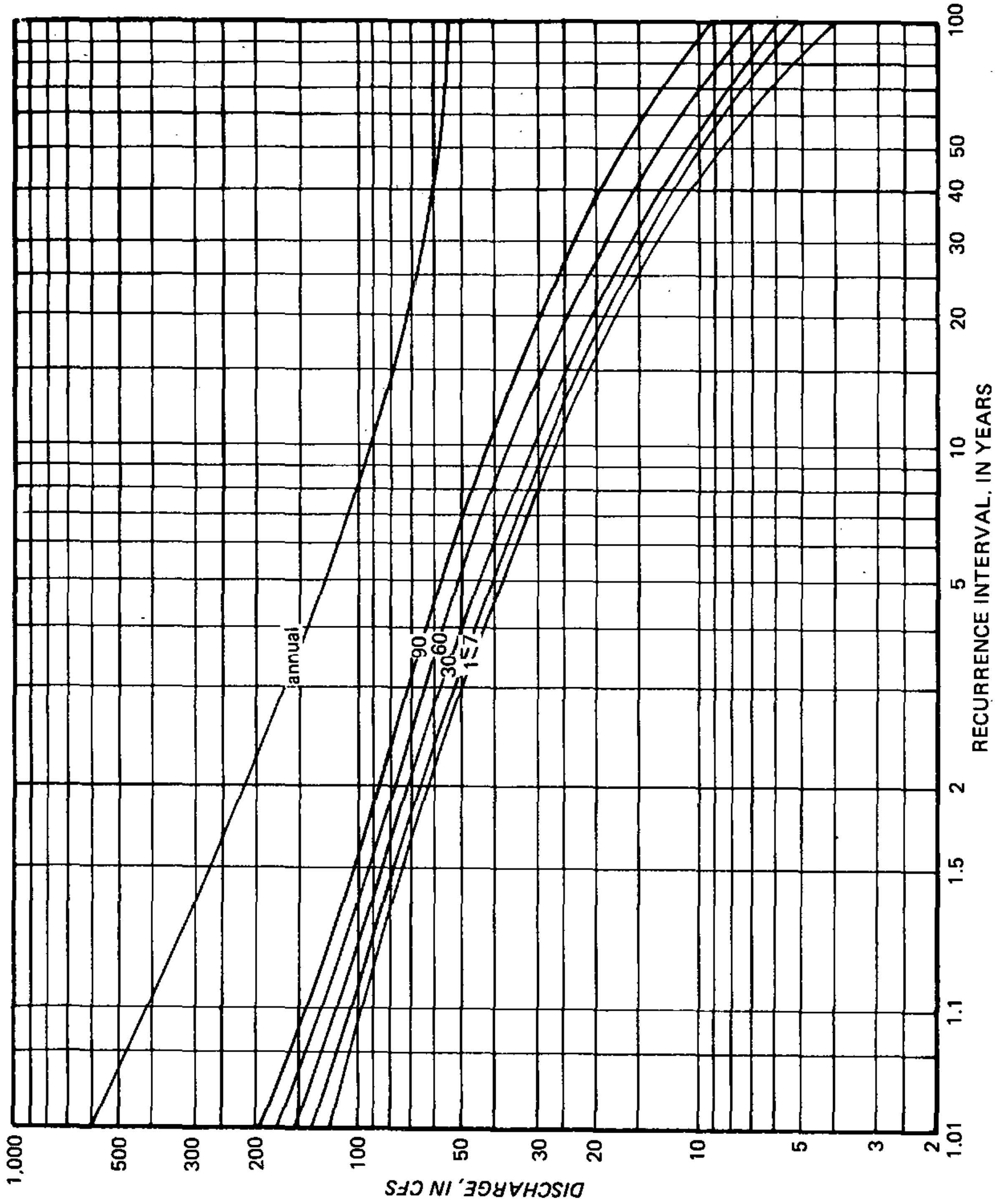



Figure 27. — Magnitude and frequency of low flows for the Elk River near Big Lake, Minn. (based on the period 1912-17, 1932-70). Station 05275000. Drainage area 615 sq mi.

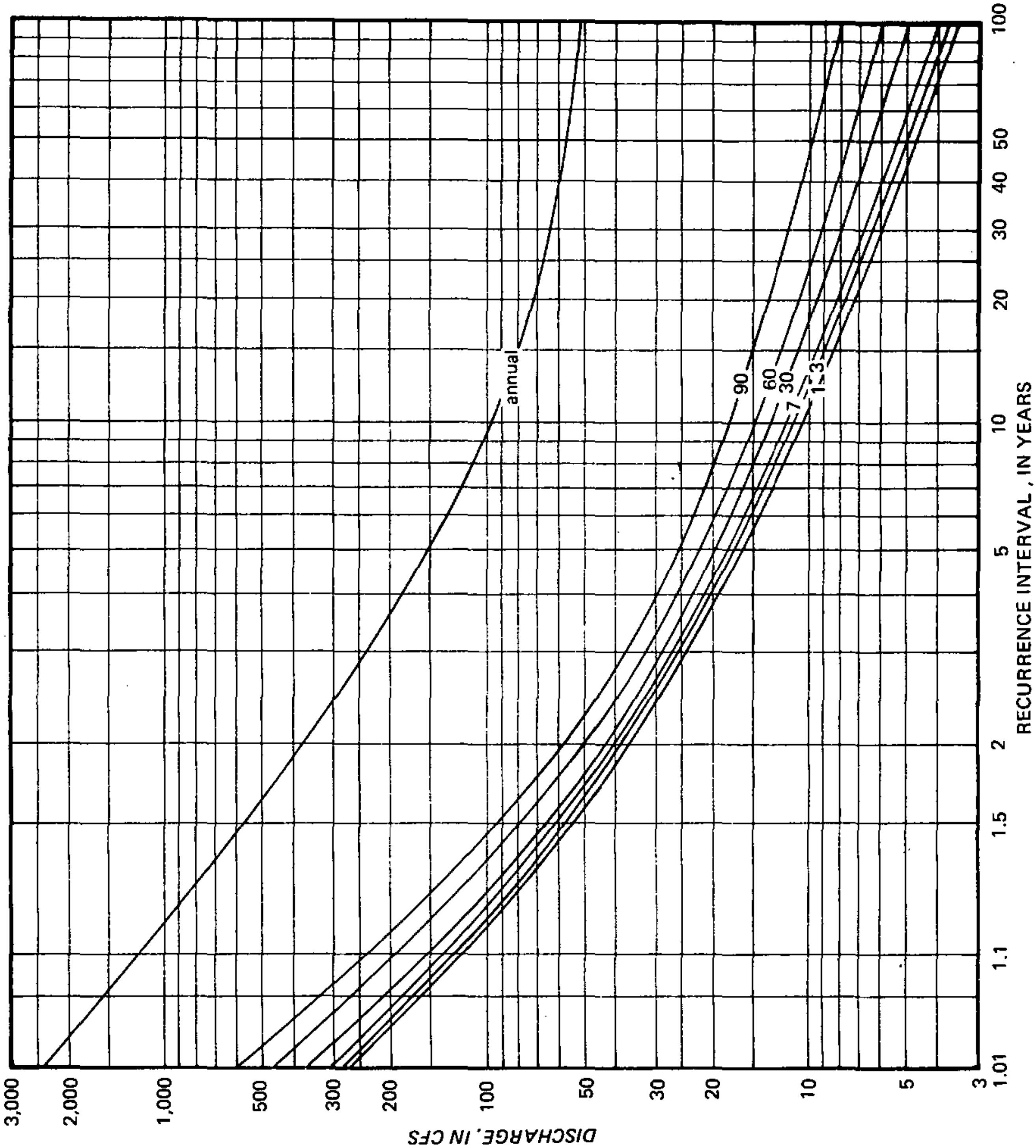



Figure 28. — Magnitude and frequency of low flows for the Crow River at Rockford, Minn. (based on the period 1910-17, 1930-70). Station drainage area.

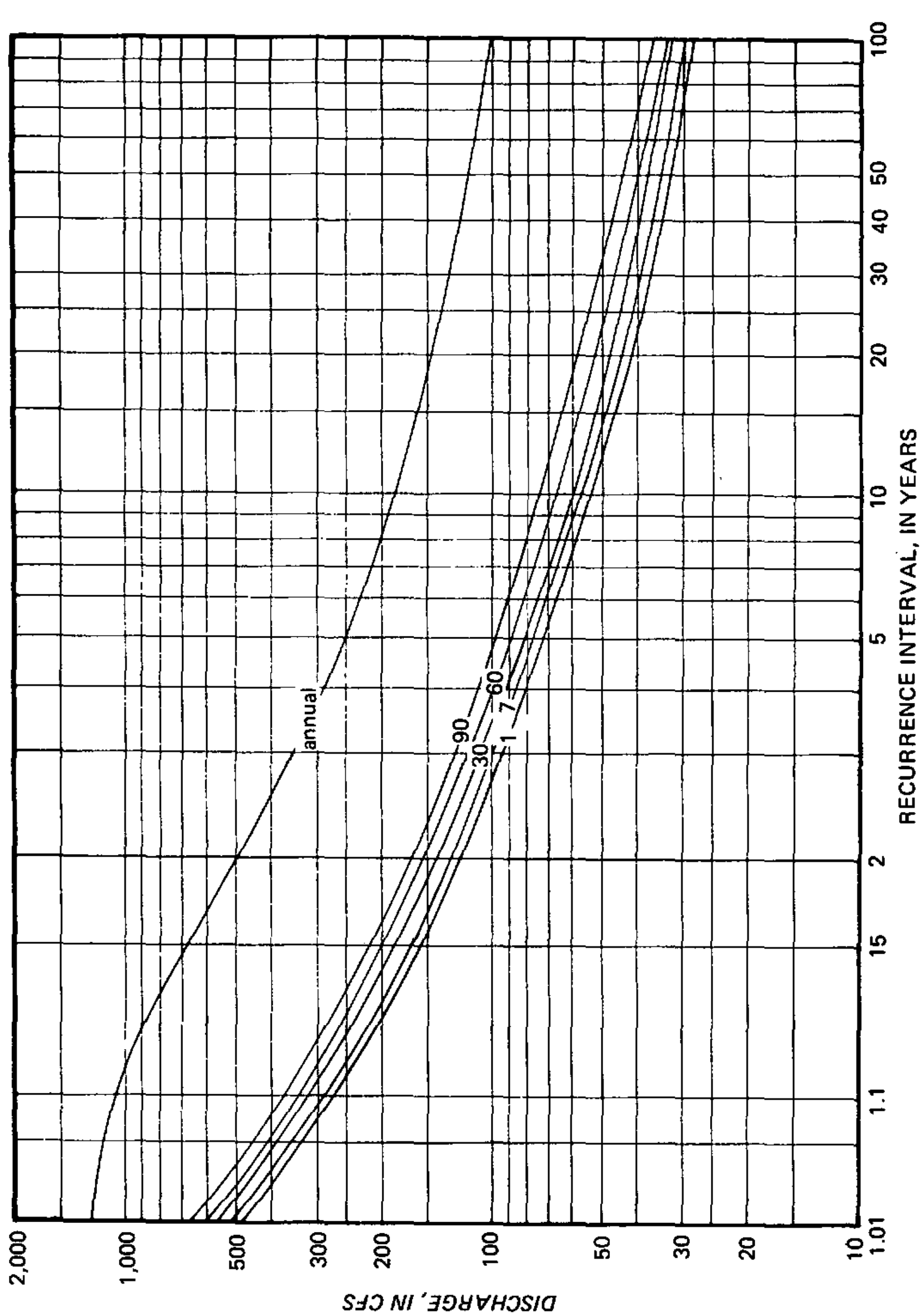



Figure 29. — Magnitude and frequency of low flows for the Rum River near St. Francis, Minn. (based on the period 1931, 1934-67). Station 05286000. Drainage area 1,360 sq mi, approximately.

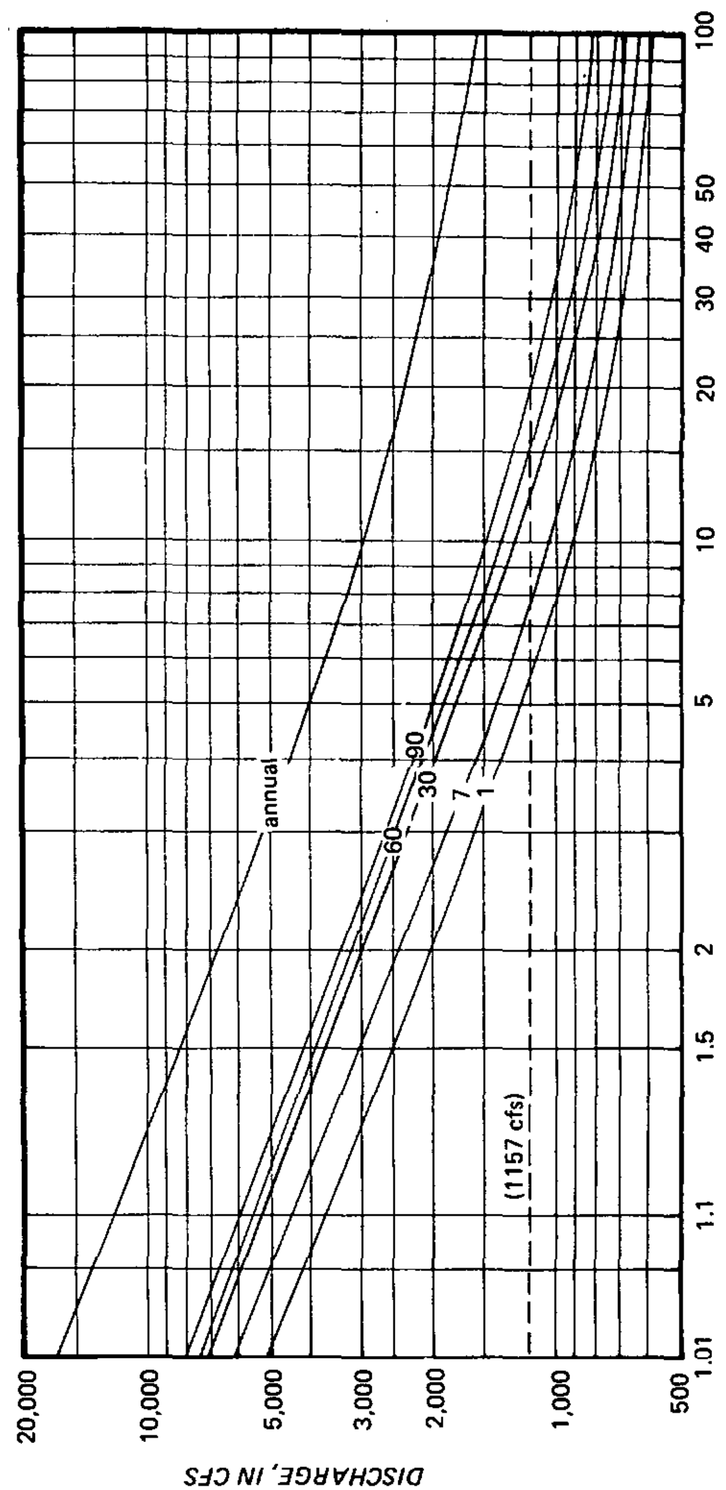



**Figure 30. — Magnitude and frequency of low flows for the Mississippi River near Anoka, Minn. (based on the period 1933-67). Station 05288500. Drainage area 19,100 sq mi, approximately.**

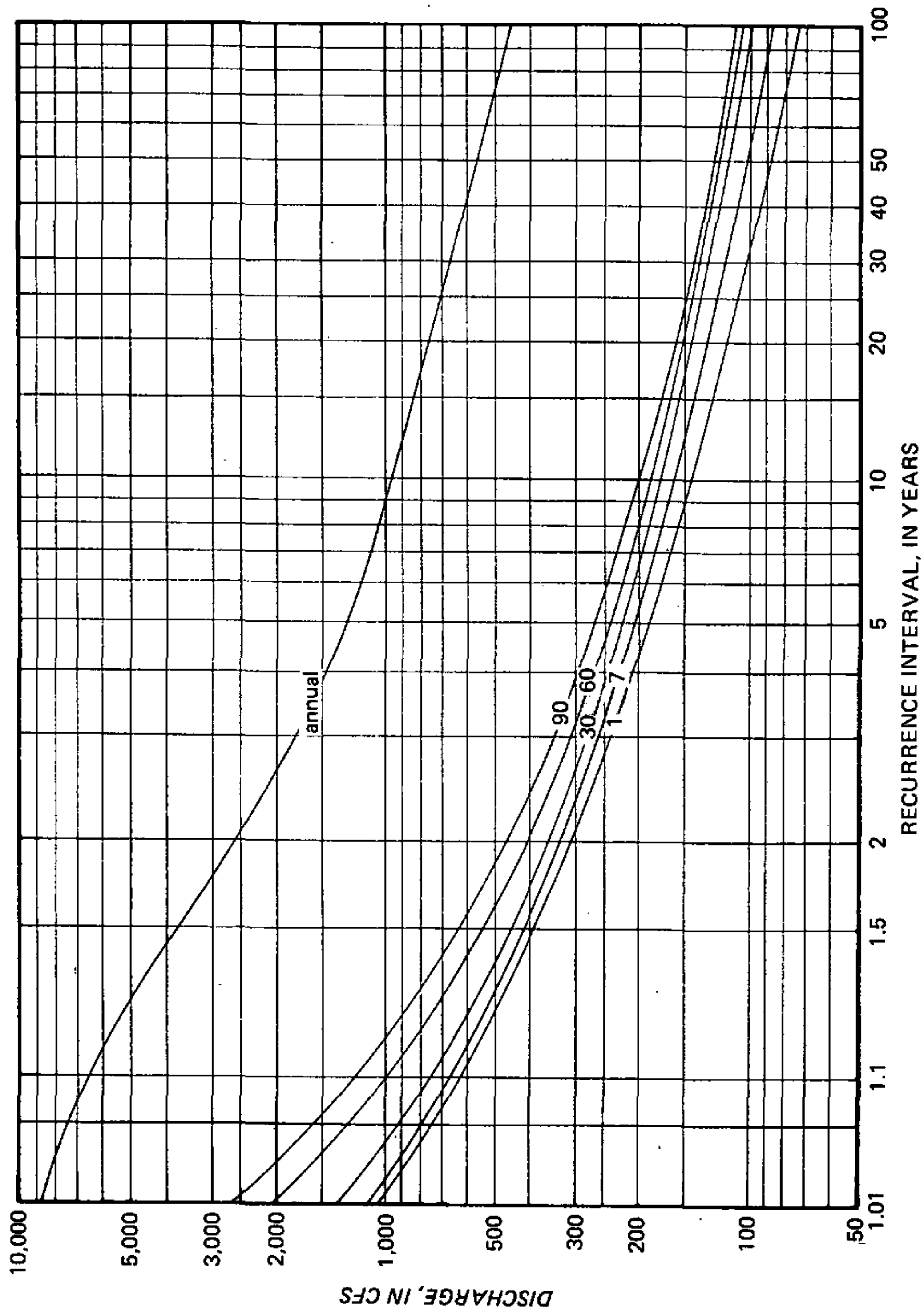



Figure 31. — Magnitude and frequency of low flows for the Minnesota River near Jordan, Minn. (based on the period 1936-67). Station 05330000. Drainage area 16,200 sq mi, approximately.

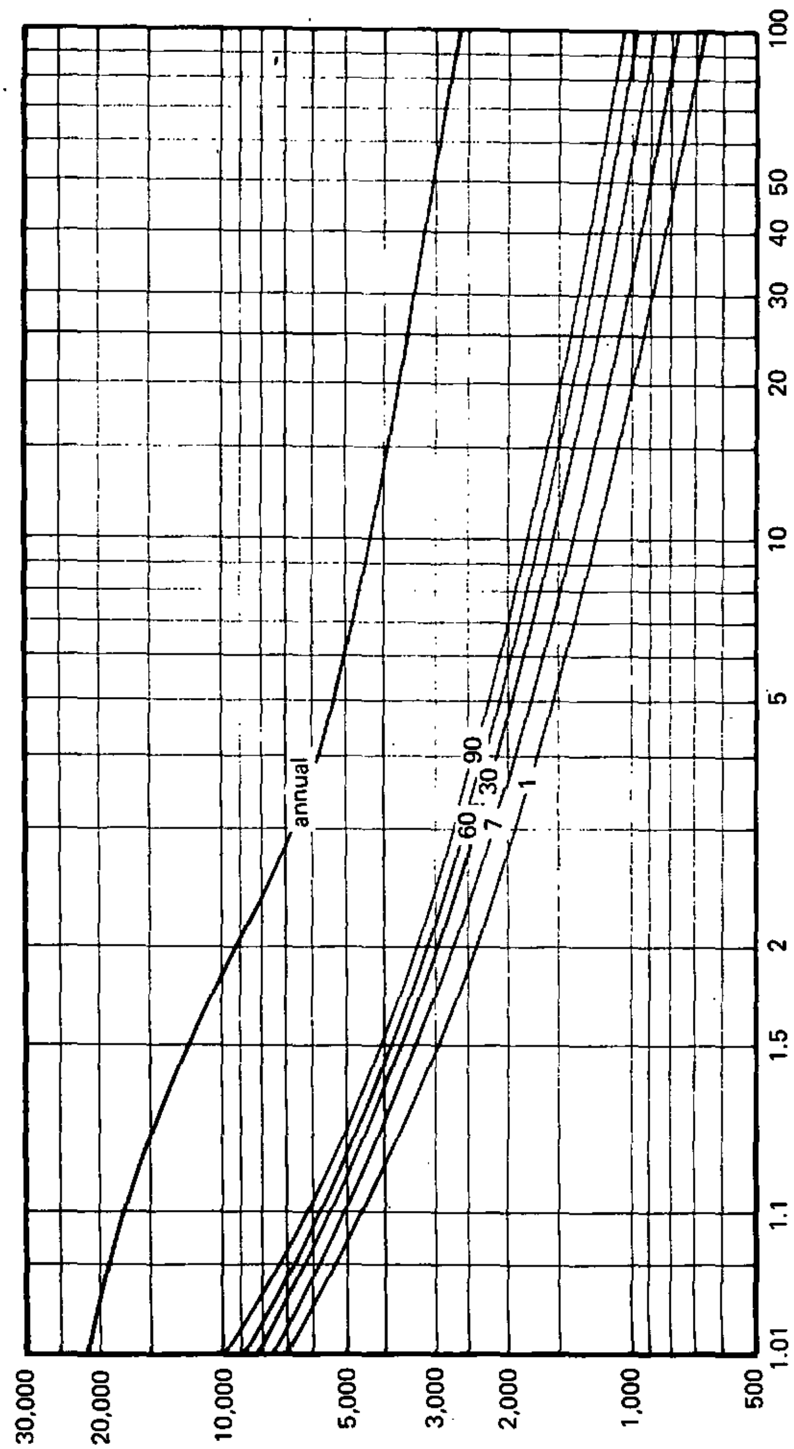



**Figure 32. — Magnitude and frequency of low flows for the Mississippi River at St. Paul, Minn. (based on the period 1895, 1897, 1901-05, 1907-67). Station 05331000. Drainage area 36,800 sq mi, approximately.**

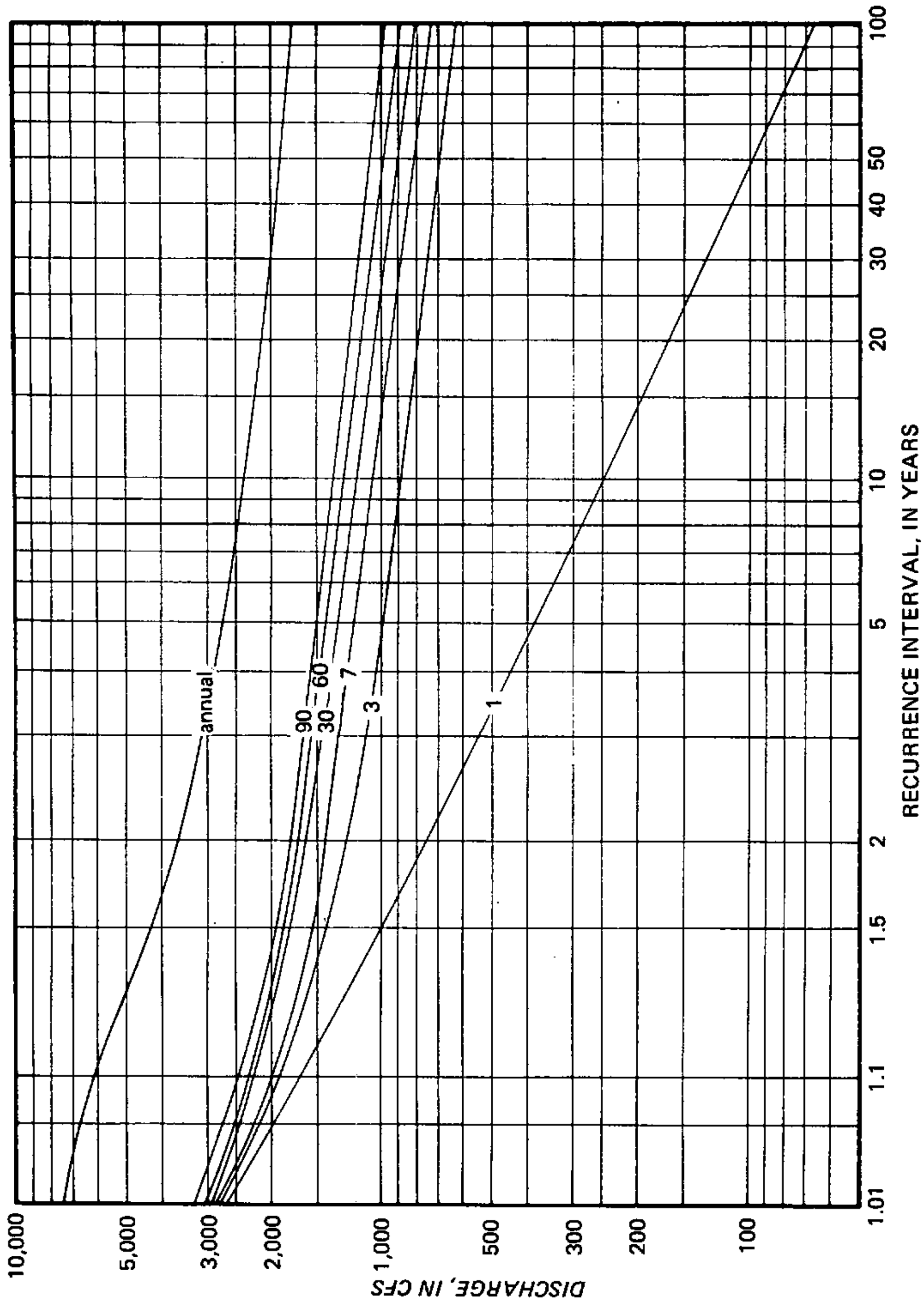



**Figure 33. — Magnitude and frequency of low flows for the St. Croix River at St. Croix Falls, Wis. (based on the period 1911-68). Station 05340500. Drainage area 5,930 sq mi, approximately.**

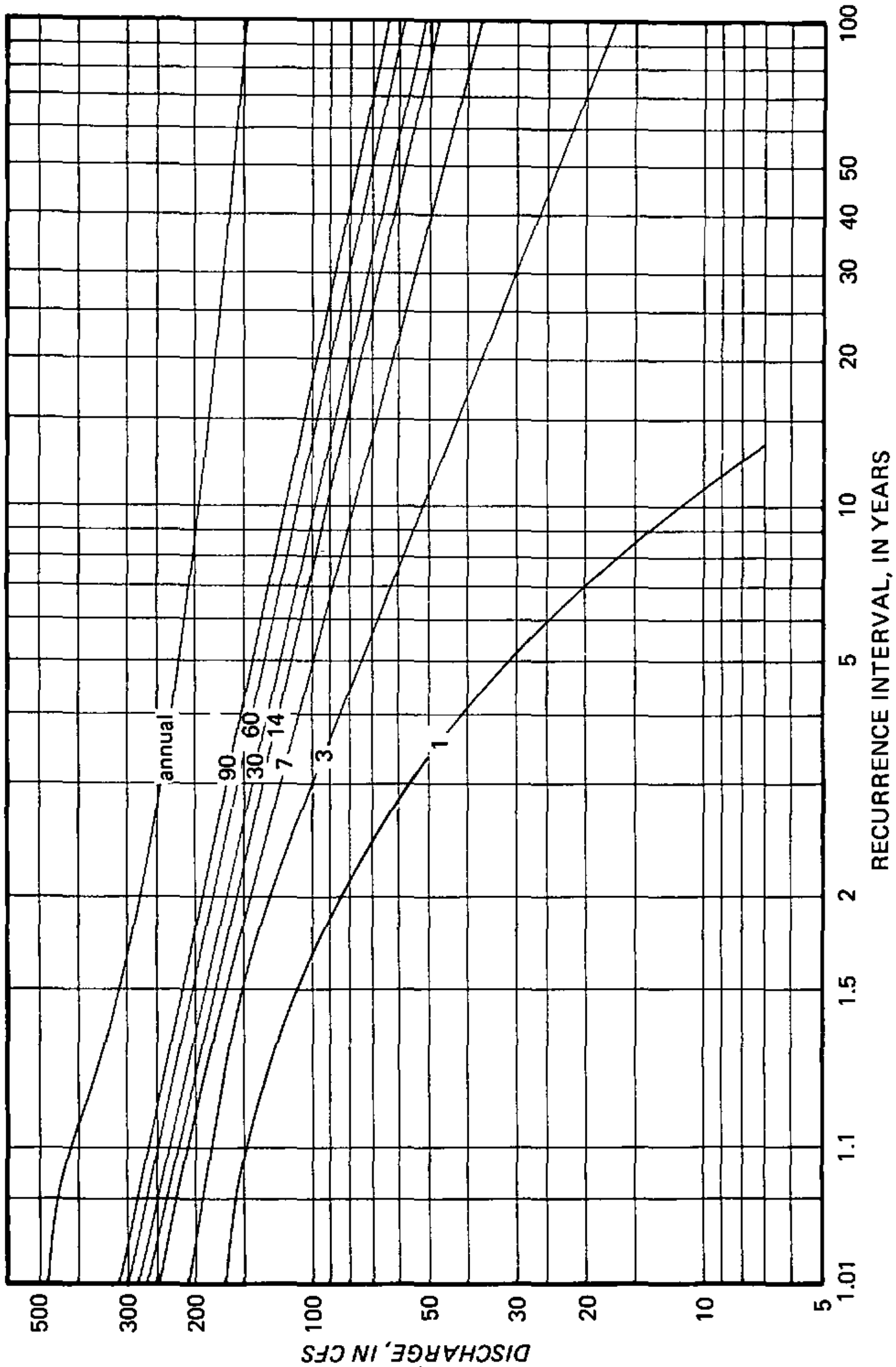



**Figure 34.** – Magnitude and frequency of low flows for the Apple River near Somerset, Wis. (based on the period 1916-67). Station 05341500. Drainage area 555 sq mi.

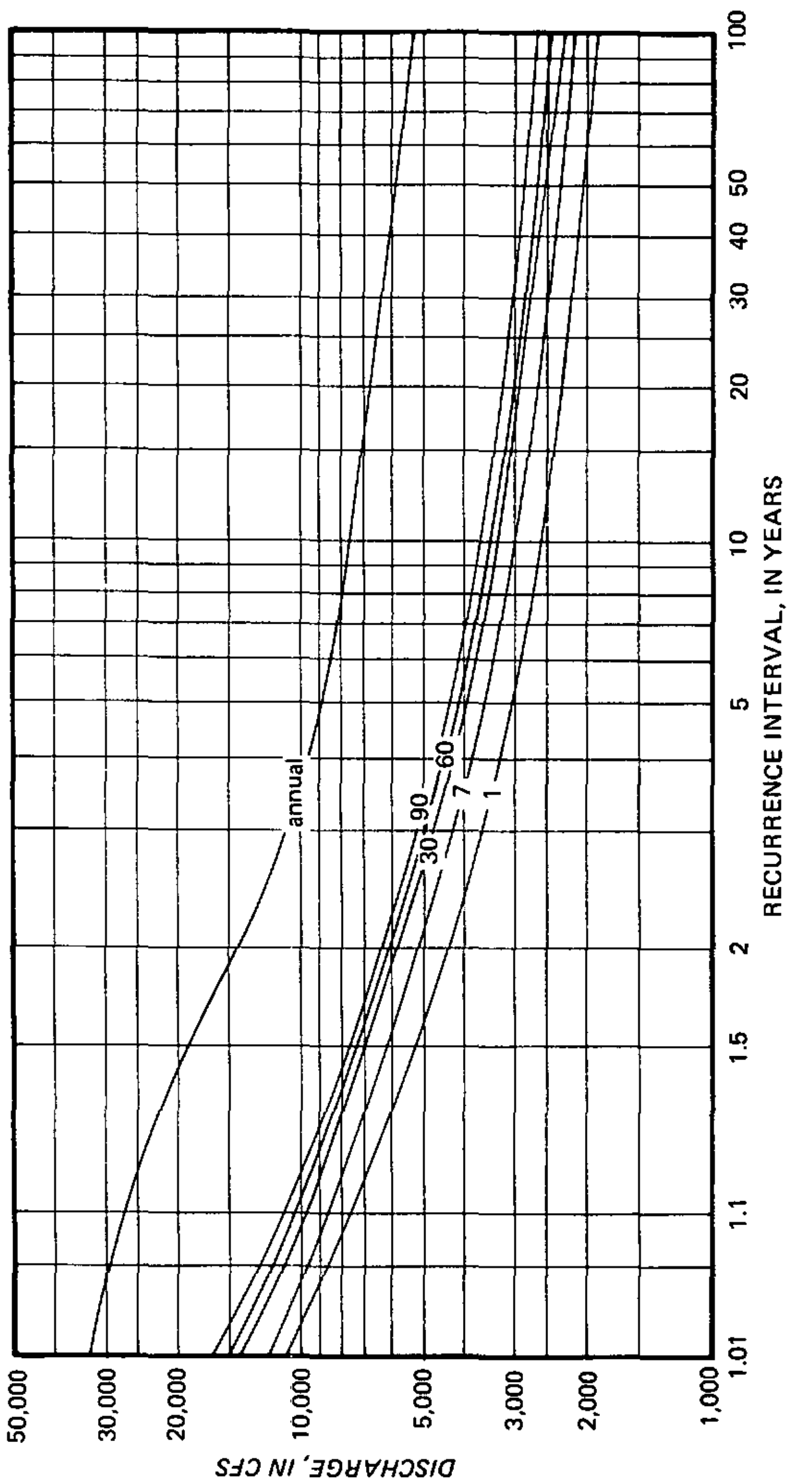



Figure 35. — Magnitude and frequency of low flows for the Mississippi River at Prescott, Wis. (based on the period 1930-67). Station 05344500. Drainage area 44,800 sq mi, approximately.

concrete explanation for the shape of these curves can be made at present. The family of curves presented for the two sites shown in Figures 33 and 34 are atypical due to power-plant operation. Additional low-flow frequency curves (3- and 14-day) are included in these figures to better define the range of discharge between the 1- and 30-day curves. The 1-day curve (Figure 34) for Apple River near Somerset, Wisconsin, ends at a discharge of 7 cfs because no lower discharge there has ever been permitted.

The 7-day 10-year low flow is the low-flow characteristic most often used in water-resources analyses for water supply and waste disposal. This flow usually occurs in late summer or early fall, when all streamflow is effluent ground water. For many uses, planning based on the 7-day 10-year low flow is adequate. The Environmental Protection Agency and the Minnesota Pollution Control Agency commonly use this flow to determine allowable pollution loadings in streams. However, where no alternative supply is feasible or where water demand must be satisfied at almost all times or pollution loading is critical, 7-day low flows of 50- or 100- year frequencies may be used as the basis for planning and design.

*Streamflow Duration*

Flow-duration curves provide a convenient means for studying the flow characteristics of streams and for comparing one stream regimen with another. They are used for investigating problems dealing with water supply, power development, and disposal of sanitary and indistrial wastes. Although not as useful a predictive tool as the low-flow frequency curves, the slope of the duration curve indicates the variability (flashiness) of streamflow and the amount of storage, either on the surface or in the ground, available to the stream in its drainage basin above the gaging station. The steeper the slope, either for the whole or for a segment, the less storage available to maintain flow; and the flatter the slope, the more storage available.

Duration curves of daily discharge for 16 sites are shown in Figures 36-39. These curves show the percentage of time, during the period of record, that the indicated daily streamflow was equaled or exceeded. No continuity of discharge is implied by the curves. For instance, the 90-percent point indicates that the discharge shown on the curve was equaled or exceeded in 90 percent of the days during the period of record. Conversely, the 90-percent point also indicates that the discharge was less than that shown on the curve in 10 percent of the days during the period of record; for example, in 10 years, 365 days scattered throughout the period have a flow less than that indicated by the 90-percent point.

Duration curves at five gaging stations on the major streams in the area are shown in Figure 36. These curves show that the drainage basin above the Mississippi River at Prescott, Wisconsin gage produces not only the highest flow but also has the most storage, as should be expected. The curve for the St. Croix River at St. Croix Falls, Wisconsin is steeper on its lower end than any of the four other curves shown. The St. Croix Falls gage is upstream from the Prescott gage and also has a longer period of record; therefore, if the curve at the Prescott gage were based on the longer period of record, it might also show a steeper lower end. Similarly, the curve for the Minnesota River near Jordan would probably be a little flatter at its lower end if it were based on a period of record as long as that on the Mississippi River at St. Paul. Care should be taken, therefore, in comparing duration curves if the record for each station is not almost identical in the years covered or at least based on a similar meteorological period.

Duration curves of tributaries to the major streams and of a few minor streams are shown in Figures 37 and 38, respectively. Although the quantities of water in these streams are relatively small, their flow variabilities suggest basin characteristics somewhat similar to those of the larger streams, with the exception of South Fork Crow River near Mayer. Flow in this stream is flashier than that in the other streams, and the drainage basin above the Mayer gage does not store water at a high enough altitude to maintain a base flow in the stream of greater than 0.1 cfs for little more than 95 percent of the time.

The duration curves in Figure 39 are for gaging stations on the St. Croix River. Of all the curves for the stations on the St. Croix River, St. Croix Falls shows the highest discharge at high flows and the lowest discharge at low flows, yet the period of record at this station is practically the same as that for the St. Croix River near Danbury, Wisconsin, an upstream station, which has the lowest discharge for most of the compared duration intervals. Although 1911-13, fairly dry years, are not included in the period of record at Danbury and are included in the St. Croix Falls record, they were not dry enough to explain the difference in shape between the lower end of the two curves. Despite the dissimilar periods of record for the other two stations, their duration curves are very similar to the Danbury curve. Apparently the unusual shape of the St. Croix Falls curve is not natural. All the days (26) of daily discharge below 370 cfs (see Figure 39) except two occurred during 1928-41, whereas those above 370 cfs and below 1,400 cfs, the beginning of the break in similarity of curves, are scattered throughout the period of record. The hydroelectric plant at St. Croix Falls is the apparent reason for the abrupt departure of the curve from what might be its normal shape. During periods of low flows, hydroelectric power-plant operations, depending upon onstream storage, have the effect of further reducing the flows. The duration curve (Figure 37) for the Apple River at Somerset, Wisconsin displays the same drop at its lower extremity. This station is also located at a hydroelectric plant, thus it can be inferred that the curve shown is not natural but depicts the effects of power-plant operations. Here then, the duration curve gives a picture of one effect man's use of streamflow has on the flow regimen.

## GROUND WATER

Ground water is water in the zone of saturation. This water is under pressure equal to or greater than atmospheric pressure. The relative importance of ground water in the metropolitan area is reflected in water use. In 1970 ground-water use was 194 mgd, or 59 percent of the total water used to supply a population of 1.87 million people. Present trends show ground-water use to be increasing at a greater rate than that of surface water.

### Principles of Occurrence

Ground water is stored in and is moving through the rocks shown in Table 2. The ability of the rocks to store and transmit water is dependent on their properties of porosity and permeability, respectively. Formations, or parts of formations, are considered to be aquifers when they contain sufficient saturated permeable material to yield water to wells or springs. A porous rock is not necessarily very permeable. Rock permeability is dependent upon the interconnection of pores by passageways of capillary and supercapillary size. A fine-grained deposit such as silt or clay may have a high porosity and contain a large volume of water when saturated, but the interstices are so small that most of the water is held by molecular attraction, thus limiting its mobility. Although sand and gravel may have only a fraction of the porosity of clay, the openings between grains are relatively large, transmit water freely, and may yield large amounts of water to wells. Aquifers have either one or both of two kinds of permeability – primary intergranular or secondary solution cavity and fracture (includes all types of partings in rocks). Examples of rocks having the different kinds of permeability are depicted in Figure 40.

The sand and gravel aquifers in the glacial drift have primary intergranular permeability. The Hinckley, Mount Simon, Galesville, Ironton, Jordan, and St. Peter sandstones can have both kinds of permeability, as they are variously cemented in part and, thus, may be fractured and jointed. The Prairie du Chien and Platteville limestone and dolomite have secondary solution cavity and fracture permeability. The type of permeability significantly controls the filtering capabilities of a rock. Organic liquid wastes, such as effluent from septic tanks, discharged through rocks with primary intergranular permeability will be purified more than wastes discharged through rocks with secondary solution cavity and fracture permeability. In the latter case, wastes dumped at or near the surface in a limestone terrain will percolate downward to contaminate the ground water with little or no improvement in quality except the dilution afforded by infiltrating precipitation. Also, permeability type often affects the hydraulic properties of a rock. Rocks with primary permeability are likely to have homogeneous hydraulic properties; whereas, rocks with secondary permeability will have heterogeneous properties. This is important in ground-water-flow analyses for there is presently no satisfactory mathematical way to treat detailed flow in heterogeneous rocks.

**Figure 36. – Duration curves of daily discharge for stations on the Mississippi, Minnesota and St. Croix Rivers.**

**Figure 37. – Duration curves of daily discharge for the Elk, Crow, Rum, Apple, and Vermillion Rivers.**

**Figure 38. – Duration curves of daily discharge for three minor streams in the study area.**

**Figure 39. – Duration curves of daily discharge for gaging stations on the St. Croix River.**

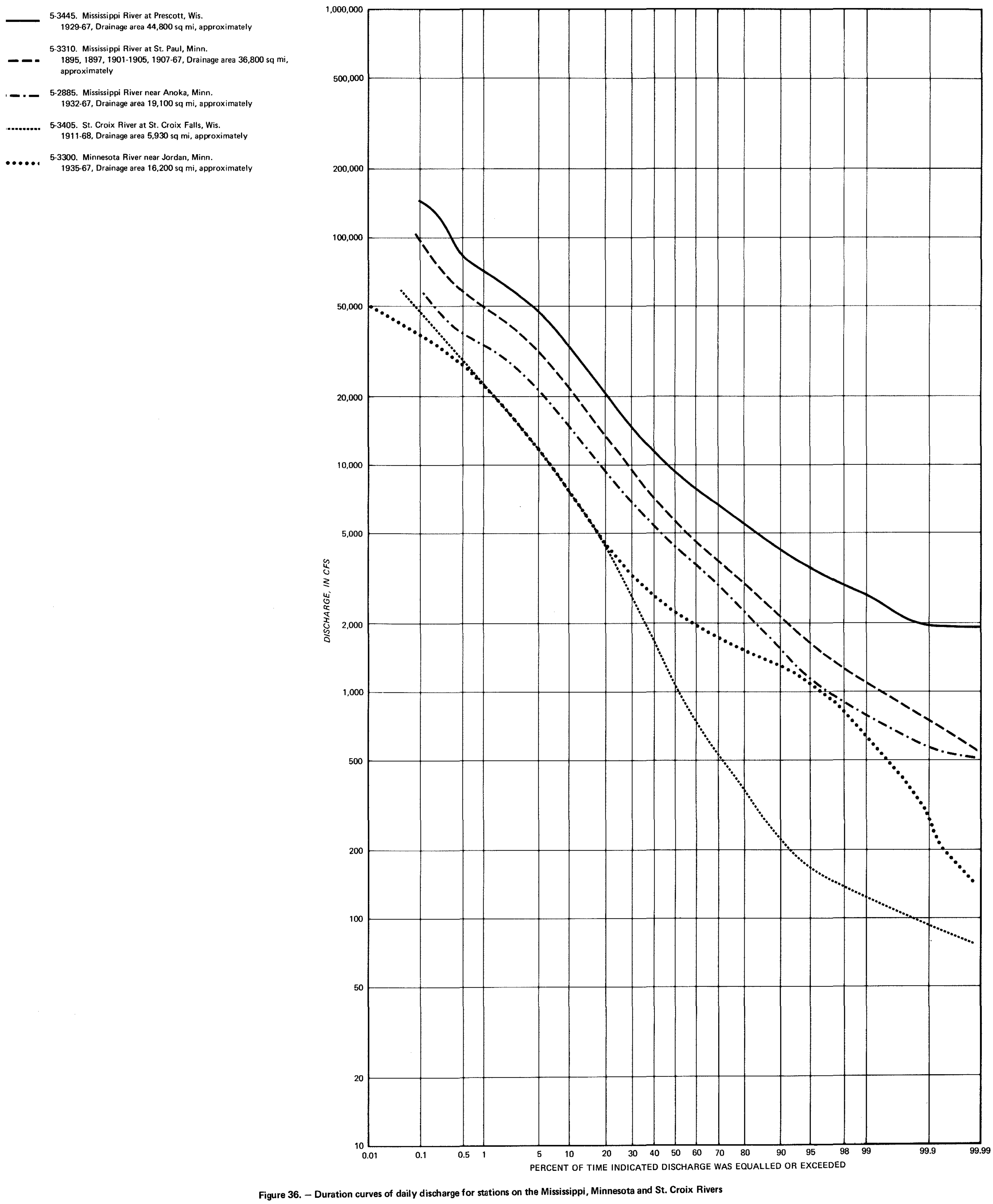



**Figure 36. – Duration curves of daily discharge for stations on the Mississippi, Minnesota and St. Croix Rivers**

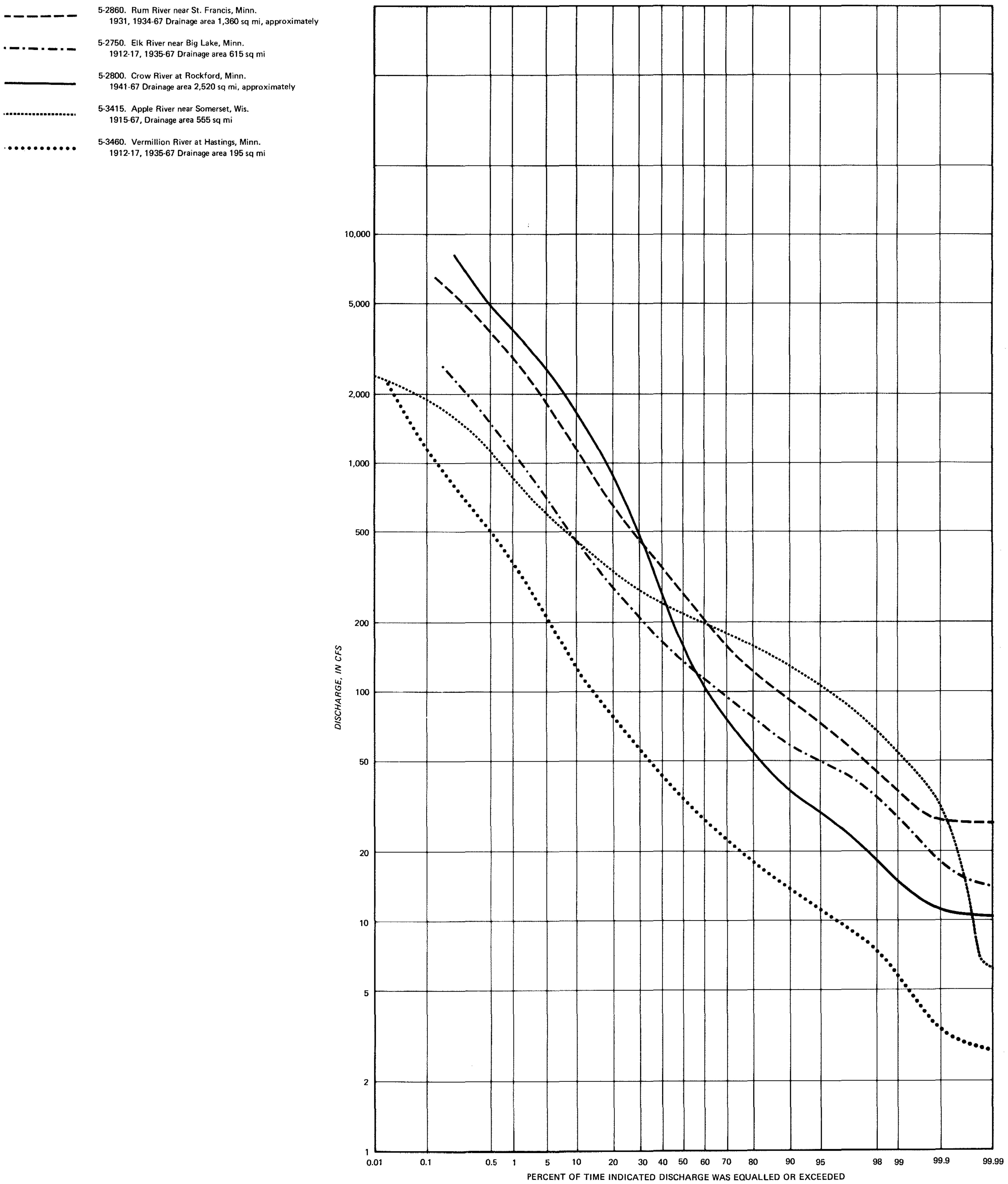



Figure 37. — Duration curves of daily discharge for the Elk, Crow, Rum, Apple, and Vermillion Rivers

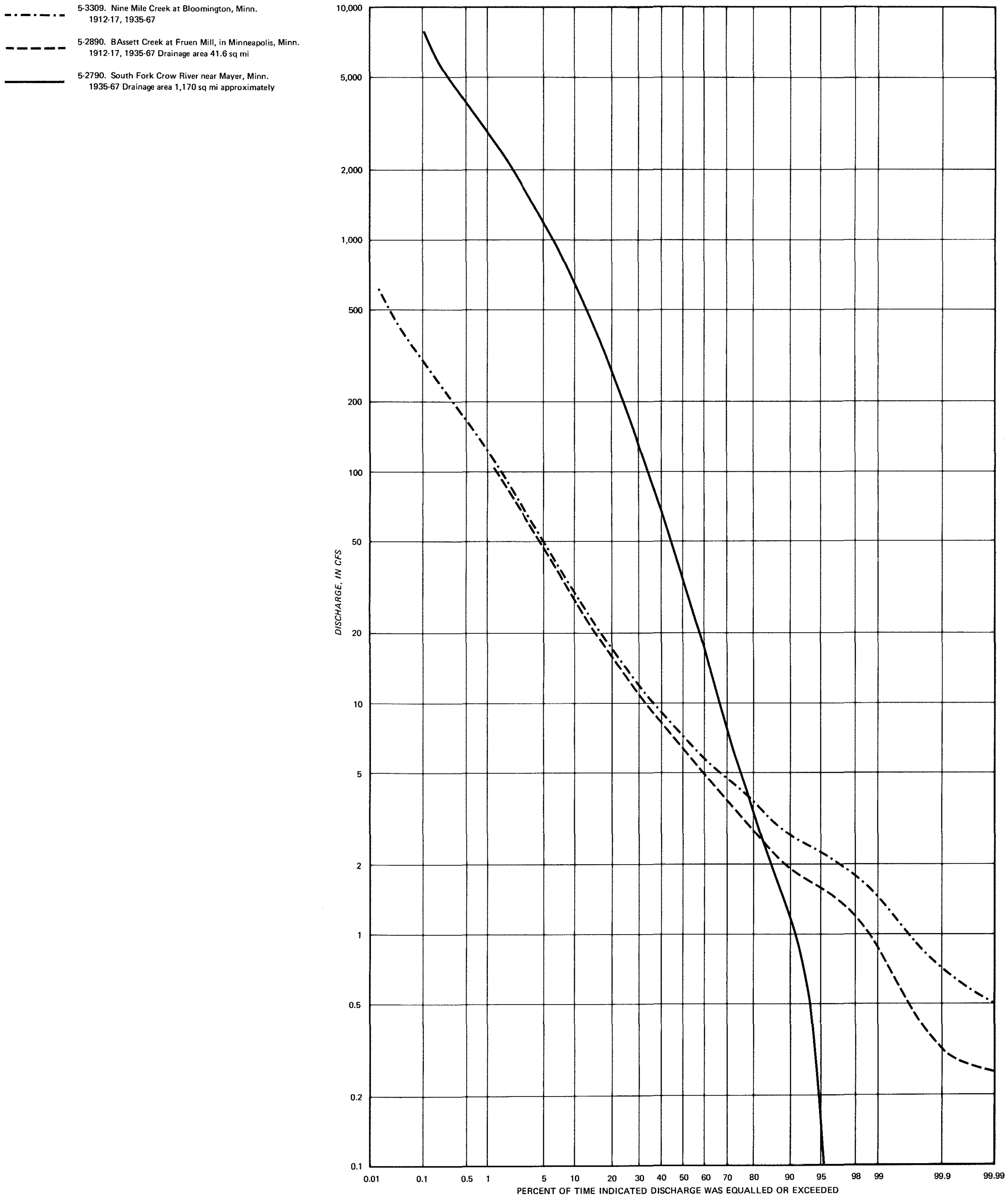



Figure 38. — Duration curves of daily discharge for three minor streams in the study area

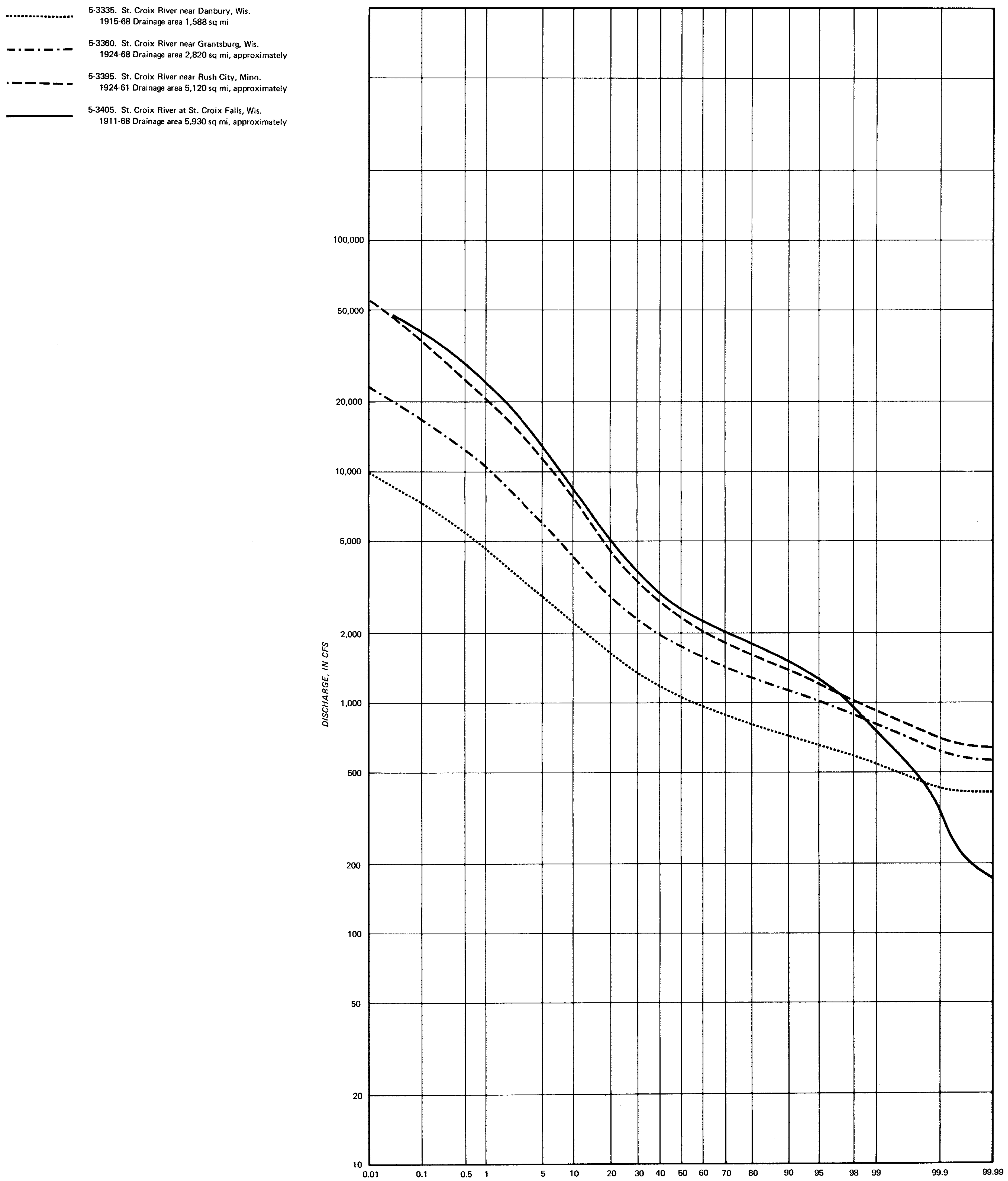



Figure 39. – Duration curves of daily discharge for four gaging stations on the St. Croix River

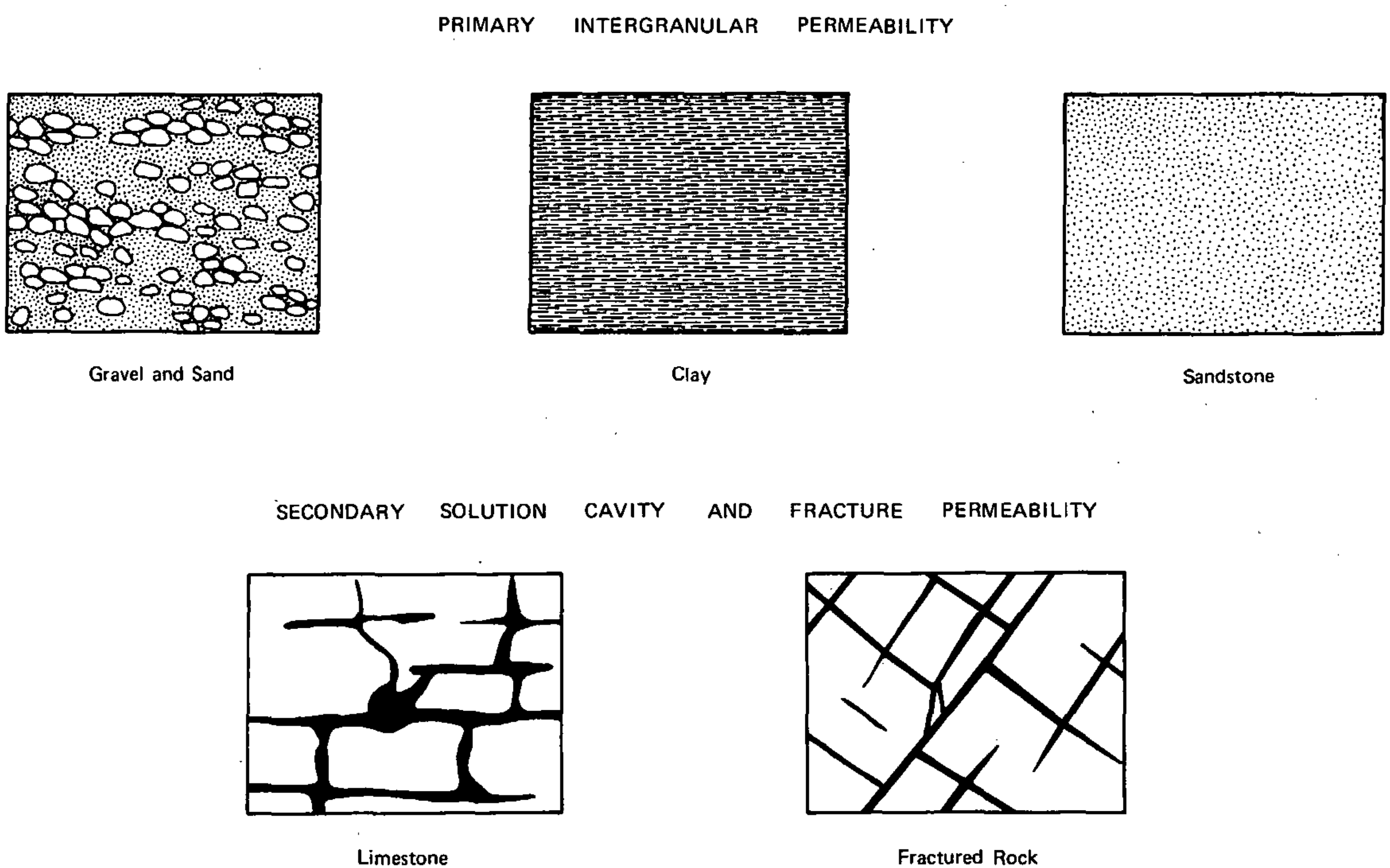



Figure 40. — Aquifer materials having primary and secondary permeabilities.

Ground water occurs either under water-table or artesian conditions. Ground water in contact with the atmosphere either directly or through the unsaturated zone immediately below the land surface is under water-table conditions and is unconfined. Under artesian conditions, the aquifer is overlain by a confining layer of lower permeability. Water in the aquifer is under sufficient pressure to rise above the base of the confining bed in a well or open hole. The level to which the water will rise is independent of the water table and is called the hydrostatic or potentiometric head.

The response of confined and unconfined aquifers to pumping may differ greatly. The diffusivity (which provides a measure of the spread of response to pumping) of an unconfined aquifer is much less than that in a confined aquifer. In an unconfined aquifer, discharge from a well is supplied from storage by gravity drainage of the aquifer materials immediately surrounding the well, and those materials within the influence of the well's pumping are dewatered. The spread of the effects of pumping are slow. In a confined aquifer, well discharge before dewatering and interception of boundaries is supplied mainly by compression of the aquifer and to some extent by an expansion of the released water. The effects of pumping are spread through pressure, not dewatering and are, thus, rapid. For practical reasons then, wells completed in water-table aquifers can generally be closer together without pronounced mutual interference than wells completed in artesian aquifers. Well interference has more complications, however, and is discussed later in the report.

Most of the water in all the bedrock aquifers below the St. Peter is under artesian pressure. Water-table conditions prevail in the Prairie du Chien-Jordan aquifer only in that part of the area hachured in Figure 41. Artesian conditions prevail in the St. Peter aquifer where it is fully saturated and overlain by the Glenwood Shale. Where the aquifer is overlain by and in hydraulic connection with sand and gravel aquifers in the glacial drift, it is probably under water-table conditions. Water-table conditions also prevail where the St. Peter is exposed and is not fully saturated.

Water in buried outwash deposits within the glacial drift is artesian in most places. The permeability of the overlying till is so low in comparison to that of the outwash that it acts as a confining bed. Water in the surficial outwash, valley train, and sand and gravel alluvial deposits is under water-table conditions, except locally where the deposits are fully saturated and are overlain by a relatively impermeable layer of Holocene alluvial deposits of silt or clay. If the water levels in the surficial deposits decline below the confining layer, the artesian conditions revert to water-table conditions.

**Source and Movement**

The source of all water available to wells is precipitation. It is estimated, from a Thiessen net analysis, (Thiessen, 1911) that 9.4 million acre-feet of water falls on the study area in an average year. Part of the precipitation becomes surface runoff, part is evaporated, part is transpired by vegetation and crops; and the remainder seeps into the subsurface to recharge the ground-water reservoirs. In addition to direct precipitation on the study area, an unknown amount of ground-water enters as underflow, particularly along the western boundary.

Ground water is constantly in motion. It moves from places of high potential to places of low potential, from areas of recharge to areas of discharge. The rate of movement is slow. For example, in parts of the Jordan Sandstone where the hydraulic gradient is 25 feet per mile, the hydraulic conductivity (permeability) 400 gpd per square foot and the porosity 20 percent, the rate of movement is only 460 feet per year.

In parts of the Mount Simon-Hinckley aquifer where the hydraulic gradient is 20 feet per mile, the hydraulic conductivity 70 gpd per square foot and

**Figure 41. – Available head above the top of the Prairie du Chien-Jordan Aquifer in winter 1970-71 in the Metropolitan Area.**

EXPLANATION

100 —— ?

Line of equal available head

Shows amount of head above the top of the Prairie du Chien-Jordan aquifer. Dashed where approximately located, queried where doubtful.

Area under non-artesian conditions

Area where aquifer is non-artesian, water level is below the top of the rock formation.

Geologic contact

Contact between the Prairie du Chien Group and the Jordan Sandstone. Modified after Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966) and Stillwater Sheet (unpublished advance version).

Geologic Contact

Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, 1936.

Fault

From Geologic Map of Minnesota, St. Paul Sheet (Minn. Geol. Survey, 1966).

Boundary of study area

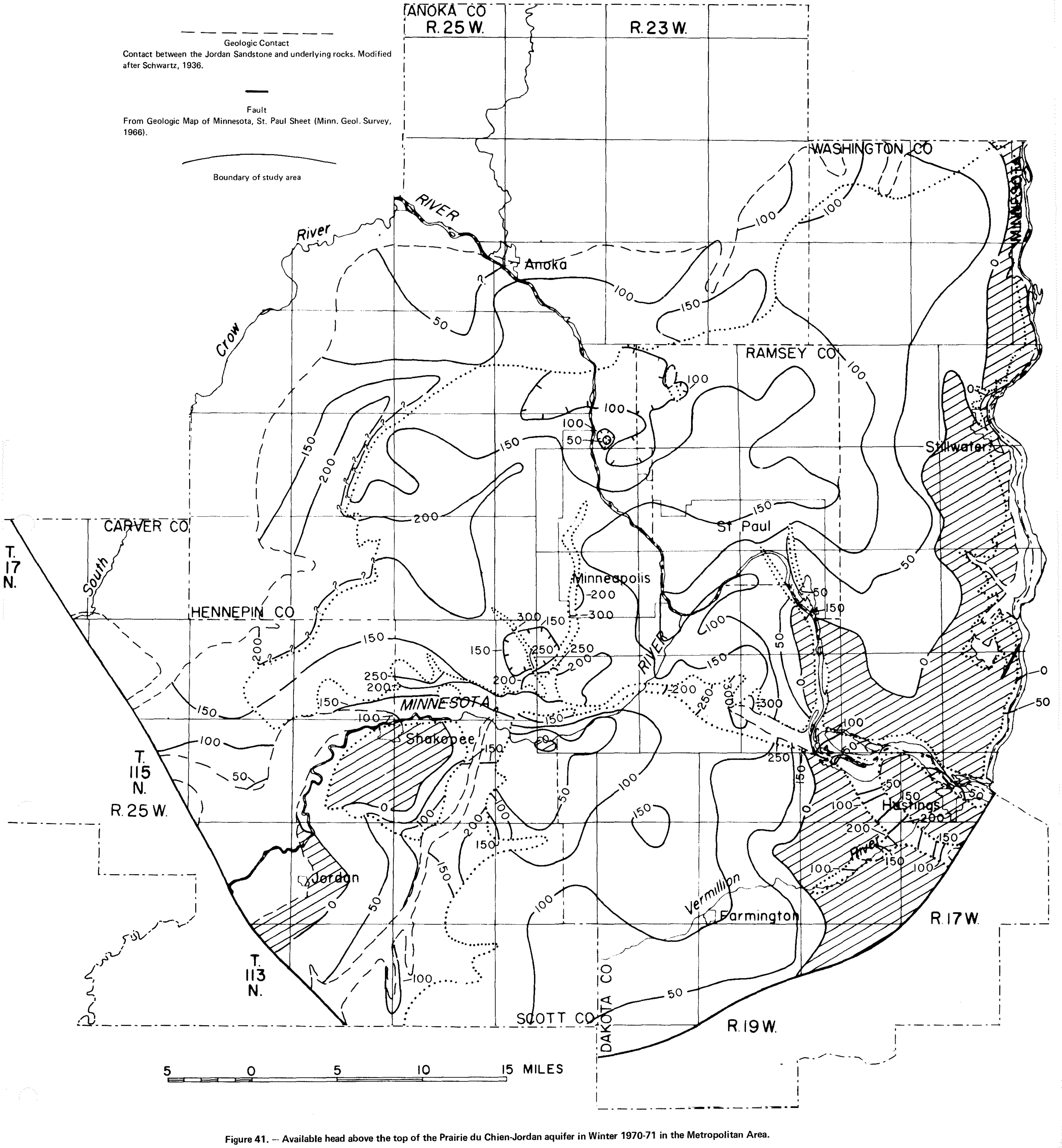



Figure 41. – Available head above the top of the Prairie du Chien-Jordan aquifer in Winter 1970-71 in the Metropolitan Area.

the porosity 20 percent, the rate of movement is only 65 feet per year.

The direction of movement is approximately perpendicular to lines of equipotential or equal head. The potential at any one place in any one aquifer is represented by the static water level or head (above mean sea level) in a well completed at that place in that aquifer. A map of the potentiometric surface of the water in an aquifer is made by contouring head differences that are measured in several wells completed in the aquifer. Potentiometric-surface maps were made for water in the St. Peter, Prairie du Chien-Jordan, and Mount Simon-Hinckley aquifers (Figure 19, 20, and 21, respectively). The potentiometric surfaces are only representative for the period of time shown on the maps because the water levels fluctuate to some extent both seasonally and annually. The generalized direction of overall lateral ground-water flow in the aquifers is depicted with arrows on the maps.

*Lateral Ground-Water Movement*

Water in the Mount Simon-Hinckley aquifer (Figure 21) flows southward from the northernmost neck of the study area to the Twin Cities. It has an eastward component of flow to the St. Croix River at least as far south as Stillwater. Long-term withdrawal of water from this aquifer has caused a depression in the city centers. Water in the southeast corner of the area that, under natural conditions, may have flowed to the southeast now apparently flows toward these centers of heavy withdrawal. Data used to draw the potentiometric surface in this aquifer were sparse. In order to refine Figure 21, more data points are needed.

Water in the Prairie du Chien-Jordan aquifer (Figure 20) flows away from three highs in its potentiometric surface – one in the northeast in the White Bear and Forest Lakes area, another in the west in the Lake Minnetonka area; and the third in the south, in the Vermillion River headwater area. Regional flow from these highs is toward the three major streams and, hence, downstream and out of the study area to the southeast. Local flow patterns are extremely complex because of the high degree of development of the aquifer. Each high-yielding well has its own flow regimen directing water to itself, and each group of wells has created even larger regimens toward which water is funneled. Some effects these larger regimens have on the regional flow pattern show up as inflections of the potentiometric contour lines shown on the map. For example, the elongate ridge in the potentiometric surface in T.117 N., R.22 W., at the east end of Lake Minnetonka, is largely caused by heavy withdrawals in the Wayzata, Plymouth, St. Louis Park, Edina, Hopkins, Minnetonka, Chanhassan, and Excelsior areas around the ridge. Dams on the Mississippi River above the mouth of the Minnesota River also affect local directions of ground-water flow because ground water is partly dammed at these places. For example, Lock and Dam No. 1 in the NE1/4 section 17, T.28N., R.23W., has a decided influence on the shape of the 725-foot contour. Other dams upstream affect the 750- 775-foot contours. Groups of wells pumping near the dams bend the potentiometric contours in the vicinity of the dams. The 650- and 675-foot contours are closed near the center of T.28 N., R.22 W., in South St. Paul, thus local ground-water flow is toward this closure. The low here is due to large perennial pumping of ground water in the area of the South St. Paul stockyards. The effects of this pumping do not seem to have spread far, however, considering that the meat-processing plants withdrew large volumes of water for many years. A recent curtailment of pumping here should result in a recovery of the effects of past pumping.

Because the volume of water pumped from the Prairie du Chien-Jordan aquifer varies greatly from winter to summer, a potentiometric surface map (Figure 43) for the summer of 1971 also was made. Although comparison of two maps (Figures 20 and 43) shows little change in the generalized regional flow directions, there is a decided change in local flow directions. Heavy summer pumpage in the Minneapolis and St. Paul city centers and in St. Louis Park and Edina have resulted in additional closed contours in the potentiometric surface. Local movement of water in the summer will be diverted toward these lows. Another pronounced change in the potnetiometric surface occurs as a migration to the northwest of the 800- to 875-foot contours southeast of Lake Minnetonka. This change is due largely to the effects of heavy summer pumping in the suburbs and municipalities around Lake Minnetonka. Similar up-gradient migration of contours occur in both Minneapolis and St. Paul. This summer configuration of the potentiometric surface should revert to the winter configuration shortly after the summer stresses on the aquifer are removed.

The potentiometric surface of water in the St. Peter aquifer in the winter of 1970-71 is shown in Figure 19. The St. Peter aquifer is highly dissected by erosion, and data used to draw the potentiometric surface map were sparse, so only a very generalized interpretation of flow in this aquifer can be made. Regional ground-water movement in this aquifer is nearly the same as that in the Prairie du Chien-Jordan aquifer, and the highs in the potentiometric surface almost coincide.

Potentiometric-surface maps of the Ironton-Galesville aquifer and of aquifers in the glacial drift were not made because of insufficient data. However, flow in the Ironton-Galesville aquifer is probably not much different from that in the Mount Simon-Hinckley aquifer. The drift is so complex and variable that it would take hundreds of water-level measurements, all recorded in a relatively short time, to construct a meaningful map of its potentiometric surface. The configuration of the water table can be postulated, however, through use of topographic maps and a map showing the location of surface drainage divides (Figure 3). The water table is a subdued replica of the surface topography; it may be assumed, therefore, that direction of ground-water movement in the glacial drift is similar to that of the present-day drainage and that surface drainage divides are roughly coincident with ground-water divides. Generalized ground-water movement then should be away from the high ground, toward the lakes and streams, and, hence, downstream out of the sub-basins.

*Vertical Ground-Water Movement*

Ground water has a vertical as well as a lateral component of flow. As with the lateral component, the vertical component moves water from places of high to places of low potential head. Thus water is interchanged between the aquifers in the artesian basin because none of the confining interbeds are totally impermeable. Generally, water moves vertically from overlying to underlying aquifers but moves upward where the potential differences allow. Flow may reverse locally in the vicinity of pumping wells where the head in an overlying aquifer (being mapped) is drawn down below the static head in an underlying aquifer. Generally the reversal is short-lived, and not much water moves from below because of the low permeability of the confining beds. However, if the reversal becomes perennial, a good part of the water discharged from the pumping wells may be supplied from the lower aquifer(s), despite low vertical permeability of confining beds. Reversal may have occurred in South St. Paul, where the static head (November 1971) in a well apparently open to aquifers in the Lower Cambrian formations (Table 2) was higher than both the static and dynamic heads in a well open to only the Prairie du Chien-Jordan aquifer.

Highly generalized vertical directions of ground-water flow in various parts of the metropolitan area are depicted in the hydrogeologic sections shown in Figure 44. The locations of these sections are shown in Figure 45. The sections represent flow conditions in the winter of 1970-71 and are based on available data. The sections would be more precise if multiple piezometers were finished at different depths at the same locations and along one line of section. Existing widely spaced wells, some projected into the line of section, actually were used. In addition, the plane of cross section should coincide with the direction of ground-water flow. Because the configuration of the water table was now known, the direction of flow was assumed to coincide with that in the Prairie du Chien-Jordan aquifer. Also, the position of the water table as shown in the sections was assumed. Despite the latitude taken in interpretation, the sections presented are probably reasonable approximations of the flow patterns at their respective locations. (See Meyboom and others, 1966, for a more complete explanation of the construction of vertical flow sections.)

**Figure 42. – Available head above the top of the Mount Simon-Hinckley aquifer in Winter 1970-71 in the metropolitan area.**

**Figure 43. – Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in August 1971 in the metropolitan area.**

**Figure 44. – Generalized hydrogeologic cross sections of the Twin Cities area. (Location of sections shown on Figure 9.)**

**Figure 45. – Subsurface extent of selected bedrock units in the Metropolitan Area.**

EXPLANATION

350 — —?—

Line of equal available head
Shows amount of head above the top of the Mount Simon-Hinckley.
Dashed where approximately located.

Boundary of study area

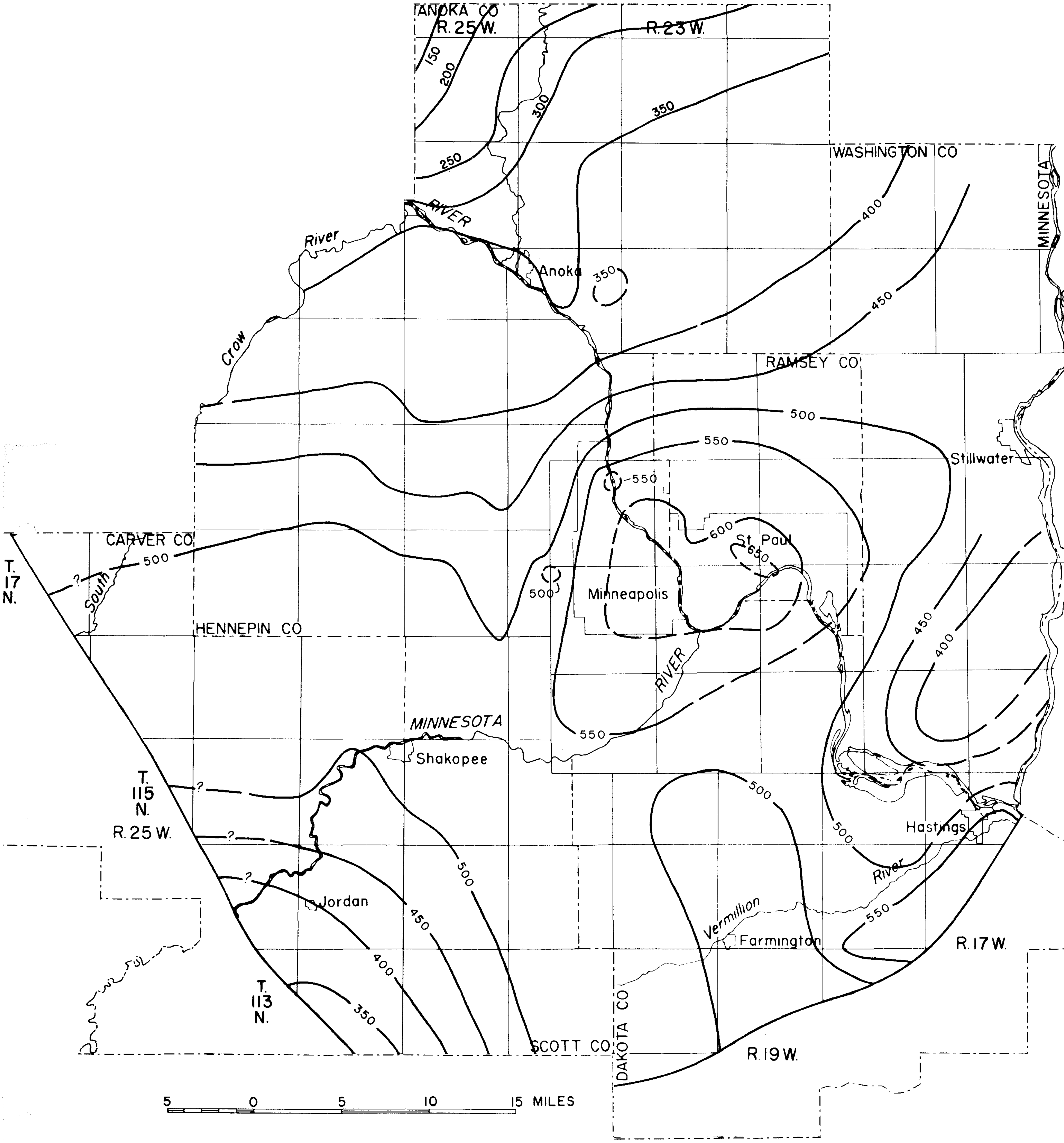



Figure 42. — Available head above the top of the Mount Simon-Hinckley aquifer in Winter 1970-71 in the Metropolitan Area.

EXPLANATION

700

Potentiometric contour
Shows altitude of potentiometric surface; dashed where approximately located.

Non-Pumping well used for control

Pumping well used as an inference

Geologic contact
Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, 1936.

Generalized direction of ground-water movement

Boundary of study area

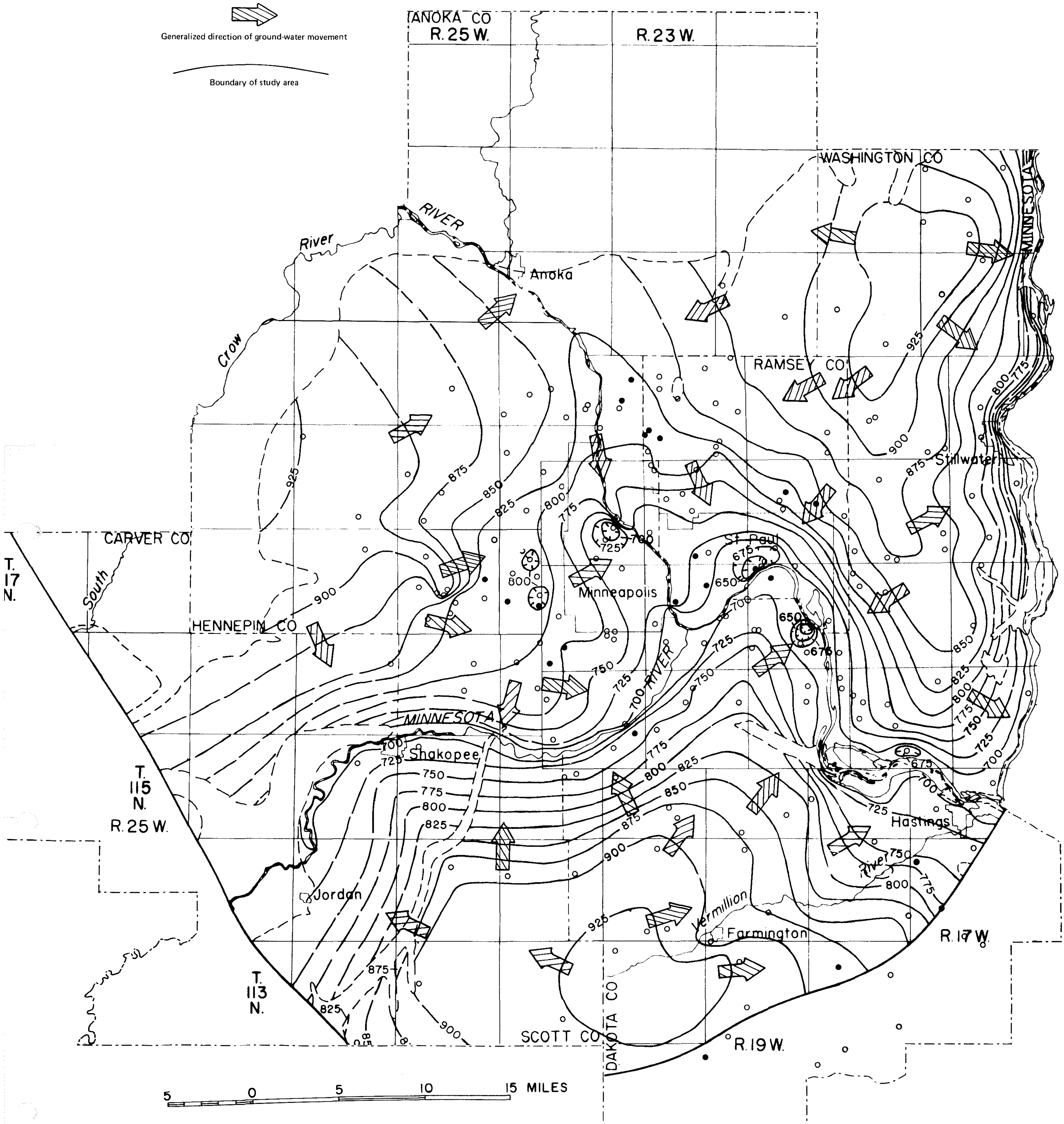
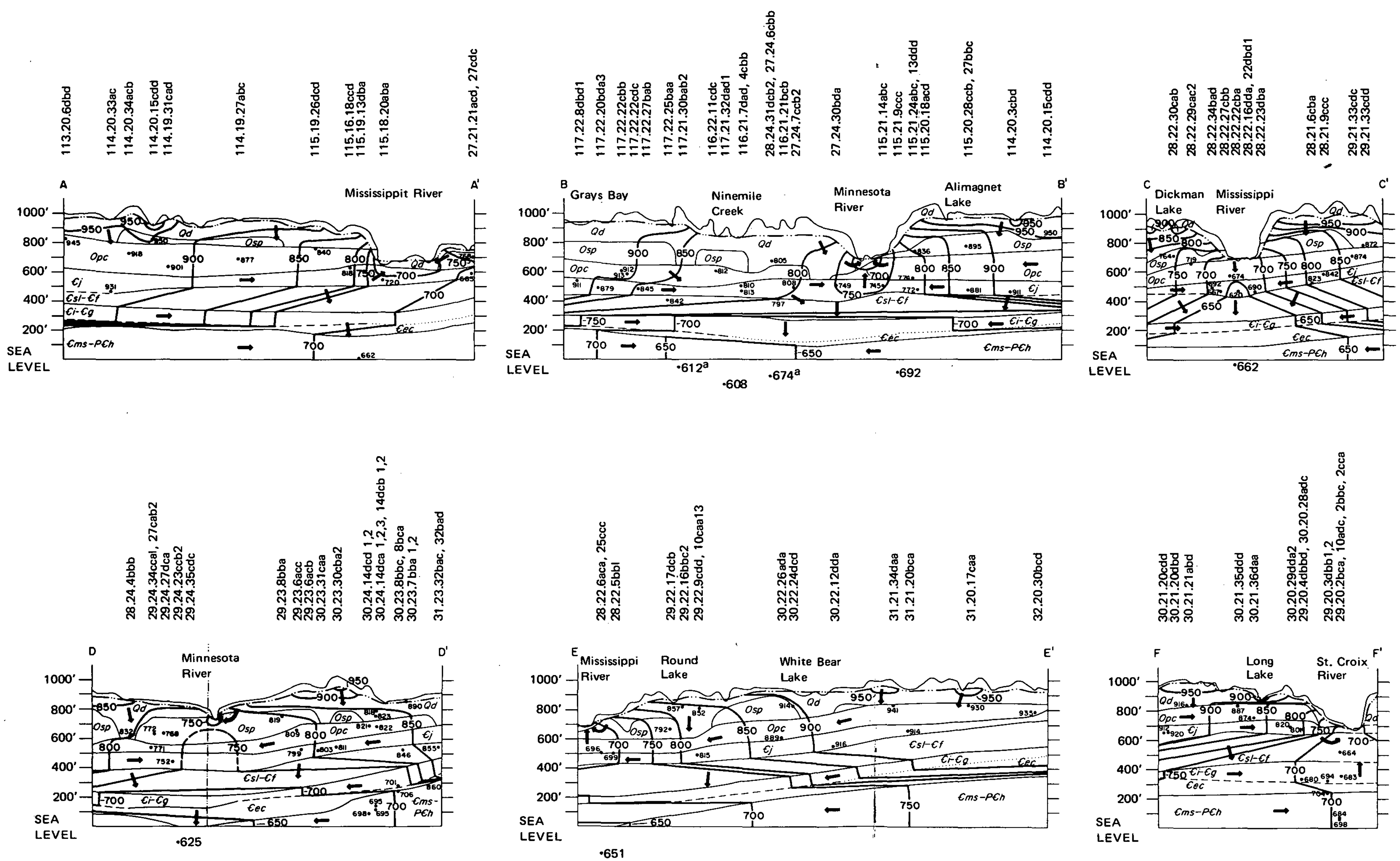



Figure 43. – Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in August 1971 in the Metropolitan Area.




## EXPLANATION

*Qd*

Glacial drift

*Osp*

St. Peter sandstone

*Opc*

Prairie du Chien group

*Cj*

Jordan sandstone

*Csl-Cf*

St. Lawrence and Franconia formations

*Ci-Cg*

Ironton and Galesville sandstones

*Cec*

Eau Claire formation

*Cms-PCh*

Mount Simon and Hinckley sandstones

Contact

Dashed where approximately located, dotted where unknown.

Water table, approximately located

•916

Well used for control

Well location number indicated above symbol; plotted at altitude of the midpoint between bottom of casing and bottom of well. Number indicates potentiometric surface of water in the well under static conditions. 612[a] indicates value obtained from adjustment of value obtained from pumping well.

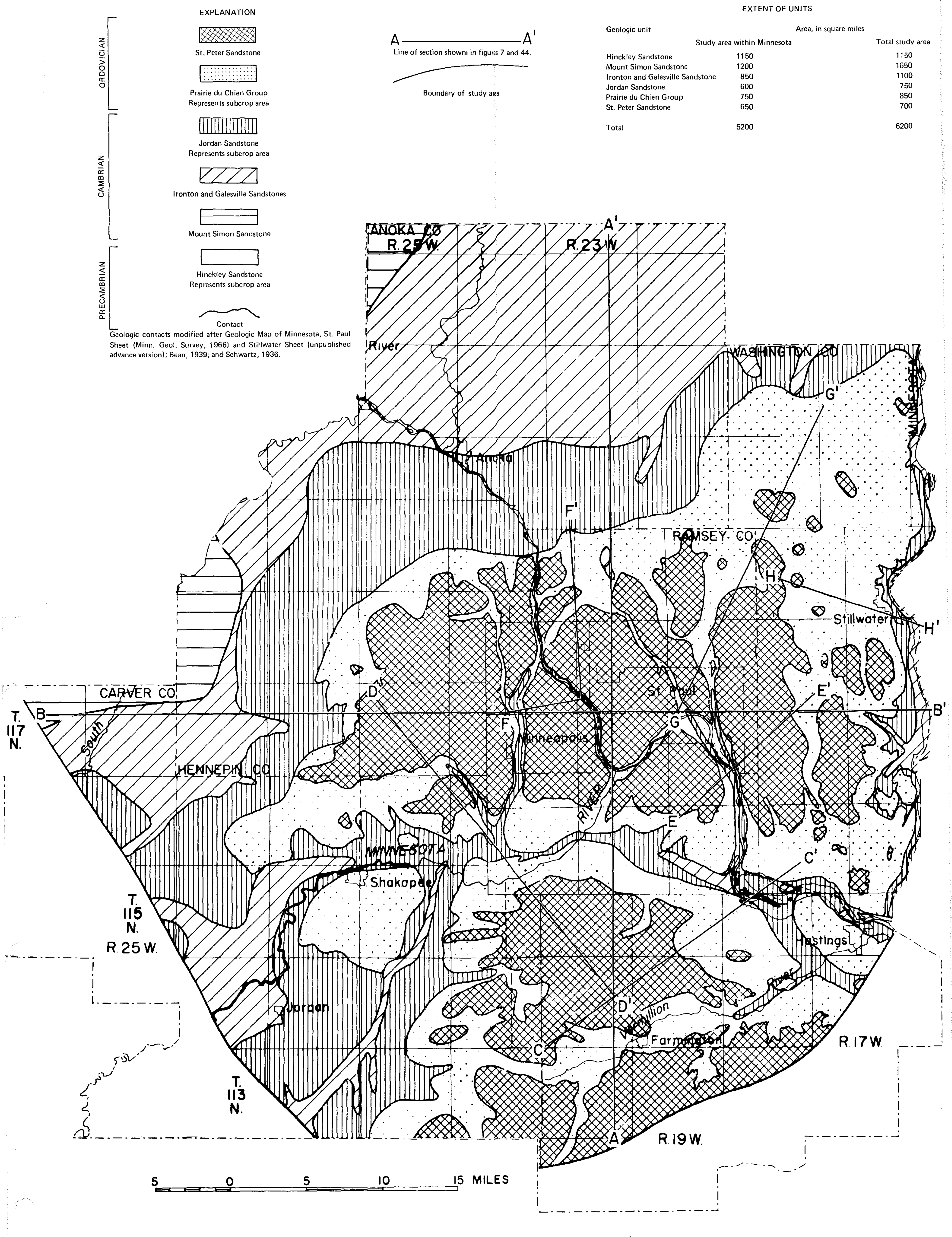
750

Equipotential line

Generalized direction of ground-water flow

Vertical exaggeration 40X

**Figure 44. – Generalized hydrogeologic cross sections of the Metropolitan Area. (Location of sections shown on Figure 45.)**




EXTENT OF UNITS

| Geologic unit | Area, in square miles: Study area within Minnesota | Area, in square miles: Total study area |
|---|---|---|
| Hinckley Sandstone | 1150 | 1150 |
| Mount Simon Sandstone | 1200 | 1650 |
| Ironton and Galesville Sandstone | 850 | 1100 |
| Jordan Sandstone | 600 | 750 |
| Prairie du Chien Group | 750 | 850 |
| St. Peter Sandstone | 650 | 700 |
| Total | 5200 | 6200 |

Figure 45. – Subsurface extent of selected bedrock units in the Metropolitan Area.

Examination of the flow sections show that in sections A-A', B-B', D-D', E-E', and F-F', water moves generally downward and laterally from highs on the water table, through the aquifers overlying the St. Lawrence Formation, and into the major stream in the section. In section C-C', water moves from the stream and from the aquifers overlying the St. Lawrence Formation downward into the Ironton-Galesville and Mount Simon-Hinckley aquifers. In section F-F', water moves upward from the Mount Simon-Hinckley and Ironton-Galesville aquifers, through the Franconia and St. Lawrence confining beds, into the Jordan Sandstone and hence into the stream.

The unique arch in the 750-foot equipotential line underlying the Mississippi River in section D-D' is probably due to the artificial control of the river by dams, causing the water in the river to be high at the same time that the water level in well 29.24.23ccb2 is low because it is in downtown Minneapolis, a heavily pumped area. Thus, although a part of the water underlying the downtown area flows to the stream, a larger part probably crosses the 750-foot potential line and flows perpendicular to the section, downstream to the south (toward the reader). In the summer, when water levels in the downtown area are drawn down from winter levels more than 70 feet, the direction of movement will be from the stream and into the aquifers. A similar seasonal reversal may occur near the streams, wherever that heavy pumping occurs.

Thus, the above sections show that all conditions of ground-water flow occur in the metropolitan area – from the streams into the aquifers, from the aquifers into the streams, from overlying aquifers into underlying aquifers, and from underlying aquifers into overlying aquifers; and the patterns can reverse from winter to summer.

In effect, the direction of the arrows (flow direction) in the sections show places of recharge and discharge in the aquifers. Where the arrows point downward and into the aquifer, recharge occurs; where the arrows point upward or downward out of the aquifer, discharge occurs. Where the arrows point laterally, the water is moving through the aquifer toward places of discharge.

**Recharge**

Most of the natural recharge to the bedrock aquifers in the study area is vertically percolating ground water from the saturated parts of the overlying glacial drift. Some direct recharge occurs where bedrock crops out, where the aquifers are exposed in the stream channels, and where the aquifers are in lateral contact with saturated rocks around the periphery of the study area. Most of the recharge to the aquifers in the glacial drift is from precipitation that percolates downward to the water table. Some appreciable recharge to the valley fill in the glacial drift occurs during times of high water in the streams and when heavy pumping from aquifers adjacent to the streams lowers ground-water levels in the drift below those in the stream channel (induced recharge). Locally, recharge may also come from underlying rocks, as previously discussed in the section on ground-water movement.

The greatest amount of recharge to the bedrock aquifers occurs in their subcrop areas. The subcrop areas of the Prairie du Chien-Jordan and Hinckley aquifers are shown in Figure 45. Recharge is probably maximum where the aquifer subcrops are in direct contact with the overlying glacial drift. The subcrop extent of the Prairie du Chien-Jordan aquifer in direct contact with the drift in the metropolitan area is about 1,350 square miles. About 450 square miles of the St. Peter is in direct contact with the drift (650 square miles minus 200 square miles of overlying Platteville Limestone). A similar determination of direct subcrop contact with the glacial drift cannot be made of the other bedrock aquifers because the extent of the intervening confining beds (Table 2) is not mapped as yet. However, the approximate subcrop of the Hinckley part of the Mount Simon-Hinckley aquifer is mapped in the northern part of the study area and is 1,160 square miles.

Vertical recharge (leakage) to the aquifers can be estimated by the following form of Darcy's Law (see Walton, 1965, p. 33);

$$Q_c/A_c = 2.8 \times 10^7 \, (P'/m')\Delta h$$

where

$Q_c/A_c$ = recharge rate, in gallons per day per sq mi

$Q_c$ = recharge through deposits, in gallons per day

$A_c$ = area of diversion, in sq mi

P' = vertical hydraulic conductivity (coefficient of vertical permeability) of deposits (confining bed), in gallons per day per sq ft

m' = saturated thickness of deposits (confining bed), in ft

$\Delta h$ = difference between the head in the aquifer and in the source bed above the deposits (confining bed) through which recharge occurs, in ft

In order to apply the preceding formula and thus arrive at recharge rates, it is necessary to know the head difference between the water in the glacial drift and that in the aquifers, and the P' of the various kinds of glacial drift that directly overlie the aquifers. Where recharge is to be determined from bedrock aquifer to bedrock aquifer, the P' of the intervening confining bed must be known. It was not within the scope of this study to make field determinations of the P' of the various kinds of glacial drift or of the bedrock units, but Norris (1962) gives values of P' of glacial till in South Dakota ranging from 0.0003 to 0.5 and averaging 0.07 gpd per square foot. These data are probably comparable with vertical conductivities in the till of the Des Moines lobe in the study area. Walton (1965, p. 35) gives values for the different kinds of drift in Illinois; part of these data are repeated in Table 7. The values of the first two lithologic types in this table are probably comparable with the outwash, valley train, valley fill, and alluvial deposits in the study area.

Table 7. – Summary of coefficients of leakage and vertical hydraulic conductivity (from Walton, 1965).

| Lithology | P' / m' (gpd/cu ft) range | P' (gpd/sq ft) range | | | P' (gpd/sq ft) average |
|---|---|---|---|---|---|
| Drift, sand, and gravel, some clay and silt | $3.4 \times 10^{-2}$ – $2.3 \times 10^{-1}$ | 1.02 | – | 1.60 | 1.31 |
| Drift, clay, and silt with considerable sand and gravel | $6.1 \times 10^{-3}$ – $5.2 \times 10^{-2}$ | 0.10 | – | 0.63 | 0.25 |
| Drift, clay, and silt with some sand and gravel | $8.3 \times 10^{-5}$ – $5.0 \times 10^{-3}$ | 0.01 | – | 0.08 | 0.03 |
| Drift, clay, and silt with some sand and gravel and dolomite | $4.5 \times 10^{-5}$ – $3.2 \times 10^{-4}$ | 0.005 | – | 0.011 | 0.008 |
| Drift, clay, and silt with some sand and gravel and shaly dolomite | $5.1 \times 10^{-5}$ | 0.005 | | | 0.005 |

The thickness and lithology of the glacial drift in the study area are extremely variable overall; however, the following approximations can be made. In a 1 square mile area where the Des Moines lobe till is 200 feet thick, P' is 0.07 gpd per square foot, and $\Delta h$ is 75 feet; the recharge rate is about 0.735 mgd. In a 1 square mile area where the outwash is 100 feet thick, P' is 1.3 gpd per square foot, and $\Delta h$ is 50 feet; the recharge rate is 18.2 mgd. Thus, over wide areas, recharge to the bedrock aquifers that are in direct contact with glacial drift may be substantial.

The St. Peter Sandstone may be capable of transmitting large volumes of water to the underlying Prairie du Chien-Jordan aquifer, as the sandstone in the metropolitan area is about 650 square miles in extent and has a relatively high P' value. Using a P' value of 80 gpd per square foot, a thickness of 100 feet, and a $\Delta h$ of 50 feet, the $Q_c$ for 1 square mile is 1,120 mgd, a tremendous volume of water. But, the St. Peter Sandstone apparently has a tight confining bed at its base whose P' is very low. Using a probable P' of 0.00003 gpd per square foot, an average thickness of 3 feet, and a $\Delta h$ of 50 feet, the $Q_c$ for 1 square mile is only 140,000 gpd, a not so large volume of water. Thus, the volumetric transmission of water between the bedrock aquifers is largely dependent on the vertical hydraulic conductivities of the intervening confining beds and not so much on that of the aquifers. Where the St. Peter is breached, however, by erosional valleys, the rate of transmission is dependent on the characteristics of the valley fill. Quantitative estimates of recharge available to the major bedrock aquifers are made later in this report.

One type of recharge that was briefly mentioned above is induced recharge. This occurs where wells, pumping in an aquifer adjacent to and in hydraulic connection with a stream, draw water levels in the aquifer below the water surface in the stream. Water, which under natural conditions would flow out of the area, is induced into the wells. The above sentence implies that the recharge water comes directly out of the river and into the aquifer at the time of withdrawal, thereby restricting induced recharge only to wells completed in the valley-fill sediments in the stream valleys and making the timeliness of withdrawals a factor for consideration. However, a delayed form of induced recharge also occurs. Wells pumping in the Prairie du Chien-Jordan aquifer underlying the valley-fill sediments induce water into the aquifer from the overlying sediments by a reversal in head differences. The water removed from storage in the valley fill then is replaced with water from the stream. The time in which replacement (recharge) occurs need not be short, for it is dependent upon the hydraulic properties of the sediments and the distance between the stream channel and the place of withdrawal. The draft on the stream during the height of the pumping season and the summer low-flow period in the stream may be minimal. Thus, some surface water that ordinarily flows out of the area during seasons of low pumpage is captured by depressions in the water table caused by pumping during the summer. Similarly, ground water that under natural conditions discharges to the streams is captured by wells pumping adjacent to the streams and does not flow out of the area. Note, however, where reversals of flow are discussed herein, that the reversal is not instantaneous but occurs gradually. In an area where natural discharge is into a stream and significant pumpage occurs, the ground-water gradient toward the stream is first diminished. Ground-water discharge is lessened; thus stream baseflow can be appreciably affected before the actual reversal of flow from the stream to the area influenced by pumpage occurs.

**Discharge**

Water from the surficial drift aquifers discharges naturally through springs, seeps, and directly into streams and lakes. It discharges where the water table is at or near the surface in swampy areas through direct evaporation from the water table and through transpiration. A large part discharges by vertical downward percolation into the underlying bedrock aquifers. Water from the bedrock aquifers discharges through springs and seeps along the valley walls; as upward leakage into the valley-fill deposits and hence into the streams; and as underflow, largely to the southeast, out of the study area. Water is also discharged from the aquifers through pumping wells and through drainage ditches, sewers, and storm drains that are deep enough to penetrate the water table. Discharge through the latter may be appreciable in the metropolitan area.

Most ground water leaving the area is discharged into the three major streams. The flow arrows shown on the maps in Figures 19, 20, and 21 and on the cross sections in Figure 44 point toward places of discharge. Nearly all the discharge from the Prairie du Chien-Jordan aquifer and overlying aquifers, exclusive of evapotranspiration and that part withdrawn from wells, is to the Minnesota, St. Croix, or Mississippi Rivers. Aquifers underlying the Prairie du Chien-Jordan discharge water into the St. Croix River at least as far downstream as Stillwater, and into the Mississippi River, as far downstream as midway between Anoka and Elk River. Some water in the deeper aquifers (Ironton-Galesville and Mount Simon-Hinckley) moves out of the study area to the southeast, probably to discharge into the Mississippi River farther downstream.

It was not possible to delineate the discharge areas in any great detail. Ground water may discharge locally to almost any lake, wetland, stream channel, or low place depending on the position of the water table. The flood plains of the major streams undoubtedly are discharge areas for the bedrock aquifers as well as for the valley-fill drift aquifers, at least during low streamflow. During high flow or floods, the flood plains may recharge these aquifers. Also, during maximum ground-water pumping, parts of the flood plains may be recharge areas.

The baseflow, including bank-storage and basin-storage discharge in streams is due to ground-water discharge. Therefore, it should be possible to determine the most significant part of the ground water discharged by measuring the gain in baseflow in the reaches of the three major streams within the area. The basin-storage discharge part of this water represents, for all practical purposes, a measure of the maximum level of ground-water development that can be attained without risking long-term depletion of ground-water storage or without resorting to recharging aquifers aritificially.

The evaluation of base flow is complex for the following reasons: 1) The boundaries cut freely across many drainage divides; therefore, baseflow in tributary streams, as well as underflow from outside, enters and leaves the area at ungaged sites. 2) Long-term stream-gaging stations were not situated at the boundaries of the area, so it was not possible to determine average annual base flow for the entire area. 3) Areal segmentation of the streamflow, so as to allow measurements of the baseflow at geologic contacts and thereby evaluate discharge from different groups of aquifers is impossible. The gradients of the major streams in the metropolitan area are flat and are controlled by dams, and the volumes of water in the channels are large. Therefore, the percentage of error incorporated in the streamflow measurements, in most places, amounts to a volume of water greater than that contributed by baseflow in any one reach; and the resolution as to the sources of water in the channels is not possible.

Despite the difficulties stated above an approximation of the average annual baseflow was made for the study area and the Twin Cities area. This flow was further separated into its components of bank-storage and basin-storage discharge (Table 5). It was found that about 500 mgd of basin-storage discharges from the part of the metropolitan area underlain by the Prairie du Chien-Jordan aquifer in an average year. Much of this basin-storage can be induced to flow into pumping wells close to the major discharge areas, and, thus, a large part of the water can be captured before it leaves the area.

**Hydraulics of Aquifers**

The hydraulic characteristics of an aquifer must be known in order to predict responses caused by the imposition of stresses on the aquifer. Responses, reflected as changes in the potentiometric surface (including the water table), result from changes in recharge to and discharge from the aquifer, either by natural or artificial means. Stresses relatively unimportant to the overall water resources in an aquifer, are those caused by compressional and decompressional forces, such as barometric pressure changes, earth tides, and even freight trains. The latter stresses are sometimes important to the hydrologist when determining hydraulic characteristics through use of aquifer (pumping) tests.

Aquifer tests are commonly used to determine the hydraulic characteristics of an aquifer. Although the results obtained from these tests are approximations, they are useful in evaluating aquifer performance. Values of transmissivity, T, and storage coefficient, S, may be computed; hydrologic boundaries located; and future effects of pumping or recharging predicted by using data obtained from these tests. Field tests were not a part of this study, but the T and S values obtained from several selected tests made in this area are compiled in Table 6. These tests are not numerous or widespread enough to give representative T's for their respective aquifers, but they do give an idea of the magnitudes to be expected. (For more information on aquifer testing, see Ferris and others, 1962, and Walton, 1962.)

All factors considered, aquifers with high T values yield more water with less drawdown to wells than aquifers with low T values. The magnitudes of the T values are dependent on the hydraulic conductivity and thickness of each aquifer. Thus, they may vary appreciably from place to place within the aquifer. The Prairie du Chien-Jordan aquifer, acting as a unit, has a greater T value on the average than either the Prairie du Chien or the Jordan acting alone. This is because of the thicker section being tested in the unit aquifer. When only a part of the aquifer is penetrated, the T obtained from pumping-test data will be lower than the actual value unless the proper adjustments are made in the data to account for the partial penetration. Adjustments were not made where the individual formations were tested as separate aquifers.

Storage coefficients, S, for some of the aquifers are shown in Table 8. S values, in addition to indicating the storage characteristics of an aquifer also indicate the hydraulic pressure condition in the aquifer. S values in water-table aquifers generally range from about 0.3 to 0.05 ($3 \times 10^{-1}$ to $5 \times 10^{-2}$) and in artesian aquifers from about 0.001 to 0.00001 ($1 \times 10^{-3}$ to $1 \times 10^{-5}$). (See Ferris and others, 1962.) All the tests for which data are available show that the water in the aquifers is under artesian pressure.

Where pumping-test data are not available, approximate T values can be determined by the following formula:

$$T = Km$$

where: T = transmissivity, in gallons per day per ft.

K = hydraulic conductivity, in gallons per day per sq. ft.

m = saturated thickness of aquifer, in feet

K values for most of the major aquifers are shown in Table 9. These data were compiled from various sources, and they were determined by laboratory analyses. Meyer (1933) determined from 74 tests that the K in the Jordan Sandstone is about 50 feet per day, or about 375 gpd per square foot (50 cu ft. per sq. ft. per day). The rock samples analyzed were taken from outcrops of the sandstone at Stillwater and Hastings. Assuming that Meyer's data are representative for a large part of the Jordan aquifer and taking the average thickness of the sandstone at 90 feet, then the average T of the Jordan aquifer is about 34,000 gpd per foot (90 x 375), somewhat less than the results obtained by pumping test analyses but in the same order of magnitude. The data in Table 9 show that the K values in the other aquifers, with the possible exception of the St. Peter, apparently are low compared with those in the Jordan.

Values for the vertical hydraulic conductivity, K', are also shown in Table 9. These data are generally obtainable from field aquifer tests only for confining beds through use of the leaky artesian aquifer formula of Hantush and Jacob (1955). Most often in aquifer-evaluation tests the aquifer is treated as an isotropic (equal flow properties in all directions) medium, hence only one K value is assumed. However, more recent work (Weeks, 1969) emphasizes the significance of the ratio of horizontal to vertical conductivity in an aquifer, so the vertical values are included here for any future application to which they may be applied. Artificial recharge may be one such application.

One parameter of aquifer performance dependent on the T and S values is hydraulic diffusivity, T/S. This governs the rate at which the effects of either pumping or recharging will spread about the center of stimulus. For example, in confined aquifers the diffusivity is commonly large, and the drawdown effects

Table 8. – Hydraulic characteristics of aquifers in the metropolitan area determined from field pumping tests in selected wells
(Data interpretations by Minnesota Division of Waters, Soils and Minerals and U.S. Geological Survey

| Well Location | Transmissivity (gpd per ft) | Storage Coefficient |
|---|---|---|
| St. Peter | | |
| 27.24. 6 ada | 37,500 | – |
| Prairie du Chien | | |
| 28.22.19 cdd2 | 51,500 (a) | $5.0 \times 10^{-5}$ (a) |
| 28.22.19 dcc2 | 46,800 (a) | $1.1 \times 10^{-5}$ (a) |
| 118.22.29 cbc | 55,000 | $3.4 \times 10^{-4}$ |
| Average | 51,100 | $1.3 \times 10^{-4}$ |
| Jordan | | |
| 27.22.16 aad | 67,400 | – |
| 27.23.19 dca | 21,800 (a) | – |
| 27.24. 2 bca | 14,600 (a) | – |
| 27.24. 3 acb2 | 20,300 | – |
| 27.24.31 cdb | 14,200 | – |
| 28.24.26 aaa | 49,900 (a) | $1.2 \times 10^{-4}$ (a) |
| 28.24.26 aab | 54,800 (a) | – |
| 28.24.26 baa | 45,600 (a) | $8.3 \times 10^{-5}$ (a) |
| 28.24.26 bbb | 80,000 (a) | – |
| 119.21.25 cdcl | 54,200 (a) | $4.9 \times 10^{-5}$ (a) |
| 119.21.25 cdc2 | 59,900 (a) | $5.8 \times 10^{-5}$ (a) |
| 119.21.36 bbb | 45,000 (e) | $5.2 \times 10^{-5}$ (e) |
| Average | 44,000 | $7.2 \times 10^{-5}$ |
| Prairie du Chien - Jordan | | |
| 27.24. 2 bca | 38,600 | $6.5 \times 10^{-4}$ |
| 28.22. 6 aca | 82,100 | $5.0 \times 10^{-4}$ (a) |
| 28.23.29 cca | 142,500 (a) | $4.8 \times 10^{-5}$ (a) |
| 28.23.29 cdb | 93,500 (a) | – |
| 28.24.26 bdc | 37,200 | – |
| 28.24.26 ccc | 44,500 | – |
| 29.22.31 cac | 48,000 (a) | – |
| 115.18.18 cbd2 | 104,000 | $4.7 \times 10^{-4}$ |
| 116.21.20 cbd | 198,000 | – |
| 118.21.33 cbb2 | 66,000 (a) | – |
| 118.22.29 cbc | 55,000 | $3.4 \times 10^{-4}$ |
| Average | 82,700 | $4.0 \times 10^{-4}$ |
| Mount Simon - Hinckley | | |
| 30.24.14 dcb | 21,500 | $7.2 \times 10^{-5}$ |
| 30.24.14 dcc | 23,200 (a) | $6.6 \times 10^{-5}$ (a) |
| 30.24.14 dda | 20,800 | – |
| 117.21. 8 dcd5 | 11,700 (a) | $8.3 \times 10^{-3}$ |
| Average | 19,300 | $2.8 \times 10^{-3}$ |

(a) average of test results (e) estimated average from a well will spread rapidly. In unconfined aquifers the diffusivity is commonly much smaller, and the drawdown effects will spread at a much slower rate. This ratio is especially important when considering the spacing of high-yield wells in artesian aquifers, which include almost all the bedrock and some of the drift aquifers in the study area.

Hydrologic boundaries, both positive (permeable) and negative (impermeable) are an important factor in the analysis of any flow system. Positive boundaries exist where an aquifer terminates at its contact with saturated permeable rocks or a surface-water body. For example, the major streams and the valley-fill deposits underlying the streams are positive boundaries to the Prairie du Chien-Jordan aquifer. When pumping or recharging this aquifer, the flow at the positive boundaries will be altered, so that no additional drawdown or build up of water levels will occur within the aquifer at those boundaries. Negative boundaries exist where an aquifer terminates at its contact with impermeable rocks. For example, clay till and confining beds are negative boundaries where they come in contact with the Prairie du Chien-Jordan aquifer. When pumping or recharging this aquifer, no significant additional drawdown or build up will occur beyond these boundaries; and any responses within the aquifer will be reflected, hence, intensified at the boundaries.

Boundary conditions are extremely complex in this hydrologic system, and the aquifer characteristics, especially transmissivity, change rapidly from place to place; therefore evaluation of the system by piece-meal analytic analyses is not feasible. Modeling the entire system would be a solution.

### Effects of Pumping

In any metropolitan area, where thousands of pumping wells yield most of the water supply, knowledge of basic principles of pumping effects is necessary for proper water management. The following discussion is based largely on a paper by Theis (1938), in

Table 9. – Hydraulic properties of rock samples as determined by laboratory analyses. (Data from U. of Minnesota, Minneapolis Gas Co., and U.S. Geological Survey.)

| Aquifer Rock Unit | Average Porosity | | Hydraulic Conductivity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Horizontal, K | | | | | Vertical, K' | | | | |
| | No. of Samples | Percent | No. of Samples | Range | | Median | | No. of Samples | Range | | Median | |
| | | | | Feet/Day | Meters/Day | Ft./Day | M/Day | | Feet/Day | Meters/Day | Ft./Day | M/Day |
| St. Peter | 10 | 28.3 | 10 | 0.16 – 26.9 | 0.05 – 8.2 | 12.5 | 3.8 | 5 | 0.03 – 43.9 | 0.01 – 13.4 | 10.9 | 3.3 |
| Prairie du Chien | 43 | 5.6 | – | – | – | – | – | – | – | – | – | – |
| Jordan | 2 | 31.8 | 3 | 4.6 – 166.0 | 1.4 – 50.6 | – | – | 2 | 0.98 – 4.59 | 0.3 – 1.4 | – | – |
| Ironton-Galesville [1] | 20 | 25.3 | 7 | 0.167 – 1.716 | 0.051 – 0.523 | 0.345 | 0.105 | 7 | 0.010 – 0.869 | 0.003 – 0.265 | 0.236 | 0.072 |
| Mount Simon [1] | 213 | 23.3 | 207 | 0.033 – >4.895 | 0.010 – >1.492 | 3.222 | 0.982 | 207 | 0.003 – >4.895 | 0.001 – >1.492 | 2.333 | 0.711 |
| Hinckley [1] (Fond du Lac) | 82 | 21.0 | 54 | 0.000 – 3.708 | 0.000 – 1.130 | 0.479 | 0.146 | 54 | 0.000 – 3.596 | 0.000 – 1.096 | 0.364 | 0.111 |

[1] Drilling cores by Minneapolis Gas Co. from wells south of the report area.

which he discusses the significance of the cone of depression in ground-water bodies.

Before being tapped by wells, an aquifer is in a near state of equilibrium, that is, natural recharge is equal to natural discharge over the long term. When additional discharge is imposed upon the aquifer by pumping, the balance is disturbed, and either natural recharge must increase, natural discharge must decrease (be captured), water storage must decline or a combination of these changes occurs. Upon pumping a well, a cone of depression (or influence), whose apex is at the well, is formed in the vicinity of the well. The lateral extent of the cone depends on the transmissivity and storage coefficient of the aquifer, the duration of pumping, and the location of positive and negative boundaries. The vertical extent is dependent upon the transmissivity and rate of pumping.

In water-table aquifers, the initial lateral growth of the cone is hundreds to possibly thousands of feet per day. In an artesian aquifer, where the storage coefficient is much smaller than that of a water-table aquifer, the initial spread is from thousands to tens of thousands of feet per day. As the cone steepens, the hydraulic gradient of the moving water in the aquifer is increased, and, in effect, water influenced by the cone is funneled into the pumping well.

As the pumping well discharges more and more water, the cone of depression expands. Initially, water comes from storage in the aquifer, and the potentiometric surface declines. When the cone extends to areas of recharge or natural discharge or both, the draft on storage is decreased, and the cone tends toward equilibrium. One source of natural discharge that may be intercepted is rejected recharge in areas where the water table is above (ponds or lakes) or near the land surface (swamps) and the aquifers are filled to capacity. Where the water table is above the land surface, water is discharged by evaporation. Where the water table is near the land surface, the growth of vegetation is promoted, and, water is discharged by evapotranspiration. Space is provided for water to enter into the ground-water reservoir by lowering the water table or pressure surface in a rejected recharge area.

Another source of natural discharge that may be affected by pumping is streamflow out of an area. If a stream falls under the influence of a cone of depression, water that ordinarily would flow out of an area is diverted to the pumping well (induced recharge). Also, in some areas, partial interception by the cone of ground water flowing toward a gaining stream causes a decrease in the rate of baseflow in the stream.

Where the cones of two or more pumping wells intersect (well interference), the decline of water level in each well is increased and the discharge of each well is reduced. This condition prevails in and around the Twin Cities.

**Water-Level Fluctuations**

Under natural conditions, water levels are generally highest in the spring, during maximum recharge from snow and frost melt; decline through the summer, when evapotranspiration is high and discharge exceeds recharge; tend to level out, but continue downward in the fall; are lowest in winter, when all potential recharge (precipitation) is stored at the land surface as snow; and rise again in the spring, to complete the annual cycle. In the metropolitan area, where ground-water pumpage for air conditioning and lawn watering peaks during the hottest days in late June, July, and early August, the annual lowest water levels occur in mid-summer; and the natural pattern of annual fluctuations is changed.

The balance between recharge and discharge in the aquifers can be monitored with water-level hydrographs. The most significant practical use of observation-well hydrographs is to determine long-term water-level trends. If water levels annually return to about the same position, climatic cycles being considered, then recharge to and discharge from the aquifer is in near balance. However, if water levels following a continuing long-term declining trend, then discharge exceeds recharge and water is being removed from storage in the aquifer.

*Long-Term Trends*

Hydrographs of wells completed in some of the major aquifers are shown in Figures 22 and 46. Wells 117.21.16cca and 29.23.30bdal, in St. Louis Park and east of the Mississippi River near downtown Minneapolis, respectively, monitor water-level changes in the Prairie du Chien-Jordan aquifer. These hydrographs show no local decline in ground-water storage since about 1958. In 1955 and in 1958, the water level in the well near downtown Minneapolis dropped 5 to 10 feet. The water-use graph in Figure 2 shows a sizeable upswing in ground-water pumpage, beginning in about 1955. Assuming increased pumpage from well 29.23.30bdal, the drop in the water levels in 1955 and 1958 is explainable. However, pumpage continued to increase since 1958, as shown by the wider and deeper water-level fluctuations during the summer periods, but long-term trends ceased to decline. The plausible explanation for this is that a positive recharge boundary was intercepted by the composite cone of depression caused by all the pumping wells near well 29.23.30bdal, and the new source of recharge is enough to supply the wells without any net removal of water from aquifer storage. This new source is most probably induced recharge from the Mississippi River plus captured aquifer discharge that ordinarily would have flowed into the river. Because these types of recharge are important to the conservation of the water resources in the metropolitan area, further elaboration on conditions near this well follow.

The altitude of the land surface at well 29.23.30bdal is about 840 feet, and the well is situated about half a mile northeast of the river, whose altitude is about 725 feet. Thus the 725-foot altitude is about 115 feet below land surface at the well site. Referring to the hydrograph (Figure 22), it can be seen that water levels at the well did not draw down appreciably below river level until the summer of 1955, from which time they continually fell below river level each successive summer. When pumping increased in 1955, the composite cone of depression spread laterally and vertically to engulf more sources of recharge, and, as ground-water levels dropped below river level, the flow gradient between the well and the river reversed itself, and water from the river began to flow seasonally into the pumping wells. The recharge sources are now sufficient to supply the wells in this vicinity, and the cone of depression for these wells has, in essence, stabilized; little, if any, water is presently being removed from storage in the aquifer.

The long-term water-level in well 117.21.16cca also has nearly stabilized. The altitude of the land surface at this site is about 917 feet, and the lowest summer pumping levels have reached little more than the 800-foot altitude; thus, recharge from the larger streams has not been induced here. The geologic maps (Figures 9 and 45) show that the Prairie du Chien-Jordan aquifer at this place is overlain by St. Peter Sandstone and glacial outwash. Comparison of the potentiometric-surface maps for winter and summer (Figures 20 and 43, respectively) show that heavy summer pumping in this general vicinity has caused an appreciable steepening of the potential gradient immediately east of Lake Minnetonka and west of the well. Examination of the winter to summer water-level-change map (Figure 47) further shows that the cone of influence created by the heavy summer pumping in this general vicinity has encompassed a very large area. Therefore, a combination of two recharge sources has probably stabilized long-term water-level conditions in this area: 1) the cone of influence has spread out far enough and induced enough additional recharge in the form of leakage from the overlying rocks to supply the heavy summer pumping demands, and 2) the cone of influence has spread out far enough to intercept a natural recharge area, Lake Minnetonka, and additional recharge also is now being induced from that area.

The effects of heavy withdrawals from the Prairie du Chien-Jordan aquifer on water in storage in the glacial drift underlying Lake Minnetonka is shown in Figure 46. Well 117.22.8bdb3 is 88 feet deep and completed in glacial sand and gravel. The water in the drift aquifer at this depth apparently is under artesian conditions. Well 117.22.8bdb2 is 503 feet deep and completed in the Prairie du Chien-Jordan aquifer. The hydraulic connection between the two aquifers is shown by the close correlation of fluctuations in the hydrographs of these two wells. Pumping in the bedrock aquifer has drawn down the water levels in the overlying drift about 13 feet during 1945-64. Measurement of water levels in both wells was terminated in 1964, but a spot measurement made on March 8, 1972, still showed about a 5-foot difference between the water levels in the two aquifers, that in the drift was 18.5 feet below land surface and that in the bedrock was 23.8 feet. Assuming a storage coefficient of 0.005 in the glacial drift, the 13 feet of drainage would amount to about 14 million gallons of water removed from storage for each square mile of drift aquifer affected by pumpage in the bedrock. Significantly the entire geologic sequence (Table 2), excluding the Decorah Shale, is present between the drift and the Prairie du Chien-Jordan aquifers at this site. Thus, the effects of pumping from the lower aquifer are rapidly transmitted through the intervening bedrock strata to the drift, and recharge water must be percolating through these intervening strata to the lower aquifer.

The hydrograph of well 29.24.27dba (Figure 22), the Minneapolis Auditorium well, shows a continual decline up through about 1963 and then a leveling out. This is a multi-aquifer well and should show the composite water levels in the aquifers penetrated, but the altitudes of the water levels in the fluctuations suggest that the potentiometric surface of the Prairie du Chien-Jordan aquifer is reflected more so than that of any other. The sudden increase in summer drawdowns since 1965 is probably due ot the installation of new well(s) somewhere nearby in the Prairie du Chien-Jordan aquifer.

The magnitude of historical water-level declines in selected wells in the Mount Simon-Hinckley aquifer throughout the metropolitan area is shown in Table 8. The maximum recorded decline is 165 feet in well 29.23.19cddl, in an industrial area just east of downtown Minneapolis. The hydrograph of this well is shown in Figure 22. Its rate of water-level decline was about 3 feet per year from 1958 to 1961 and about 7 feet per year from 1961 to 1966. (Unfortunately, this well is no longer representative of potentiometric levels in the Mount Simon-Hinckley aquifer, for an apparent rupture in the well casing allowed water from the overlying aquifers to enter the well. As a result, the water level rose about 76 feet in 2 years, to where it became nearly equal to water levels in the Prairie du Chien-Jordan aquifer.) The hydrograph of well 117.21.32dadl (Table 10 and Figure 22) shows a continued drop of water levels of about 10 feet per year, but the 1970 levels suggest a possible reduction in this rate. Both Edina and St. Louis Park have municipal wells completed in this aquifer in this general area, so the annual withdrawals here are appreciable. The long-term declines shown on the above two hydrographs indicate that discharge by pumping exceeds recharge to the aquifer. Recharge by vertical leakage from the rocks above the Mount Simon-Hinckley is relatively slight because of tight confining beds in the overlying Eau Claire Sandstone. Most of the recharge moves laterally from places where the aquifer is directly overlain by glacial drift at the outskirts of the metropolitan area. Ground-water movement is slow, roughly 60 feet per year, in the 18 miles between the outermost extent of the Ironton-Galesville aquifer in the NW1/4 sec.4, T.117 N., R.24 W., to the site of well 177.21.32dadl (Figures 3 and 45). Water levels will continue to decline in this aquifer until the composite cones of depression have spread far enough and deep enough to move in enough water to supply the pumping demands or until pumpage is reduced. Up to that time, water will continue to be removed from storage in the aquifer.

The hydrographs shown in Figures 22 and 46 represent the best long-term records available of water-level fluctuations in the major aquifers. A look at the data-collection-site map (Figure 3) shows that the areal representation afforded by these records is small in comparison to the size of the area. No long-term continuous records of water levels in the glacial drift or in the St. Peter aquifers are presently being recorded. The significance of monitoring water levels in the shallower aquifers is emphasized in Figure 46. An enlarged observation-well program in the metropolitan area would aid greatly in future evaluations of the water resources.

*Short-Term Changes*

In this report, short-term changes are those of 5 years or less. The hydrographs discussed previously show annual and seasonal short-term changes at specific sites but do not depict the areal distribution of

**Figure 46. – Long-term water-level fluctuations in two wells east of Lake Minnetonka.**

**Figure 47. – Water-level changes from December 1970 to late August 1971 in the Prairie du Chien-Jordan aquifer in the metropolitan area.**

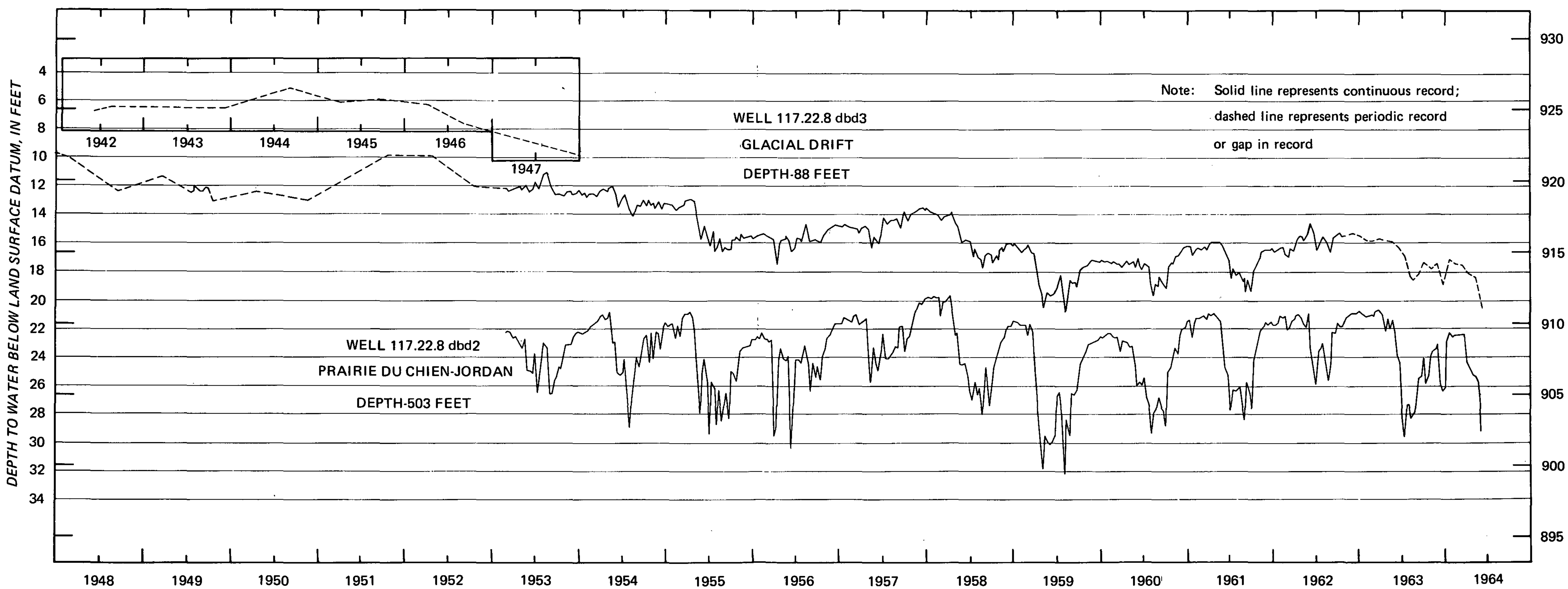



**Figure 46. — Long-term water-level fluctuations in two wells east of Lake Minnetonka.**

EXPLANATION

—— -30 — —

Line of equal water-level change
August 1971 water level indicated above (+) or below (-) the December 1970 level. The Minnesota, Mississippi, and St. Croix Rivers represent lines of zero change. Interval 5 and 10 feet.

○

Non-pumping well used for control

●

Pumping well used as an inference

— — — — — — —

Contact
Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, 1936.

———

Boundary of study area

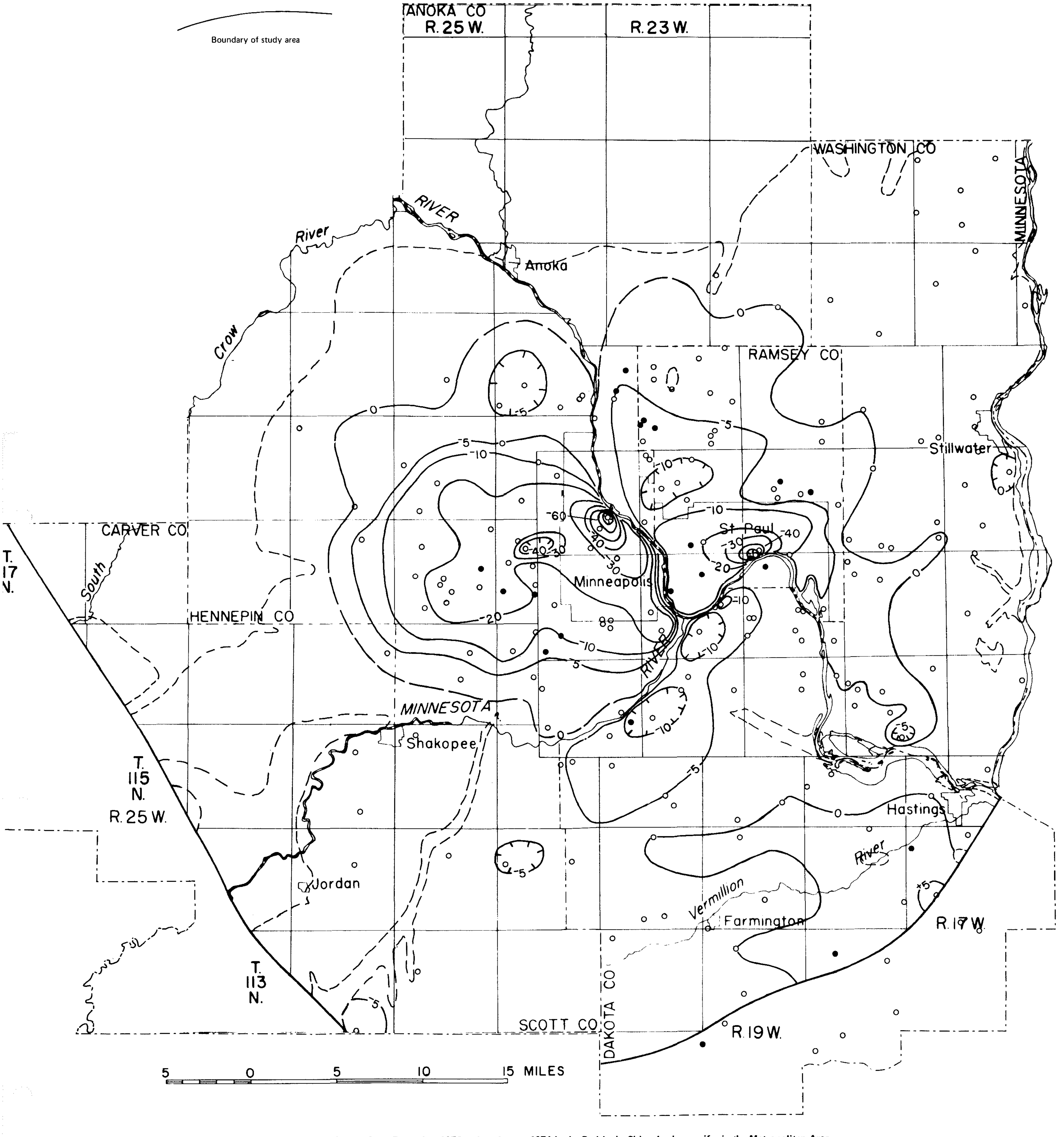



**Figure 47. — Water-level changes from December 1970 to late August 1971 in the Prairie du Chien-Jordan aquifer in the Metropolitan Area.**

Table 10. – Historical water-level changes in the Mount Simon-Hinckley aquifer in the metropolitan area.

| | | Water Level Measurements | | | | |
|---|---|---|---|---|---|---|
| | | Initial | | Most Recent | | |
| Well Number | Owner | Date | Water level, in feet below measuring point | Date | Water level, in feet below land surface | Difference in feet |
| 28.24.31dcb2 | Village of Edina | 1963 | 149 | Dec. 1970 | 237 | -88 |
| 29.22.30bab2 | Burlington Northern Railway | 1947 | 152 | Dec. 1970 | 168 | -16 |
| 29.23.19cddl | Burlington Northern Railway | 1912 | 47 | 1966 | 212 | -165 |
| 25ccc | Burlington Northern Railway | 1913 | 77 | Dec. 1970 | 205 | -128 |
| 29.24.22dad2 | Nicollet Hotel | 1925 | 98 | 1968 | 177 | -79 |
| 22ddd | Federal Reserve Bank | 1922 | 98 | 1971 | 215 | -117 |
| 29.24.25dbcl | St. Mary's Hospital | 1931 | 125 | Nov. 1971 | 190 | -65 |
| 27aaa | Curtis Hotel | 1926 | 106 | 1971 | 212 | -106 |
| 27abal | American Linen | 1928 | 109 | Dec. 1970 | 220 | -111 |
| 35cdc | Sears-Roebuck | 1928 | 112 | Jan. 1971 | 231 | -119 |
| 30.23. 8bbc | Village of Mounds View | 1962 | 160 | Dec. 1970 | 209 | -49 |
| 30.24.14dcal | Village of Fridley | 1962 | 140 | Feb. 1971 | 185 | -45 |
| 14dcb | Village of Fridley | 1962 | 120 | Feb. 1971 | 170 | -50 |
| 14dcb | Village of Fridley | 1962 | 151 | Feb. 1971 | 192 | -41 |
| 31.21. 1cbbl | Village of Anoka | 1959 | 8 | 1971 | 34 | -26 |
| 32.21. 5dcb | Village of Forest Lake | 1965 | 85 | Dec. 1970 | 93 | -8 |
| 33.21.20bcb | Village of Wyoming | 1965 | 26 | Jan. 1971 | 18 | -8 |
| 33.26.34cab | City of Elk River | 1919 | +15 | Feb. 1971 | +6 | -9 |
| 115.19.13dba | Great Northern Oil Company | 1964 | 240 | Feb. 1971 | 266 | -26 |
| 115.26.28ccc2 | Village of Hamburg | 1943 | 128 | Jan. 1971 | 116 | +12 |
| 117.21. 8dcd5 | Village of St. Louis Park | 1960 | 221 | Dec. 1970 | 329 | -108 |
| 30bab2 | Village of Edina | 1964 | 252 | Aug. 1971 | 325 | -73 |
| 32ad1 | Village of Edina | 1957 | 212 | Dec. 1970 | 312 | -100 |
| 117.24.13bbc | Village of Mound | 1962 | 70 | Dec. 1970 | 72 | -2 |
| 118.27. 3cacl | Village of Howard Lake | 1956 | 148 | Dec. 1970 | 147 | +1 |
| 119.21.22ccb | Village of Brooklyn Park | 1961 | 106 | Aug. 1971 | 162 | -56 |
| 119.21.23cdd | Village of Brooklyn Park | 1961 | 115 | Dec 1970 | 164 | -49 |
| 119.26.35dda | Village of Montrose | 1940 | 78 | Dec. 1970 | 78 | 0 |

change. Therefore, as a part of this study, water-level measurements were made in the winter of 1970-71 and in the late summer of 1971 in wells completed mainly in the St. Peter, Prairie du Chien-Jordan, and Mount Simon-Hinckley aquifers. Data were sufficient to make water-level-change maps (Figures 47 and 48) only for the Prairie du Chien-Jordan aquifer, the major source of ground water in the metropolitan area. The data that were collected on water levels in the lesser aquifers, however, will be useful for spot evaluations of change when these same wells are re-measured in the future.

A 5-year water-level-change map for the Prairie du Chien-Jordan aquifer is shown in Figure 48. Although more than 300 wells were measured, only the wells spotted on the map were available for the 5-year comparison. The major areas of water-level decline are in the west Minneapolis suburbs, especially in the Edina, St. Louis Park, and Hopkins vicinities; in the mid-north Minneapolis and St. Paul area near St. Anthony; and in the newly populated area immediately south of the Minnesota River, which includes Burnsville and Eagan Township. Rises in water levels may also have occurred in the aquifer. The rise west of the Mississippi River near the center of T.28 N., R.22 W. may reflect a reduction in industrial withdrawal since 1970. However, some of the other rises are unexpected and unexplainable.

A seasonal water-level-change map from winter 1970-71 to late summer 1971 is shown in Figure 47. Centers of heavy summer pumping are easily discernible on the map. Also the extents of the composite cones of depression are circumscribed about these pumping centers. Already the drawdown cones in downtown Minneapolis and in the west Minneapolis suburbs share the 20-foot isocline, and the 30-foot isoclines are either near or connected to each other. If summer pumping increases appreciably, the 30-foot and 40-foot isoclines should merge, the wells will interfere with one another more so than now, and these two cones of depression will deepen more rapidly. Therefore, more excessive summer drawdowns than were experienced in 1971 may be expected in the future unless pumping is abated. Recirculating and reusing air conditioning water, such as some of the new building in the Minneapolis downtown area, would aid in pumping abatement.

Places where recharge water is being induced from the Mississippi River are also shown on Figure 47. Minneapolis, where the winter potentiometric surface (Figure 20) is at an altitude of about 775 feet, and St. Paul, where the winter potentiometric surface is at about 725 feet, each have summer drawdown cones greater than 70 and 50 feet in depth, respectively. The altitudes of the pumping levels in these cones are below the surface altitude of the river in both cities; thus, the potential exists for natural discharge from the aquifer and recharge from the river to be directed into the pumping wells.

The isoclines on the map terminate steeply along the rivers, which are shown as lines of zero water-level change. The lines of zero change away from the rivers show the approximate extent of the overall area affected by the increased summer pumpage in the metropolitan area. The slight rise in water levels in the extreme southeast corner of the map is probably due to an abundance of recharge for this year (1971) in an area where summer ground-water pumpage is not excessive.

The changes shown in Figure 47 are seasonally transitory, and the drawdown cones shown will have recovered almost fully by the next December.

### Lake-Level Fluctuations

The maintenance of lake levels has become an almost perennial problem for some of the lakes in the metropolitan area; however, the reason for declining levels is not always clearly understood. Efforts to restore levels include diversion of streamflow, pumping of water from wells into the lakes, and temporary damming of lake outlets. At some places where falling levels were suspected to be due to leakage through lake bottoms, large volumes of soil-binding materials were spread in an effort to plug the leaks.

Most lakes in glaciated areas are surface manifestations of the water table, and their levels fluctuate

**Figure 48. – Water-level changes from Winter 1965 to Winter 1970 in the Prairie du Chien-Jordan aquifer in the Metropolitan Area.**

EXPLANATION

+2

Line of equal water-level change
Approximately located, dashed where questionable. Winter 1970 water level indicated above (+) or below (-) the Winter 1965 level. The Minnesota, Mississippi, and St. Croix Rivers represent lines of zero change. Interval 2 feet.

Note: Winter water levels represent relatively static conditions in this aquifer — the hydrologic system is not static owing to perennial withdrawal, thus some of the water levels observed may be affected by nearby pumping and may give false impressions of long-term water-level changes.

Well used for control

Geologic contact
Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, 1936.

Boundary of study area

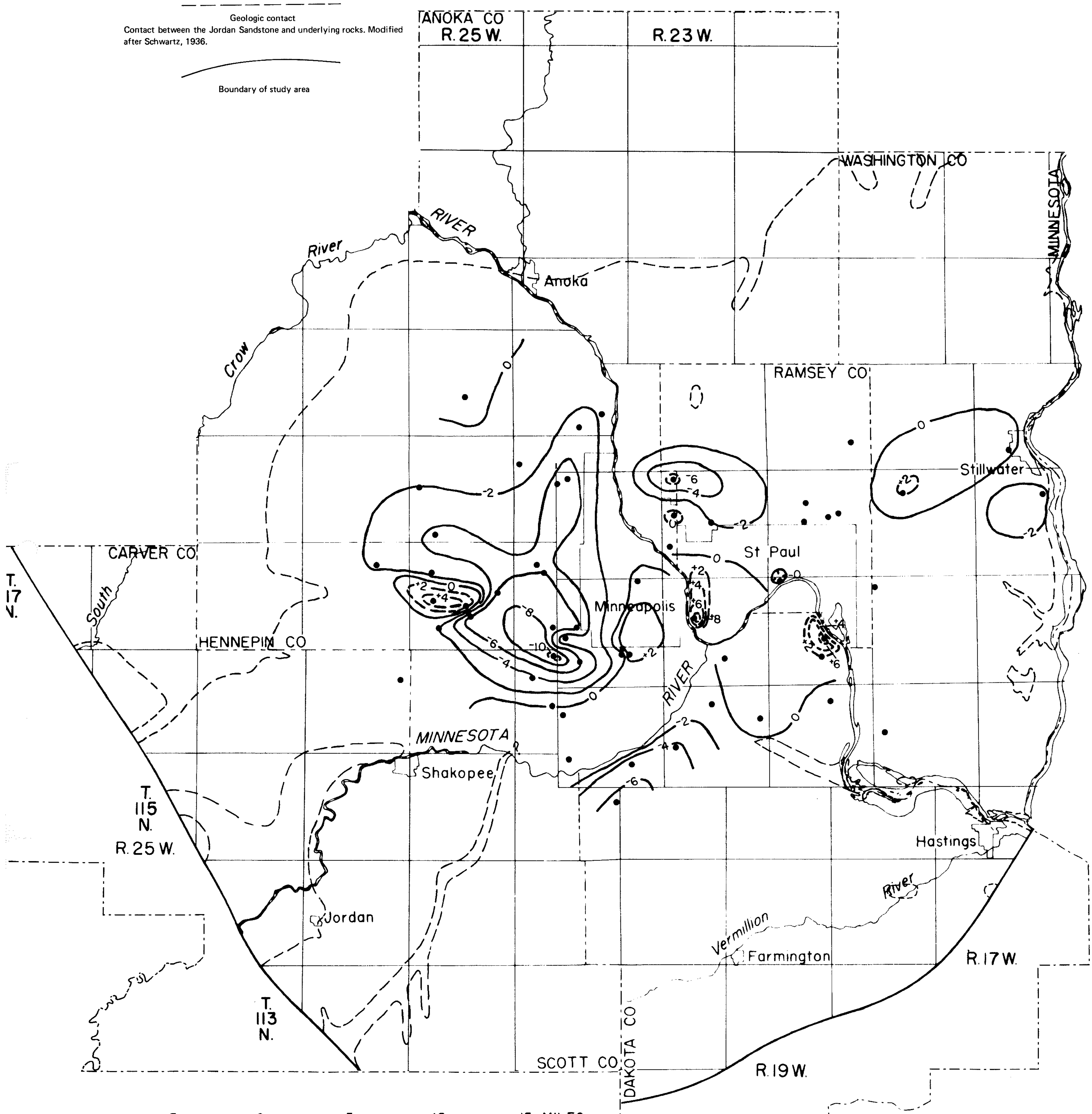



Figure 48. — Water-level changes from Winter 1965 to Winter 1970 in the Prairie du Chien-Jordan aquifer in the Metropolitan Area.

in response to the balance between ground-water discharge and recharge. Each lake has its own water budget. Discharge occurs at the outlet, if any; direct evaporation from the lake surface; transpiration by vegetation in the lake and around the shoreline; and leakage through the bottom. Water moves naturally through the lake bottom in response to the head differential between the lake water surface and the water table. When pumping from nearby wells pulls the water table below the lake surface, recharge to the well is induced from the lake.

Lake recharge occurs as natural inflow, if any; direct precipitation on the lake; overland runoff in rivulets and sheet flow around the lake; drainage from storm sewers and waste effluent (in some lakes); artificial recharge from wells and diverted streamflow; and upward leakage through the lake bottom, generally in response to a rising water table. In places such as Centerville Lake in southern Anoka County, where the head in the Prairie du Chien-Jordan aquifer is higher than the water surface in the lake, the lake can be recharged by upward leakage from underlying aquifers.

The water in a lake can seldom be separated from its ground-water component. Sealing of some lakes to prevent leakage through the bottoms may hinder recharge to the lakes from below, as adjacent water tables rise. Also, pumping of wells close to a lake being recharged may create cones of depression that will induce recharge from the lake into the wells, and a partly closed circulatory system may be set up, the lake constituting a positive recharge boundary for the well. Prolonged pumping to fill a lake causes increased drawdown in the adjacent aquifer. As the head difference between the lake surface (or the water table) and the pumping level in the aquifer is increased, the rate of leakage from the lake, or from the rocks overlying the aquifer, increases in direct proportion – doubling the head difference doubles the rate of leakage. If the hydraulic connection between the water table and the artesian aquifer is good, an appreciable amount of water could be withdrawn from the lake by the pumping well. If the lake bottom sediments are low in permeability, the leakage rate may be slow. In any event, the relation between the water in the lake and the water in the ground at each particular lake would logically be determined before modifications of the natural system are made.

Three possible lake-ground-water regimens are shown in Figure 49. The figure and part of the following discussion are adapted from Maclay and others (1971). In A, isopotential lines 11 are situated so that ground water can move into the lake, but the lake water at the level shown cannot move into the ground. If the lake level is raised above 11, water will move from the lake into the ground-water system. Also, a pumping well at the side of the lake could divert the potential lines from 11 and above into a cone of depression and induce water to flow out of the lake. In B, the isopotential lines are situated so that water is free to percolate through the lake-bottom sediments and into the ground. It is likely that water moves into the lake around the edges, but moves out of the lake at its center. In C, the water table on one side of the lake is lower than the lake level. Here water moves from the lake into the ground-water system on the left side and from the ground-water system into the lake on the right.

These examples are simple and used only to present concepts. In nature, hydrogeologic settings differ widely, and the lake-ground water relation may differ at each setting. Wide fluctuations in lake levels through the year will affect the direction of flow where the water table at the lake nearly coincides with the lake level. For example, in the spring, when surface runoff is high, causing lake levels to rise above the surrounding water table, water moves from the lake into the ground-water system. Conversely, during dry, hot summers, when evapotranspiration is at a peak and overland recharge to the lake has ceased, lake levels fall below the surrounding water table, and ground water moves into the lake.

The rates of movement both in and out of lakes are governed by the vertical conductivity of lake-bottom sediments. But, as no natural sediment is totally impermeable, some degree of movement will occur in the direction from high to low head potential. If the lake-ground-water relation is to be studied, piezometers around and in the lake are needed in order to measure ground-water gradients directly.

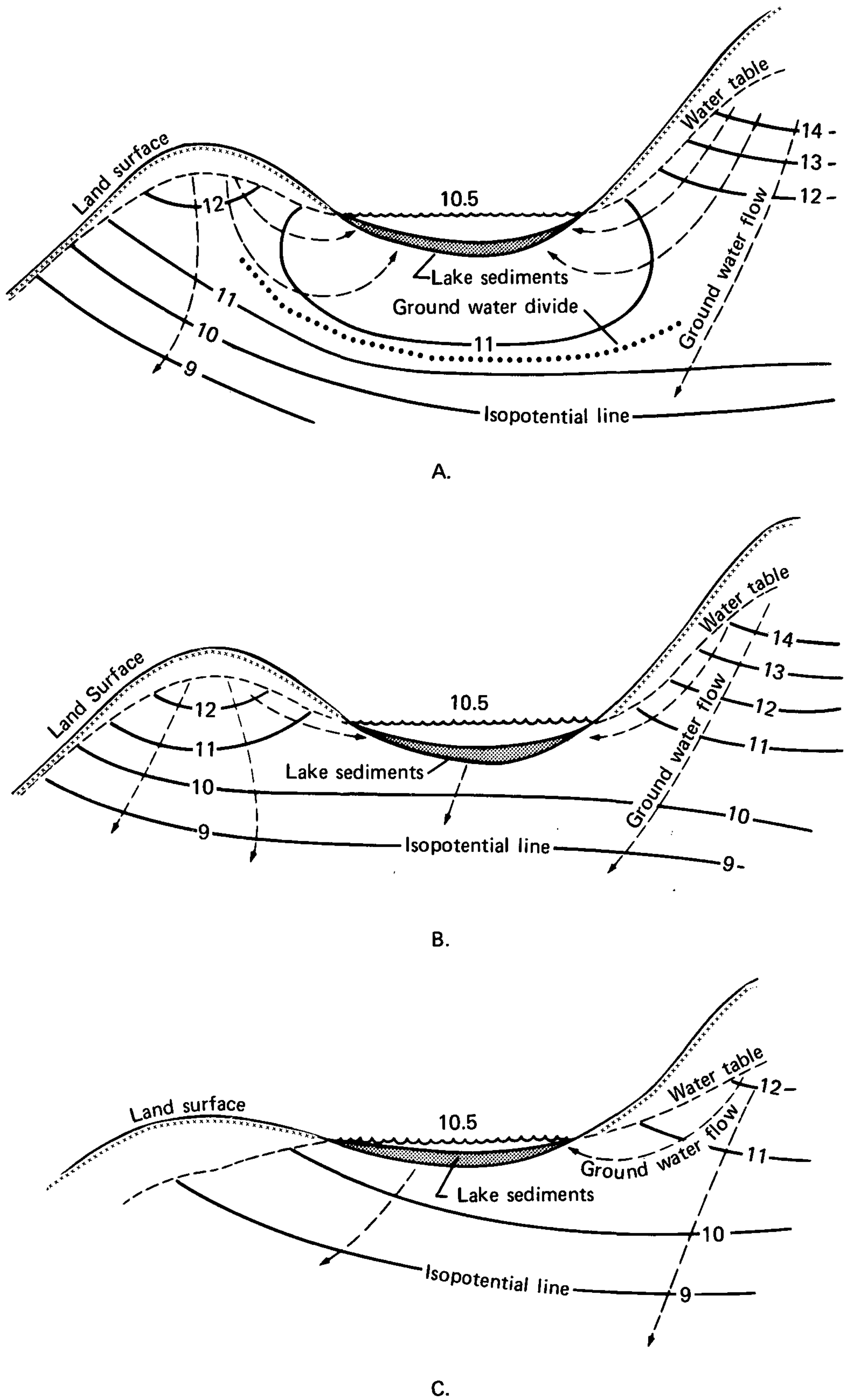



**Figure 49. — Hypothetical lake and ground-water regimens showing intermediate directions of flow.**

Also, vertical conductivities of the lake sediments and the underlying deposits need to be determined.

Lake-level graphs, showing historical seasonal and long-term fluctuations and volumes of water added for lake-level maintenance in some of the large lakes in the metropolitan area, are shown in Figure 50. The graphs show generally that lake levels fell below normal in the period of below-normal precipitation from 1929 to 1937, despite the addition of large volumes of water to the lakes. Also, lake levels were near or above normal in the period of above-normal precipitation from 1940 to 1946, with little or no addition of water. In the period of below normal precipitation from 1947 to 1950, levels dropped in Lake Calhoun, where no water was added, but were maintained, with some decline, in Gervais, Keller, and Phalen Lakes, with the addition of relatively small amounts of water. Since about 1952, water levels in Lake Calhoun hovered generally below normal, even though precipitation alternated above and below normal, and large volumes of water were added. Abundant precipitation in 1965 and 1968 plus addition of water barely brought the lake elevation back to normal. Progressively increasing withdrawals of ground water beginning in about 1952 (Figure 2) may be having an effect on this lake.

Lake elevations in Gervais, Keller, and Phalen Lakes show a slight general declining trend. When the stop logs are placed between Keller and Phalen Lakes, the level in Phalen drops accordingly. The hydrologic aspects of these lakes are complex, and more information than are shown on these graphs is needed before reasonable interpretations of the significance of the declines can be made.

Historical extremes in lake-level altitudes in selected lakes in the St. Paul area are shown in Table 11. Most of the lowest altitudes were in the late 1920's and early 1930's during the prolonged drought. Only Lake Phalen reached its lowest point in recent time; therefore, it seems that increased ground-water pumpage has not yet significantly affected most of the lakes. The highest altitudes are coincident with or immediately follow years of abundant rainfall, almost without exception. Thus, it seems that the climate is the major control on most of the lake levels.

Because the hydrologic regimens of lakes vary considerably, hydrologic evaluations of individual lakes are necessary to understand fully the causes of short- and long-term declines in lake surfaces.

**Hydraulics and Records of Wells**

The literature on hydraulics of wells is abundant, ranging from practical explanations to detailed mathematical treatments. Some technical accounts of interest to a wide range of those interested in ground water include publications by Johnson (1966), Walton (1970), and Hantush (1964). Only the basics of well hydraulics are discussed below.

Thousands of wells have been installed in the study area. They include large-diameter dug or bored wells for domestic and farm use; 1-1/4 to 2-inch diameter sandpoint driven wells for observation of water levels and for some domestic use; 4- to 6-inch-diameter drilled and cased wells for domestic and farm use; and 4- to 30-inch drilled and cased wells for municipal, industrial, and irrigation uses. Some of the wells are finished with screens; some have open-end casing; and some, especially those completed in the Prairie du Chien-Jordan aquifer, are cased only through the overlying less competent strata and are open hole through the limestone, dolomite, and sandstone. Many wells finished in the Jordan Sandstone are blasted to form a large cavity at the bottom. This seems to increase the production of the well and to decrease the pumping of fine sand. Wells completed in the Mount Simon-Hinckley aquifer are generally open hole and cased through all the overlying formations. Some of the older wells were drilled open hole through more than one water-bearing formation and, thus are multi-aquifer wells, allowing free passage of water between the different strata that naturally were separated by confining beds.

More than 3,000 records on the wells in the metropolitan area were compiled as a part of this study. Most of these records were obtained from the files of the Division of Waters, Soils, and Minerals of the Minnesota Department of Natural Resources, the

Table 11. – Extremes in lake-level altitudes in selected lakes in the St. Paul area for the period 1925-1970. (Data from Ramsey County engineer.)

| Lake | Normal Altitude | Highest on record | | Lowest on record | |
|---|---|---|---|---|---|
| | | Altitude | Date | Altitude | Date |
| Bald Eagle | 910.70 | 912.45 | 5-15-44 | 906.20 | 11-22-25 |
| Birch | 919.50 | 921.28 | 4-16-52 | 914.15 | 6-4-30 |
| Gervais | 859.00 | 861.70 | 6-4-42 | 855.97 | 2-15-38 |
| Island | 944.00 | 947.27 | 4-21-66 | 938.40 | dry 7-31-31 |
| Johanna | 877.50 | 879.72 | 6-9-65 | 870.35 | 7-21-26 |
| Josephine | 884.20 | 885.70 | 6-4-42 | 881.50 | 7-10-26 |
| Keller | 859.00 | 861.70 | 6-4-42 | 854.60 | 2-29-26 |
| Long | 864.90 | 867.90 | 5-16-44 | 862.70 | 9-16-34 |
| McCarrons | 840.80 | 841.80 | 4-17-57<br>7-21-51 | 837.70 | 2-12-38 |
| Otter | 910.70 | 912.45 | 5-15-44 | 906.20 | 11-22-25 |
| Owasso | 887.00 | 888.78 | 4-9-52 | 883.00 | 1-31-26 |
| Phalen | 859.00 | 861.70 | 6-4-42 | 849.99 | 4-7-70 |
| Round | 902.90 | 908.37 | 6-28-44 | 895.10 | dry -33<br>-34 |
| Silver W. | 932.00 | 936.30 | 6-21-67 | 923.05 | 9-20-33 |
| Silver E. | 988.50 | 990.80 | 8-3-42 | 980.75 | 9-20-34 |
| Snail | 883.50 | 884.45 | 6-19-43 | 877.30 | 9-8-26 |
| Turtle | 892.00 | 893.20 | 5-31-42 | 888.70 | 8-14-26 |
| Valentine | 876.50 | 880.50 | 6-2-65 | 874.15 | 9-21-34 |
| Wabasso | 886.00 | 888.36 | 4-16-52 | 884.14 | 2-18-59<br>4-1-59 |
| Wakefield | 884.00 | 891.53 | 4-14-65 | 881.00 | 7-27-55 |
| White Bear | 924.50 | 926.70 | 6-20-43 | 920.05 | 8-19-34 |
| Spring | 903.00 | 905.00 | 10-6-65 | 900.30 | 6-13-56 |
| Beaver | 947.50 | 953.34 | 6-4-65 | 946.30 | 10-26-55 |

**Figure 50. – Long-term precipitation, lake-level fluctuations, and pumpage into selected lakes in the metropolitan area.**

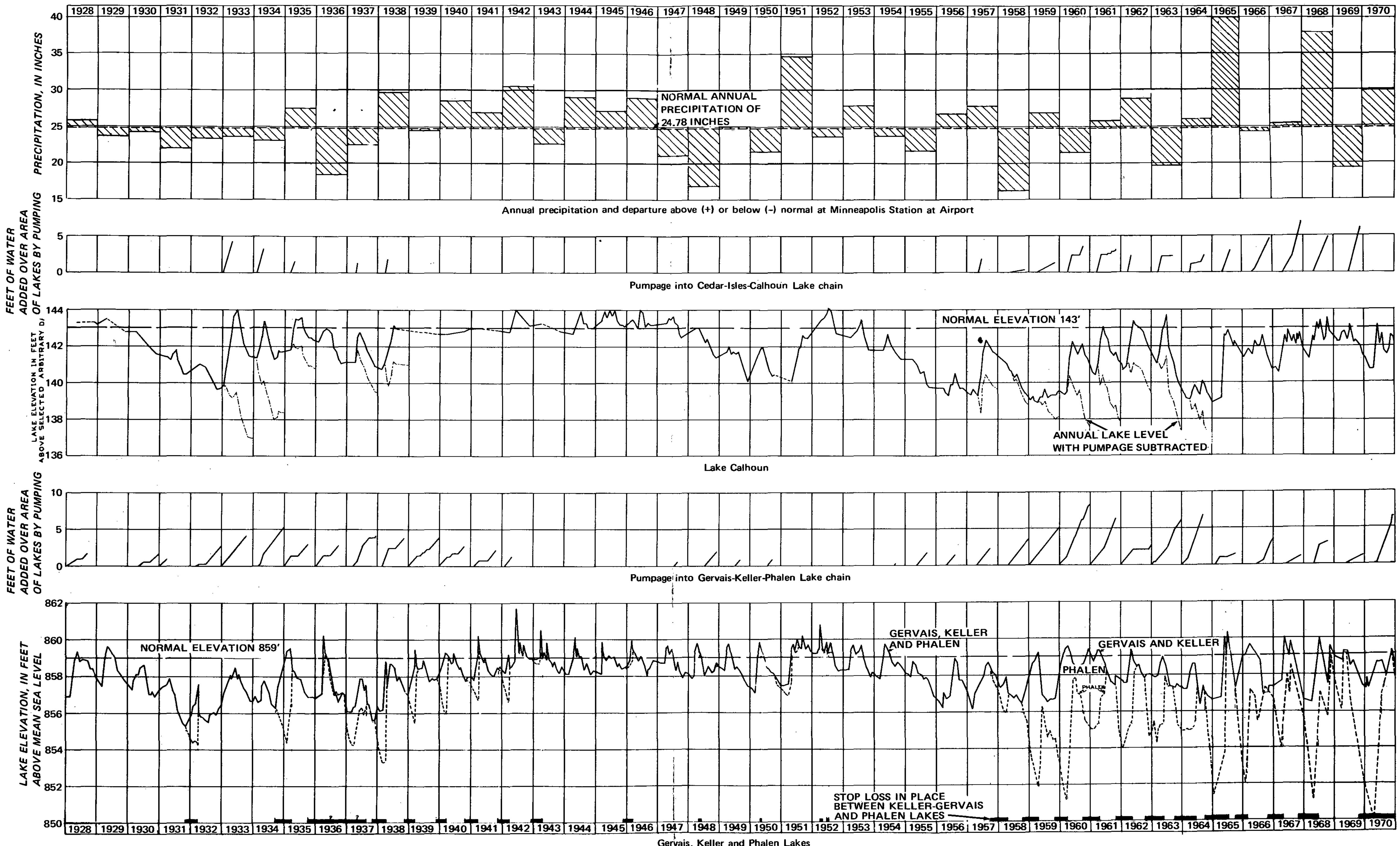



**Figure 50. — Long-term precipitation, lake-level fluctuations, and pumpage into selected lakes in the Metropolitan Area.**

Minnesota Geological Survey, and the U.S. Geological Survey. Some additional records were obtained from various municipalities, well drillers, and consultants. Data from many of the records were used to draw the hydrogeologic maps included in this report and to aid in the interpretation of the hydrology. Unfortunately, many of the records were lacking useful information. The basic information lacking on some of the records include 1) location, 2) geologic log, 3) casing record, 4) static water level, and 5) yield data. These are discussed as follows: Location – on some of the records compiled. the well locations were found to be in error. County highway maps and Geological Survey topographic maps in either the 1:24,000 or the 1:250.000 scale are available for the entire State. It would be a great help if each well were located within a 10-acre tract, as explained in the section on "Well-numbering system" near the beginning of this report. Well logs – geologic logs of formations penetrated were absent on many records. Materials in the glacial drift were lumped under one rock type on some logs. The composition of the individual drift deposits, however, is useful information. The maps and geologic sections included in this report should help greatly in well drilling and logging. By the same token, better logging data will help to improve these maps. Casing record – depth, diameter, and interconnection between casings and casing and borehole are necessary to know which aquifer or aquifers are open to the well. Static water level – the static water level, or nonpumping level, is measured after the well has been developed and allowed to recover until the static level is attained. The water level then is measured at least to the nearest foot or tenth of a foot, corrected to land surface datum, and recorded with the day, month, and year of measurement Note if the water level is fluctuating because of nearby pumping. Instruments for measuring water levels include the chalked tape and the electric tape. Yield data – the most useful yield data to be obtained without elaborate pumping tests are those relating to specific capacity of wells. Specific capacity is the ratio between well yield and drawdown of water level, usually recorded as gallons per minute per foot of drawdown. A well pumping 100 gpm with 5 feet of drawdown has a specific capacity of 20 gpm per foot. Specific capacity usually decreases with increases in pumping rate and length of time of pumping; therefore, pumping rate and length of pumping period are recorded, if specific-capacity data are to be meaningful. Estimates of transmissivity for the aquifer being pumped can be obtained from specific-capacity data. Methods are given by Theis (1963), Brown (1963), and Walton (1970)

*Well Interference*

Groups of wells withdrawing water from the same area constitute well fields. The overall effects of these well fields on summer water levels in the metropolitan area are shown in Figure 47. A computer program was made to illustrate the effects that each well in a well field has on neighboring wells. This program is not available for practical use because the parameters needed for the simulation of the hydrologic system in this area are not yet known. The program calculates the net drawdown after a specified time at each of a set of fully penetrating pumping (or observation) wells in an isotropic leaky artesian aquifer, under constant discharge conditions, and without water released from storage in the confining bed. The results are printed in tabular form, showing the net drawdown in each well and the contribution of each well to that drawdown. The aquifer is assumed to be infinite in areal extent; that is, no boundary conditions are imposed. The program was written by M. S. McBride of the Geological Survey and is based on a model in Hantush and Jacob (1955).

A hypothetical set of conditions were set up. The array of wells used might be any set of wells in the Minneapolis, or St. Paul loop areas pumping from the Prairie du Chien-Jordan aquifer. The following parameters were used:

T = 80,000 gpd per ft. or 10,700 sq. ft. per day

S = $3.8 \times 10^{-4}$

t = 90 days, length of pumping season

p' = 0.000003 ft. per day, vertical permeability of confining bed

m' = 3 feet, thickness of confining bed

The results obtained from the hypothetical pumping conditions and a plan view of the well array are shown in Figure 51. The tabular data read from left to right; stated in sentence form, for example, the drawdown in well 1 caused by pumping well 3 is 7.92 feet. The drawdown in well 5 caused by pumping well 5 is 30.43 feet, and the total drawdown in well 5 caused by pumping all wells is 54.82 feet. Thus, the interference drawdown in well 5 is the difference between the total drawdown and the drawdown caused by its own pumping, or 24.39 feet. Well 2 is considered to be an observation well and is not pumped, yet its drawdown at the end of the 90-day pumping season is 33.91 feet. In reality, the drawdown in each of the pumping wells would be somewhat more than that shown owing to well-loss factors. These are caused by individual well characteristics and were not considered in the program. A reasonable correction would be to increase the drawdown in each well owing to its own pumping by about 5 percent.

## Present Water Use

The evaluation of water use made here is largely focused on usage in that part of the seven-county metropolitan area plus that part of Wright County that falls within the boundary of this study. Only municipal-use data are tabulated for the part of this study area not included above. Most of the quantitative ground-water data presented were derived from pumping records provided by the Minnesota Department of Conservation, Division of Waters, Soils, and Minerals. Under Minnesota Statutes 105.41, all self-supplied water users, including municipalities, are required to obtain permits and to report annual water pumpage. Some data were obtained by telephone, and some were estimated. The population shown in Table 12 are supposedly those served by the public supply system. Estimates of population where necessary were derived by assuming four persons per service connection. (See Minn. Dept. of Health, 1971.)

The general locations of the municipal water-supply systems in the metropolitan area are included in Figure 52.

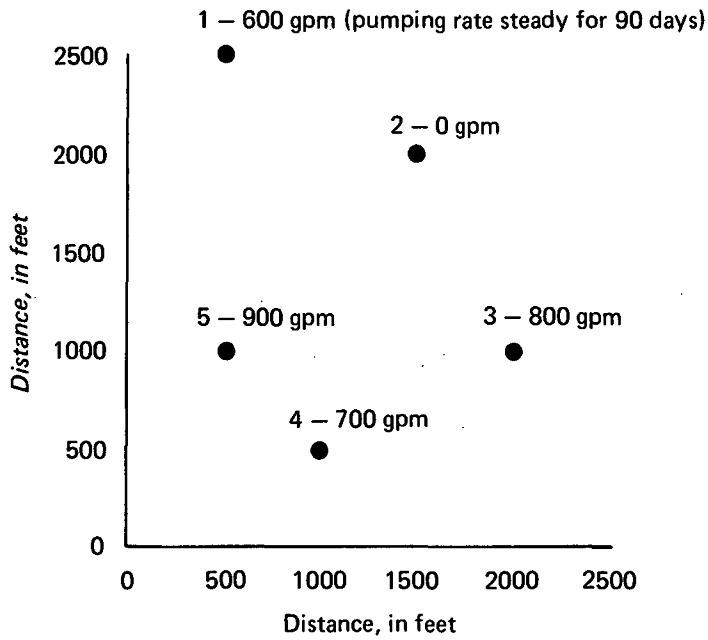
### *Ground Water*

About 660,000 people within the study area are provided with ground water from public supply systems (Table 12). The systems pump 65 mgd for all water uses. Eight are privately owned, and 30 others are outside the 7-county metropolitan area. Those within the metropolitan area supply about 623,000 people and pump about 60 mgd. About 220,000 people within the metropolitan part of the study are self-supplied. Many of these people live in suburban communities but, as yet, are not publicly supplied. Others live on farms. At 50 gpd per person, they use 11 mgd.

An estimate was made of the ground-water use by livestock (Minn. Agric. Statistics, 1971) in the metropolitan part of the study area. Livestock includes milk cows, beef cattle, hogs, sheep and goats, and chickens each using 20, 10, 3, 2, and 0.04 gpd, respectively, Assuming 85 percent of their total supply is from ground-water sources, they use about 2.0 mgd.

The quantitative distribution of ground-water use by category in the metropolitan part of the area is shown in Table 13. Data used to derive this table were obtained by mailed questionnaires. Cards were sent to 760 water users requesting percentage estimates of their categories of use. About 80 percent of the cards were returned. Column H in the table is the total amount of water use reported by appropriated water users to the Division of Waters, Soils, and Minerals of the State of Minnesota. It is certain that not all water users send annual pumpage reports to the State. Nonreporters probably amount to about 20 percent of the users, but they are estimated to use only about 6 percent of the total water pumped in 1970. Thus, column J is the estimated total amount of ground-water pumpage; it was obtained by dividing column I by 0.94.

Ground-water pumpage by counties during 1966-70 is shown in Table 14. The adjusted-figure column shown annually is corrected by 10 percent for 1966 and reduced by 1 percent each year to a 6 percent correction for 1970. This percentage-adjustment reduction is arbitrary. Minnesota Statute




DRAWDOWN, IN FEET

| | | Due to well | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | Total |
| *In well* | 1 | 20.29 | 0.00 | 7.92 | 6.99 | 9.81 | 45.01 |
| | 2 | 7.04 | 0.00 | 9.39 | 7.52 | 9.96 | 33.91 |
| | 3 | 5.94 | 0.00 | 27.05 | 8.22 | 9.81 | 51.02 |
| | 4 | 5.99 | 0.00 | 9.39 | 23.67 | 11.74 | 50.79 |
| | 5 | 6.54 | 0.00 | 8.72 | 9.13 | 30.43 | 54.82 |

**Figure 51. – Hypothetical well field showing relative drawdown interference among wells.**

Table 12. – Data on municipalities supplied by ground water in 1970.

| Municipality | Population served (1970) | Annual pumpage (million gal.) | Storage 1000 gallons | Per capita use (gpd) | Number of wells |
|---|---|---|---|---|---|
| Albertville * | 451 | 11.9 | 50 e | 72 | 1 |
| Anoka | 13,489 | 756.7 | 1,000 e | 154 | 5 |
| Apple Valley | 7,967 | 258.8 | 3,700 e | 89 | 3 |
| Askov * | 287 | 7.9 | 50 e | 75 | 2 |
| Bayport | 2,987 | 91.1 | 120 g | 84 | 3 |
| Big Lake * | 1,015 | 51.2 | 50 e | 138 | 2 |
| Birchwood | (926) | | (See White Bear Lake) | | |
| Blaine | 19.905 | 529.9 | 1,000 e | 73 | 7 |
| Braham * | 744 | 22.3 a | 150 e | 82 a | 2 |
| Brooklyn Center | 35,173 | 934.1 | 1,500 e | 73 | 6 |
| | | | 1,000 e | | |
| Brooklyn Park | 26,230 | 721.6 | 2,000 g | 75 | 6 |
| Buffalo * | 3,275 | 138.9 | 80 e | 116 | 3 |
| | | | 250 e | | |
| Burnsville | 19,940 | 613.5 | 1,000 g | 84 | 6 |
| Cambridge * | 3,467 | 104.4 | 100 e | 82 | 3 |
| Center City * | 324 | 8.9 a | 50 e | 75 a | 1 |
| Chanhassen | 928 a | 33.0 | 100 e | 97 a | 2 |
| | | | 300 e | | |
| Chaska | 4,352 | 104.7 | 350 g | 66 | 3 |
| Chisago City * | 1,068 | 54.8 a | 50 e | 140 a | 3 |
| Circle Pines | 3,918 | 93.5 | 500 e | 65 | 2 |
| Cologne | 518 | 9.6 | 75 e | 51 | 2 |
| | | | 1,500 e | | |
| Coon Rapids | 30,505 | 814.2 | 5,500 g | 73 | 9 |
| | | | 150 e | | |
| Cottage Grove | 11,891 | 476.7 | 1,000 g | 110 | 5 |
| Delano * | 1,851 | 82.7 | 496 g | 122 | 3 |
| | | | 600 e | | |
| Eagan Township | 9,500 a | 340.7 | 5,000 g | 98 a | 4 |
| | | | 1,000 e | | |
| Edina | 44,046 | 1,963.3 | 4,000 g | 122 | 13 |
| Elko | 115 | 3.1 a | 2.3 p | 74 a | 1 |
| Elk River * | 2,252 | 135.2 | 200 e | 164 | 2 |
| | | | 80 e | | |
| Excelsior | 2,563 | 113.4 | 300 g | 121 | 2 |
| Farmington | 3,104 | 150.9 | 50 e | 133 | 3 |
| Finlayson * | 192 | 10.2 a | 50 e | 146 a | 1 |
| Forest Hills | 96 a | 4.4 | 3 p | 125 a | 1 |
| Forest Lake | 3,207 | 86.7 | 100 e | 74 | 3 |
| Friendly Hills (in Mendota Heights) | 924 a | 49.8 | | 148 a | 1 |
| | | | 500 e | | |
| Fridley | 29,233 | 1,097.4 | 4,500 g | 103 | 9 |
| Hampton | 369 | 8.4 | 75 e | 62 | 1 |
| | | | 150 e | | |
| Hastings | 12,195 | 448.3 | 750 g | 101 | 5 |

Table 12. – Data on municipalities supplied by ground water in 1970. – Continued

| Municipality | Population served (1970) | Annual pumpage (million gal.) | Storage 1000 gallons | Per capita use (gpd) | Number of wells |
|---|---|---|---|---|---|
| Hinckley * | 885 | 50.2 | 100 e | 156 | 1 |
| | | | 1,500 e | | |
| Hopkins | 13,428 | 773.0 | 1,700 g | 158 | 4 |
| Hugo | 751 | 15.9 | 100 e | 58 | 1 |
| Inver Grove Heights | 5,200 a | 158.3 | 800 g | 83 a | 2 |
| Jordan | 1,836 | 39.0 | 300 e | 58 | 4 |
| Kingswood (in Eagen) | – | – | – | – | – |
| Lake Elmo | 700 a | 15.4 | 75 e | 60 a | 1 |
| Lakeville | 3,600 a | 96.8 | 1,175 e | 74 a | 4 |
| Landfall | 671 | 1.5 a | 1 p | 60 a | 3 |
| Lexington | 1,926 | 69.2 | 100 e | 98 | 1 |
| Lindstrom * | 1,260 | 79.5 | | 173 | 2 |
| Long Lake | 1,506 | 57.8 | 50 e | 105 | 2 |
| Loretto | 340 | 19.0 | 50 e | 153 | 2 |
| Mahtomedi | 3,290 | 101.6 | 120 e | 85 | 3 |
| Maple Lake * | 1,124 | 65.7 a | | 160 a | 1 |
| Maple Plain | 1,169 | 40.2 a | 50 e | 94 a | 2 |
| Mayer | 325 | 8.7 | 50 e | 74 | 1 |
| Medina | 596 a | 12.8 | 75 e | 59 a | 1 |
| Morningside | 260 a | 11.0 a | | 115 a | 2 |
| Minnetonka | 12,000 a | 239.8 | 2,050 e | 55 a | 11 |
| | | | 50 e | | |
| Minnetonka Beach | 586 | 12.8 a | 75 g | 60 a | 2 |
| Monticello * | 1,636 | 90.3 | – | 151 | 1 |
| Montrose * | 379 | 11.0 a | 50 e | 79 a | 1 |
| Moose Lake * | 1,400 | 75.9 | 50 e | 149 | 2 |
| Mora * | 2,582 | 194.4 | 200 e | 206 | 4 |
| Mound | 7,572 | 385.5 | 375 e | 139 | 5 |
| | | | 80 e | | |
| Mounds View | 9,988 | 188.3 | 2,000 g | 52 | 6 |
| | | | 420 e | | |
| New Brighton | 19,507 | 562.6 | 1,300 g | 79 | 8 |
| New Market | 215 | 6.6 a | – | 84 a | 1 |
| Newport | 2,922 | 92.4 | 250 g | 87 | 1 |
| New Prague | 2,680 | 82.4 | – | 84 | 3 |
| North Branch * | 1,106 | 51.7 | 75 e | 128 | 1 |
| North St. Paul | 11,950 | 386.4 | 800 e | 89 | 4 |
| Oakdale | 5,240 a | 131.0 | 900 e | 68 a | 3 |
| Oak Park Heights | 1,238 | 32.6 | 250 e | 72 | 1 |
| Osseo | 2,908 | 94.9 a | 250 e | 89 a | 2 |
| Pine City * | 2,143 | 73.0 | 75 e | 92 | 3 |
| Plymouth | 4,800 a | 130.2 | 1,650 e | 74 a | 4 |
| Princeton * | 2,531 | 100.9 | 290 e | 109 | 3 |
| Prior Lake | 1,114 | 54.8 a | 45 e | 135 | 2 |
| | | | 2,500 e | | |
| Richfield | 47,231 | 1,369.4 | 2,500 g | 79 | 6 |
| | | | 600 e | | |
| Robbinsdale | 16,845 | 616.1 | 1,250 g | 100 | 5 |

Table 12. – Data on municipalities supplied by ground water in 1970. – Continued

| Municipality | Population served (1970) | | Annual pumpage (million gal.) | | Storage 1000 gallons | | Per capita use (gpd) | | Number of wells |
|---|---|---|---|---|---|---|---|---|---|
| Rockford * | 730 | | 17.4 | | 75 | e | 65 | | 2 |
| Rogers | 160 | a | 7.3 | a | 50 | e | 125 | a | 2 |
| | | | | | 75 | e | | | |
| Rosemount | 1,337 | | 57.7 | | 3.1 | p | 118 | | 6 |
| Rosemount Township Utility | 750 | a | 12.9 | | – | | 46 | | 1 |
| Rush City * | 1,130 | | 85.0 | | 75 | e | 206 | | 3 |
| | | | | | 250 | e | | | |
| St. Anthony | 9,239 | | 380.8 | | 2,000 | g | 113 | | 3 |
| St. Bonifacius | 685 | | 11.3 | | 50 | e | 45 | | 1 |
| | | | | | 2,600 | e | | | |
| St. Louis Park | 48,883 | | 2,296.0 | | 5,000 | g | 129 | | 15 |
| St. Michael * | 1,021 | | 20.8 | | 60 | e | 56 | | 1 |
| St. Paul Park | 5,587 | | 159.8 | | 600 | e | 78 | | 3 |
| | | | | | 150 | e | | | |
| Sandstone * | 1,641 | | 46.9 | | 112 | g | 78 | | 2 |
| Savage | 3,611 | | 96.2 | | 250 | e | 73 | | 1 |
| Scandia | – | | – | | – | | – | | – |
| Shafer * | 149 | | 5.5 | a | 1.4 | p | 101 | | 1 |
| Shakopee | 6,876 | | 257.9 | | 250 | e | 103 | | 3 |
| Shoreview | 2,000 | a | 83.1 | | 100 | e | 114 | a | 2 |
| Snail Lake Park Addition (in Shoreview) | 192 | a | 9.0 | | 3.5 | p | 128 | a | 1 |
| | | | | | 525 | e | | | |
| South St. Paul | 25,016 | | 982.5 | | 2,000 | g | 108 | | 4 |
| Spring Lake Park | 6,417 | | 221.4 | | 250 | e | 95 | | 3 |
| Spring Park | 1,087 | | 31.0 | | 50 | e | 78 | | 2 |
| Stacy * | 278 | | 12.8 | a | 1.2 | p | 126 | a | 1 |
| Stillwater | 10,191 | | 533.7 | | 1,600 | g | 143 | | 4 |
| | | | | | 25 | e | | | |
| Taylors Falls * | 587 | | 23.2 | | 100 | g | 109 | | 3 |
| Waconia | 2,445 | | 126.6 | | – | | 141 | | 4 |
| Watertown | 1,390 | | – | | – | | – | | 2 |
| Waverly * | 546 | | 37.7 | | 50 | e | 189 | | 1 |
| Wayzata | 3,700 | | 192.9 | | 100 | e | 143 | | 4 |
| Webster Township | – | | – | | – | | | | 2 |
| | | | | | 3,000 | e | | | |
| White Bear Lake | 24,239 | | 787.4 | | 1,000 | g | 89 | | 6 |
| White Bear Township | – | | – | | 100 | e | – | | 2 |
| Willernie | (650) | | | | (See Mahtomedi) | | | | |
| | | | | | 1,500 | e | | | |
| Woodbury | 4,061 | | 176.8 | | 100 | g | 119 | | 3 |
| Woodend Shores (in Minnetrista) | – | | | | 10 | p | – | | 1 |
| Wyoming * | 695 | | 25.9 | | 75 | e | 102 | | 1 |
| Total | 660,164 | | 23,630.4 | | 86,003.5 | (avg.) | 102 | | 331 |

Table 12. – Data on municipalities supplied by ground water in 1970. – Continued

Total annual pumpage in study area 21,934.1 million gallons.

a – estimated
e – elevated
g – ground
p – pressure tank
* – outside of 7-county metropolitan area
– privately owned
– merged with Vil. of Rosemount (1971)

Table 13. – Reported ground-water use in 1970, in million gallons

| A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|
| | Domestic | Industrial | Air Cond. | Commercial | Irrigation | Other | Cards Total Rept. | 1970 Total Pumpage | 1970 Est. Total 1 |
| Anoka | 2,208.48 | 931.84 | 40.66 | 261.45 | 283.52 | 11.54 | 3,737.49 | 4,729.8 | 5,032 |
| Carver (part) | 115.34 | 100.25 | 2.09 | 13.00 | 9.45 | 1.00 | 241.13 | 400.6 | 426 |
| Dakota (part) | 2,319.57 | 5,590.91 | 53.65 | 1,210.47 | 427.97 | 258.76 | 9,861.33 | 10,673.7 | 11,355 |
| Hennepin | 5,433.42 | 5,136.51 | 5,588.95 | 1,007.87 | 1,555.46 | 121.37 | 18,843.58 | 22,853.3 | 24,312 |
| Ramsey | 2,206.32 | 9,300.54 | 2,371.02 | 320.50 | 237.22 | 2,073.34 | 16,508.94 | 17,944.6 | 19,090 |
| Scott (part) | 178.58 | 1,138.69 | 37.10 | 122.60 | 63.19 | .46 | 1,540.62 | 1,733.3 | 1,844 |
| Washington | 1,498.19 | 3,337.72 | 39.90 | 371.50 | 72.24 | 158.29 | 5,477.84 | 7,806.9 | 8,305 |
| Wright (part) | 78.16 | 32.65 | -0- | 7.41 | 65.23 | -0- | 183.45 | 508.9 | 541 |
| Total T' | 14,038.06 | 25,569.11 | 8,133.37 | 3,314.80 | 2,714.28 | 2,624.76 | 56,394.38 | 66,651.1 | 70,905 |
| Adjusted Total 2 | 17,650 | 32,150 | 10,225 | 4,170 | 3,410 | 3,300 | | | |
| Percent of Total | 24.9 | 45.3 | 14.4 | 5.9 | 4.8 | 4.7 | | | |
| Million Gallons per Day | 48.4 | 88.1 | 74.6 3 | 11.4 | 37.9 4 | 9.0 | 154.5 | 182.6 | 194 |

1 Estimated total = I/O.94

2 Adjusted total = T'/(HT'/JT')

3 Based on 137 days

4 Based on 90 days

Figure 52. – General locations of municipal water-supply systems and treatment employed for drinking and sanitary disposal in the metropolitan area.

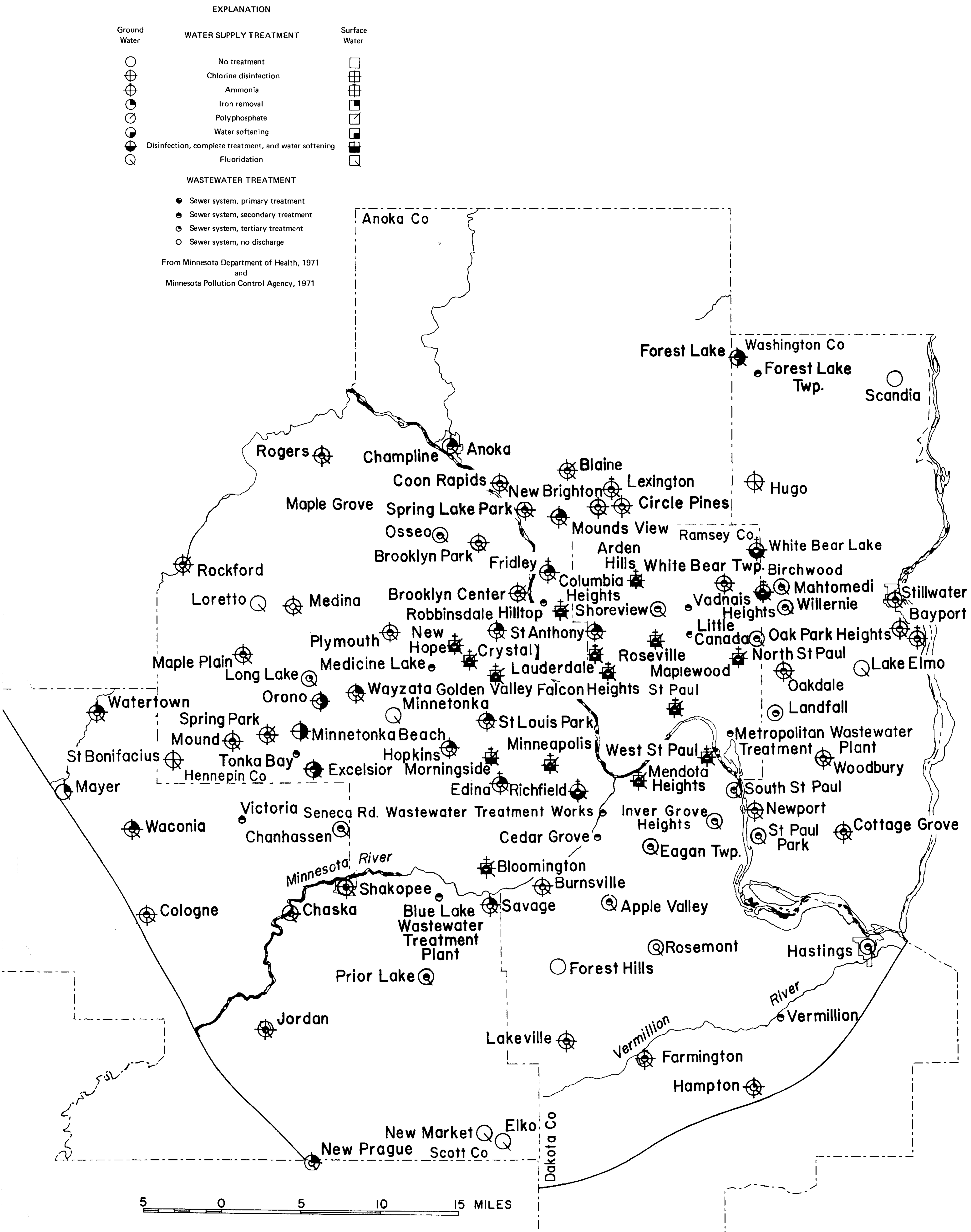



Figure 52. — General locations of municipal water-supply systems and treatment employed for drinking and sanitary disposal in the Metropolitan Area.

Table 14. – Reported ground-water pumpage, in million gallons, for 1966-1970.

| County | 1966 | | 1967 | | 1968 | | 1969 | | 1970 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Reported | Adjusted by 10% | Reported | Adjusted by 9% | Reported | Adjusted by 8% | Reported | Adjusted by 7% | Reported | Adjusted by 6% |
| Anoka | 2,802.7 | 3,114 | 3,205.0 | 3,522 | 3,393.8 | 3,689 | 4,618.6 | 4,966 | 4,729.8 | 5,032 |
| Carver (part) | 243.9 | 271 | 305.6 | 336 | 284.0 | 309 | 388.4 | 418 | 400.6 | 426 |
| Dakota (part) | 12,436.2 | 13,818 | 14,741.3 | 16,199 | 12,443.3 | 13,525 | 9,784.1 | 10,520 | 10,673.7 | 11,355 |
| Hennepin | 16,447.1 | 18,275 | 16,969.4 | 18,648 | 18,334.4 | 19,929 | 19,071.5 | 20,507 | 22,853.3 | 24,312 |
| Ramsey | 15,376.4 | 17,085 | 14,323.7 | 15,740 | 14,378.4 | 15,629 | 17,175.5 | 18,468 | 17,944.6 | 19,090 |
| Scott (part) | 1,733.2 | 1,926 | 1,804.0 | 1,982 | 1,563.0 | 1,699 | 1,754.1 | 1,886 | 1,733.3 | 1,844 |
| Washington | 3,855.7 | 4,284 | 5,043.5 | 5,542 | 4,506.5 | 4,898 | 5,397.0 | 5,803 | 7,806.9 | 8,305 |
| Wright (part) | 552.9 | 614 | 525.9 | 578 | 470.6 | 512 | 790.9 | 850 | 508.9 | 541 |
| Adjusted annual total (million gallons) | 59,387 | | 62,547 | | 60,190 | | 63,418 | | 70,905 | |
| Adjusted average daily (million gallons) | 163 | | 171 | | 165 | | 174 | | 194 | |

105 was revised in 1965, thereby giving water users more incentive to report pumpage. In 1966, probably 25 percent of the users were not reporting, accounting for about 10 percent of the water. In 1971, the adjustment should probably be 5 percent, but beyond this time little change in total reported accuracy is likely.

A spot check of the validity of the pumpage totals in Table 13 is afforded by comparing the water metered through private wells (St. Paul Water Department, Table 43, 1970) in the city of St. Paul, with the adjusted total in 1970 for Ramsey County. Although Ramsey County includes many municipalities other than St. Paul, much of the county pumpage is within the city. The city pumpage was metered at 16.6 billion gallons (45.5 mgd) in 1970, whereas total county pumpage was 19.1 billion gallons (52.3 mgd), a reasonable comparison. The city of Minneapolis also meters well water that goes into the sanitary sewers, but much of the pumped water used for cooling and other purposes is discharged into storm sewers and is not metered. Therefore, a similar comparison in Hennepin County was not made.

As shown in Table 14, pumpage in 1970 rose 12 percent from the preceding year. Prior annual changes since 1966 were no more than 6 percent, either up or down. Thus, it seems that some reason(s) other than population growth and expansion of the economy has caused the increase. Two climatic factors affecting the use of water are shown in Figure 53. Part of the 1970 rise was undoubtedly due to greater use of air-conditioning water, as indicated by the graph of degree days. The degree-day base used here is 60$^{o}$F, the approximate temperature at which air conditioning begins. For example, if the median temperature between the daily high and daily low is 70$^{o}$ for 1 day, that day contains 10 degree days. If the median temperature is 60$^{o}$ or lower, that day contains 0 degree days. By comparison, then, this graph is an indicator of relative amounts of water needed for air conditioning. Another factor for the 12 percent rise may have been an increase in industrial use of water, the largest use (45.3 percent) of ground water in the area. However, no data are available on annual gross area production. The influence of temperature and precipitation on water use is shown in Figure 53. For example, total water use in 1968 declined, even though the trend had been progressively upward. The year 1968 was wet and relatively cool; thus, water use declined despite the trend.

Water-use data are compiled for 1959 in Bulletin No. 11 (Minnesota Division of Waters, 1961). The areas considered in that and in this study are somewhat similar, so reasonable comparison can be made. In 1959, industrial use of ground water was 72.2 mgd; in 1970, it was 88.1 mgd, and increase of 22 percent. In 1959, commercial use was 15.6 mgd (including air conditioning); in 1970, it was 39 mgd (including air conditioning), an increase of 150 percent. Commercial establishments have grown steadily in the past decade, and air conditioning, a former luxury, has become commonplace. Cooling systems have been installed in many of the older and all of the new office buildings, in hospitals, hotels, apartment houses, theatres, large department stores, and in large enclosed shopping centers. Some of the newer buildings are equipped with mechanical cooling units, but many are still cooled by water, either from individually owned wells or from municipal-supply systems. Greater use of mechanical units would, of course, relieve the seasonal stress on water resources, especially in the urban hub areas.

*Surface Water*

The Minneapolis and St. Paul water systems use surface water entirely for their public supplies. Together, they supply about 55 percent of the total population of the metropolitan area.

The following descriptions of the Twin City supply systems are taken from Bulletin No. 11 (Minnesota Division of Waters, 1961, p. 29). Changes in transcript are made, where updating is necessary.

*Minneapolis Water-Supply System*

The Minneapolis water department pumps water from the Mississippi River at Fridley into a softening plant with a capacity of 120 mgd. Softened water is then pumped to the Fridley filtration plant, which

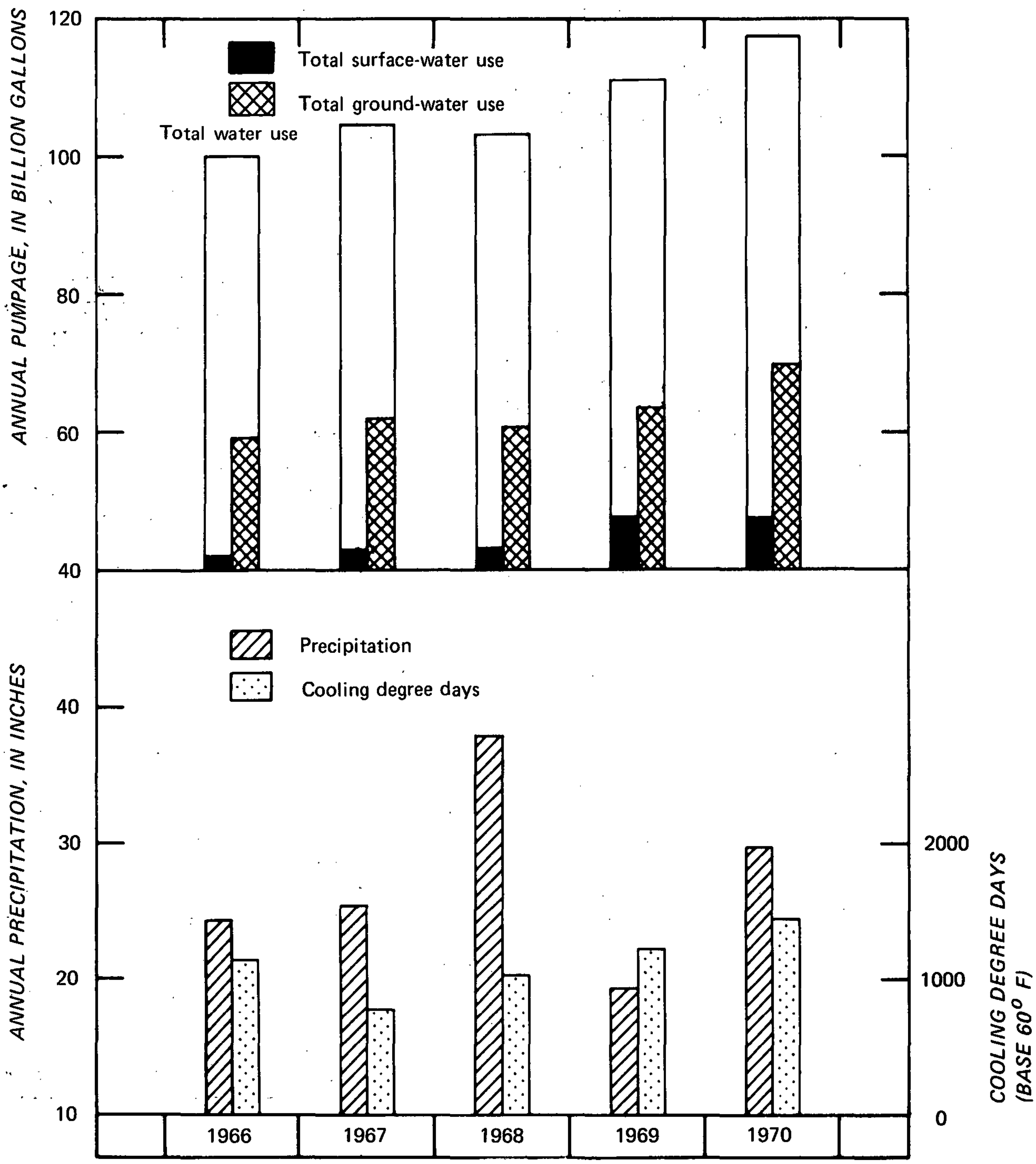



**Figure 53. — Probable effects of climatic factors on water use in the Metropolitan Area.**

has a capacity of 135 mgd, or to the Columbia Heights filtration plant, which has a capacity of 78 mgd. Treated water is then distributed to three storage reservoirs in Fridley, Columbia Heights, and Hilltop, which have capacities of 32, 45, and 40 million gallons, respectively. The distribution system is so constructed that either of the two treatment plants could supply the entire service area except during periods of maximum water use.

In 1970, the total water pumped into the Minneapolis water system during July, the month of maximum use, was 3,581 mg, at an average rate of 116 mgd. On the maximum day (June 30), pumpage (high service) was 176.5 mg.

*St. Paul Water-Supply System*

St. Paul has two sources of water supply. Most of the water is taken from the Mississippi River near Fridley, where the pumping stating has a capacity of 80 mgd. An auxiliary pumping station at Centerville, which draws water from the Centerville chain of lakes, consists of two pumps having rated capacities of 25 and 15 mgd. These pumps are usually operated only when sufficient water has been stored in the Centerville Lake chain. All the water pumped from the Mississippi River or from the Centerville Lake chain goes into the Vadnais Lake system, from which it is pumped into the McCarron Lake filtration and purification plant, which has a capacity of 144 mgd. Treated water is distributed to eight ground or surface reservoirs having a total capacity of 115 million gallons. In addition, five pumping stations, having a combined rated capacity of 31.9 mgd, lift water into seven elevated storage tanks, whose combined capacity is 7.7 million gallons.

In 1970, total water delivered to the St. Paul system, during the month of maximum use (July) was 2,518 million gallons, at an average rate of 81 mgd. Pumpage on the day of maximum use (July 10) was 119.3 million gallons.

The growth of surface-water use in the Twin City water system is shown in Table 15. Data for this table were taken from Bulletin No. 11 (Minnesota Division of Waters, 1961, Table 5) and updated to include data for 1970.

Detailed breakdowns on pumpage and specifics on systems operations are annually published by the Minneapolis Water Department and the St. Paul Board of Water Commissioners. Information on the availability of these reports can be obtained by contacting the respective city water departments.

Table 15. - Water pumped by Minneapolis and St. Paul water systems.

| | Minneapolis | | | St. Paul | | |
|---|---|---|---|---|---|---|
| Year | Annual pumpage (mg) | Average daily pumpage (mg) | Population served | Annual pumpage (mg) | Average daily pumpage (mg) | Population served |
| 1930 | 20,137 | 55.2 | 470,000 | 9,135 | 24.2 | 270,000 |
| 1940 | 18,674 | 51.0 | 490,000 | 7,940 | 23.2 | 288,000 |
| 1950 | 20,060 | 55.0 | 515,000 | 12,279 | 33.1 | 310,000 |
| 1960 | 21,429 | 58.7 | 515,000 | 15,654 | 42.9 | 333,000 |
| 1970 | 28,098 | 77.0 | 618,000 | 20,333 | 55.7 | 404,000 |

*Combined Water Use*

Total water use in 1970 in the metropolitan part of the study area from both surface-water and ground-water sources was 327 mgd – 133 mgd surface water and 194 mgd ground water. This compares with the total water use in 1959 (Minnesota Division of Waters, 1961, p. 32) of 233 mgd – 96.8 mgd surface water and 136.2 mgd ground water. This amounts to an overall increase in water use of 40 percent since 1958 – 37 percent in surface-water use and 42 percent in ground-water use. The approximate increase in population in this interim was about 24 percent (1,505,000 in 1960 versus 1,865,000 in 1970). It seems that a direct correlation between population and water use does not exist. Some reasons for the more rapid rise in water use include increased industrial production and the rising standard of living, which is reflected in water use, especially for air conditioning and lawn care.

*Future Water Use*

Future water needs are discussed in some detail in Bulletin No. 11 (Minnesota Division of Waters, 1961, p. 33-37). Most of the tenets held in that work are still valid. Table 8 in Bulletin No. 11 shows present and future water use in the metropolitan area. The totals from that table, together with the totals obtained in this study, are shown in Table 16 below.

Usage between 1959 and 1970 within the metropolitan area has increased by about 40 percent. A graph of the predictions in Bulletin No. 11 would show that the 1970 pumpage should have been about 318 mgd, which is only 9 mgd less than the 1970 computed figure, and that the 1980 usage should be about 400 mgd and the 2000 usage close to 490 mgd. Predictions by Metcalf and Eddy, Inc. (1968) show that total water usage in the metropolitan area is expected to increase to 454 mgd by 1985 and to 673 mgd by 2000.

By projection of the trends shown on Figure 2, 1980 total water use is shown to be about 400 mgd – 250 ground water and 150 surface water, in substantial agreement with the projections based on Bulletin No. 11 and existing data. Similarly by 2000, total use is projected to be about 620 mgd – 400 ground water and 220 surface water, somewhat greater than that based on Bulletin No. 11 but similar to that in the Metcalf and Eddy study. A projection such as this has little statistical basis, but it does seem to have some predictive merit.

The Water Resources Coordinating Committee (1970, p. 126) projected future water usage on a maximum daily basis (the above projections are based on average daily use). Maximum usage in 1980 is predicted to be 639 mgd; in 2000, 816 mgd; and in 2020 – 1,300 mgd.

Table 16. – Past, Present and Future Water Use, Metropolitan Area

| | **1959 (million gallons)** | | **1970 (million gallons)** | | **1980 (million gallons)** | | **2000 (million gallons)** | |
|---|---|---|---|---|---|---|---|---|
| **All uses** | **Daily** | **Annual** | **Daily** | **Annual** | **Daily** | **Annual** | **Daily** | **Annual** |
| Total | 233.0 | 85,000 | 327 | 119,400 | 391 | 142,700 | 474<br>(673) 1/ | 173,000<br>(244,000) 1/ |
| Ground Water | 136.2 | 49,700 | 194 | 70,900 | – | – | | |
| Surface Water | 96.8 | 35,300 | 133 | 48,500 | – | – | | |

1/ Metcalf and Eddy, Inc. (1968)

The water-availability part of this report shows that more than 1,000 mgd may be developed from ground-water sources in and around the metropolitan area. Thus, an ample supply of water is obtainable for at least the next 30 years and more. Sustaining this level of development, however, will require excellent planning and management. Present surface-water demands during the summer low-flow period in the Mississippi River are near optimum. River-flow demands (3,500-3,800 cfs) for sanitary-effluent assimilation at times during the summer exceed the low flow in the river. Furthermore, recurrence of a drought similar to that of the 1930's would greatly curtail electric power-plant operations, practically eliminate summer sanitary-effluent reduction, and place a stress on the Minneapolis and St. Paul public-supply systems. Wells, tied into the city distribution systems but located far enough from the river systems so that they would not immediately affect baseflow in the streams, could be used to supplement the city surface-water supplies during critical periods. In effect, the wells would greatly enlarge the reservoir capacity, especially that of the Minneapolis system, for the ground-water reservoirs hold more water than could ever be stored on the surface in this highly urbanized area.

**Water Available for Development**

The evaluation of water available for development, as discussed herein, applies only to that in the study area. Ground-water availability is estimated largely for withdrawals from the two major aquifers – the Prairie du Chien-Jordan and the Mount Simon-Hinckley. It was necessary to determine quantitatively 1) the present (1970) level of water-resources development; 2) the areal extent affected and depletion that resulted by this level of development; and 3) the areal extent and water remaining in the system that would allow a sustained level of development. The sustained practical level of development, as arbitrarily used in this report, in the ground-water part of the system is that level beyond which significant physical changes in water-bearing characteristics will occur in the major aquifers. Significant changes in an artesian aquifer occur when the long-term water levels decline below the top of the aquifer over a wide area, transmissivity and storage values change, and water-table conditions begin to prevail. This results when discharge from an aquifer significantly exceeds recharge for an extended period of time.

The optimum level of development in the surface-water part of the system is that level of withdrawal beyond which minimum streamflow requirements for waste-effluent assimilation, biotic habitation, navigation, and power-plant operations are not met. The optimum level of water-resources development, thus, is a socio-economic problem as well as a hydrologic problem.

*Surface Water*

Data presented in the low-flow and flow-duration curves shown in Figures 27-35 and 36-39, respectively, can be used to approximate the availability of surface water in various parts of the study area. As stated earlier, a fair indication of the adequacy of a surface-water supply is the 7-day 10-year low-flow probability. Flow at the gaging station near Anoka is assumed to be the amount of water available from the Mississippi River for surface-water supply, such as the Minneapolis and St. Paul water-supply system. Flow at the Anoka gage plus flow at the gages on the Minnesota River near Jordan and the St. Croix River at St. Croix Falls, Wisconsin, is assumed to be the amount of water available if all the major rivers in the area were incorporated into the Twin Cities water-supply system. In outlying parts, flows of the Elk, Rum, Crow, Vermillion, and Apple Rivers may possibly be sufficient for development of small municipal or industrial supplies with little attendant loss to downstream users, as most water used for municipal and industrial purposes could be discharged with appropriate treatment a short distance downstream from the water-supply intake. However, the quality of water both before and after use would weigh heavily in deciding whether these smaller streams should be developed or alternative sources of supply should be sought.

Data in Table 17 were obtained from the low-flow-frequency curves in this report. It summarizes the practical availability of surface water in different parts of the study area. The locations of these gaging-station sites are shown in Figure 3.

*Streamflow During Extreme Drought*

The following discussion indicates that the surface-water resources of the Twin Cities area would not be adequate to meet all demands if a drought similar to that of the early 1930's recurs. Streamflow conditions in the Twin Cities during peak monthly summer water use during such a drought are outlined. Only approximate stream discharges can be predicted because ground-water pumpage and its effects on the system have increased greatly since the 1930's and because returns of used water and base inflow to the streams cannot be quantitatively determined exactly. The results obtained, however, give a general idea of probable conditions.

Hypothetical streamflow budgets for reaches of the Minnesota and Mississippi Rivers in the Twin Cities area are shown in Table 18. The initial streamflow values were taken from the 100-year 30-day low-flow curves (Figures 30 and 31). This duration period and frequency interval were selected because 30 days is long enough to minimize any undue short-term effects and because the drought of the 1930's seems to have a recurrence interval of about 100 years. The withdrawal values (negative figures) were taken from water-use records of peak monthly withdrawals in 1970. Inflows to the streams are listed as ground-water returns, transmission-loss returns, natural ground-water inflow, and sewage-treatment plants (effluent). Ground-water return is the balance of pumped water (464 cfs), after accounting for a 15 percent consumptive loss and effluent from treatment plants. The 15 percent consumptive loss is also applied to the surface water used. Effluent from all plants other than the Metropolitan is considered to be from ground-water pumpage. Effluent from the Metropolitan plant that exceeds adjusted surface-water usage also is considered to be derived from ground water.

Transmission-loss return is based on a combined 15 percent loss in both the Minneapolis and St. Paul water-supply system. It is arbitrarily returned to the Mississippi River equally in the upper and lower reaches.

Natural ground-water inflow during a prolonged drought is unknown. In 1934, the most severe drought year, enough data were collected to show

Table 17. – Probability of streamflow availability at selected stations.

| Stream and station number | 7-day 10-year low flow cfs | 7-day 10-year low flow mgd |
|---|---|---|
| Mississippi River near Anoka 05283500 | 1,040 | 672 |
| Minnesota River near Jordan 05330000 | 160 | 103 |
| St. Croix River at St. Croix Falls, Wis. 05340500 | 1,060 | 685 |
| Elk River near Big Lake 05275000 | 28 | 18 |
| Crow River at Rockford 05280000 | 12 | 7.8 |
| Rum River near St. Francis 05286000 | 57 | 37 |
| Apple River near Somerset, Wis. 05341500 | 78 | 50 |
| Vermillion River at Hastings 05346000 | 2.8 1/ | 1.8 |

1/ Estimated

that the Minnesota River gained about 60 cfs between Carver and the mouth. Under present heavy ground-water pumping, it is assumed that this gain would have been decreased by one-third in 1970. It is arbitrarily considered representative of the entire area and added to the streamflow, as shown in Table 18.

Table 18. – Hypothetical streamflow budget during extreme drought (100-year 30-day low flow) and peak monthly water use under 1970 levels of water-resources development in the Twin Cities area.

| Stream segment | Estimated discharge, in cfs |
|---|---|
| Mississippi River above St. Paul | |
| Near Anoka | 690 |
| St. Paul withdrawal | -135 |
| Minneapolis withdrawal | -199 |
| Subtotal | 356 |
| Ground-water returns | 128 |
| Transmission loss returns | 25 |
| Natural ground-water inflow | 40 |
| Subtotal at Lock and Dam No. 1 | 549 |
| Minnesota River | |
| Near Jordan | 99 |
| Chaska, Blue Lake, Savage, Burnsville treatment plants | 8 |
| Subtotal at Black Dog powerplant | 107 |
| Seneca, Eagan treatment plants | 1 |
| Natural ground-water inflow | 40 |
| Subtotal at mouth | 148 |
| Mississippi River below St. Paul | |
| Subtotal below Minnesota River | 697 |
| Ground-water returns | 100 |
| Transmission loss returns | 25 |
| Natural ground-water inflow | 20 |
| Subtotal above Metropolitan treatment plant | 842 |
| Metropolitan treatment plant | 377 1/ |
| Subtotal below Metropolitan treatment plant | 1219 |
| South St. Paul, Newport, St. Paul Park, Inver Grove Heights, and Cottage Grove treatment plants | 18 |
| Natural ground-water inflow | 20 |
| Subtotal at Lock and Dam No. 2 | 1257 |
| Hastings treatment plant | 3 |
| Total above confluence with St. Croix River | 1260 |

1/ Greater than the rated capacity of 337 cfs because of effluent bypass in August 1970.

Treatment-plant discharges are based on average daily capacities (Table 19) converted from million gallons per day to cubic feet per second.

Overland runoff from precipitation was negligible and not added to the inflow. No accounting was made for induced recharge that is extracted from the streams to the pumping wells because this is probably a delayed response, and much of the induced water is returned directly to the streams. Also, the withdrawals for city supplies assume no curbs on water use during a drought – which is not likely.

Inflows to the streams cannot be pinpointed; therefore, they are added totally at the lower end of each stream segment. The stream-discharge values thus derived are close enough approximations to evaluate the effects that drought could have on the operation of utilities dependent on streamflow in the Twin Cities area.

### *Streamflow-Dependent Utility Operations During Extreme Drought*

Location of gaging stations, mouths of streams, points of withdrawal and outfall, locks and dams, and power plants on the Mississippi, Minnesota, and St. Croix Rivers, in terms of river mileage, are listed in Table 20. Mileage is referenced above the mouth of the Ohio River for the Mississippi River and above their own mouths for the Minnesota and St. Croix Rivers. The map locations of many of these places are shown in Figure 54. Probable effects of drought-time streamflow on utility operations are discussed below, using the locations in Table 20, the discharges in Table 18, and water requirements for power-plant operations in Table 21. Water demands for peak-capacity plant output are used in the discussion.

#### Mississippi River Above St. Paul

Beginning at the Anoka gaging station under 1970 conditions (Figure 54), the flow of 690 cfs is reduced to 356 cfs by withdrawals (Table 18). Assuming that about one-third of the returns and inflow occurs above the Riverside plant, 420 cfs is available for cooling water in the plant, which has a maximum water demand of 823 cfs (Table 21). With only half the necessary cooling water available, the plant cannot operate at peak capacity. The demand of the largest single generating unit is 236 cfs, for the two largest units 447 cfs. which makes the ability of the plant to function at any more than about half capacity questionable. Even partial operation would depend upon the effluent cooling water meeting water-temperature standards. Saint Anthony Falls Upper Lock and Dam, Main Street (discontinued) and Hennepin Island hydropower plants, the Southeast Minneapolis steam-power plant (standby), Lower Saint Anthony Falls Lock and Dam, and the Lower Saint Anthony Falls hydropower plant are located successively downstream. Assuming that half or even all the returns and inflow entering the reach is available here, 452 to 549 cfs is available in this stretch. Bulletin No. 11 (Minnesota Division of Waters, 1961) states that the hydropower stations probably cannot operate below 1,000 cfs. According to this same publication, St. Anthony Falls Lock and Dam needs a minimum of 350 cfs and, thus, would seem to be operable. The steam-power plant (southeast Minneapolis), unlike the Riverside plant, can operate at capacity, but this plant delivers only 30 megawatts, which would not make up for the loss of power at the Riverside plant. Lock and Dam No. 1 and the Ford Motor Company hydroelectric plant at mile 847.7 are next downstream. The lock and dam can operate on the available flow of 452 cfs or slightly less, but it is doubtful that the Ford plant could generate much electricity, if any.

#### Minnesota River

The hypothetical data developed (Table 18) shows a river flow of 148 cfs at the mouth of the Minnesota River. The Black Dog steam plant demands 575 cfs at peak capacity. With less than one-fourth of the necessary water available, plant output would be curtailed considerably and probably subject to temperature restrictions.

Table 19. – Metropolitan Sewer Board Wastewater Treatment Plants

| Treatment plant(s) | Capacity (MGD) | 1971 Flow (MGD)* | Effluent to |
|---|---|---|---|
| Anoka | 2.5 | 1.8 | Mississippi River |
| Apple Valley | .5 (1.5) | .59 | Vermillion River |
| Bayport | .65 | .48 | St. Croix River |
| Blue Lake a/ | 2.5 (20) | 1.20 | Minnesota River |
| Burnsville b/ | 1.5 | 1.73 | Minnesota River |
| Chanhassen c/ | .14 | .16 | Minnesota River |
| Chaska | .7 | .53 | Minnesota River |
| Cottage Grove | .9 | .75 | Mississippi River |
| Eagan b/ | .23 | d.7 | Minnesota River |
| Excelsior e/ | .54 | .52 | Minnetonka Lake |
| Farmington f/ | .54 | .36 | Vermillion River |
| Forest Lake Township g/ | .08 | .15 | Howard Lake to Rice Creek |
| Forest Lake Village g/ | .18 | .23 | Howard Lake to Rice Creek |
| Hastings | 1.8 | .91 | Mississippi River |
| Inver Grove Heights g/ | .48 | .59 | Mississippi River |
| Lakeville f/ | .25 | .46 | Vermillion River |
| Long Lake e/ | .18 | .18 | Minnetonka Lake |
| Maple Plain | .22 | .21 | Minnetonka Lake |
| Medina | .1 | .07 | To ground |
| Metropolitan | 218 (290) | 215 | Mississippi River |
| Mound e/ | 1.25 | 1.07 | Langdon Lake |
| Newport g/ | .3 | .19 | Mississippi River |
| Oak Park Heights h/ | .25 | .07 | St. Croix River |
| Orono e/ | .4 | .20 | Minnetonka Lake |
| Prior Lake e/ | .2 | .09 | Credit River to Minnesota River |
| Rosemount i/ | .1 (.6) | .10 | Effluent pond |
| St. Paul Park e/ | .2 | .31 | Mississippi River |
| Savage | .36 | .30 | Minnesota River |
| Seneca j/ | (24) | – | Minnesota River |
| South St. Paul e/ | 10 | 10.2 | Mississippi River |
| Stillwater | 3.0 | 2.24 | St. Croix River |
| Victoria e/ | .09 | d.05 | Lake Auburn |
| Wayzata k/ | .8 | .53 | Lake Minnetonka |

≠ Figures in parantheses are for plant expansions presently under construction.
* Monthly average, Jan. – Oct.
a/ Blue Lake start-up in July when Shakopee plant was phased out.
b/ Scheduled for phase-out in first quarter of 1972 with flow to go to Seneca treatment plant.
c/ Phased out in December 1971 with flow diverted to Blue Lake treatment plant.
d/ Estimated.
e/ Scheduled for phase-out and diversion to Blue Lake treatment plant.
f/ Scheduled for phase-out and diversion to new Lakeville-Farmington treatment plant.
g/ Scheduled for diversion to Metropolitan plant when interceptor completed.
h/ Scheduled for phase-out and diversion to Stillwater treatment plant.
i/ Scheduled for phase-out and diversion to new Rosemount treatment plant which will discharge to Mississippi River.
j/ Scheduled to begin operation early in 1972.
k/ Phased out in October with flow diverted to Blue Lake treatment plant.

Table 20. – River mileage of mouths of streams, points of withdrawal and outfall, locks and dams, and power plants on the Mississippi and Minnesota Rivers in the Twin Cities area.

| Location | | |
|---|---|---|
| Mile | Bank | Mississippi River |
| 866.2 | – | Coon Rapids dam and hydropower plant (discontinued) |
| 865.2 | L | Coon Creek |
| 864.8 | R | U.S.G.S. gaging station, Mississippi River near Anoka |
| 862.8 | L | St. Paul pumping station |
| 861.9 | L | Rice Creek |
| 859 | L | Minneapolis waterworks |
| 857.9 | R | Shingle Creek (County ditch 13) |
| 856.9 | L | Riverside steam-power plant |
| 853.8 | – | Upper St. Anthony Falls Lock and Dam |
| 853.75 | L | Main St. (discontinued) and Hennepin Island hydropower plants |
| 853.5 | L | Southeast Minneapolis steam-power plant |
| 853.4 | – | Lower St. Anthony Falls Lock and Dam |
| 853.36 | L | Lower St. Anthony Falls hydropower plant |
| 849.8 | R | Bassett Creek |
| 847.7 | – | Lock and Dam No. 1 (Twin Cities Lock and Dam) and Ford Motor Co. hydropower plant |
| 847.1 | R | Minnehaha Creek |
| 844 | L | Minnesota River |
| 840.9 | L | Island steam-power plant |
| 840.5 | L | High Bridge steam-power plant |
| 839.3 | L | U.S.G.S. gaging station, Mississippi River at St. Paul |
| 836.3 | L | Metropolitan sewage-treatment plant |
| 833.9 | R | U.S.G.S. auxiliary gage for Mississippi River at St. Paul |
| 833.4 | R | South St. Paul sewage-treatment plant |
| 833.3 | L | Battle Creek (Pigs Eye Lake outlet) |
| 830.3 | L | Newport sewage-treatment plant |
| 829.3 | L | St. Paul Park sewage-treatment plant |
| 829.3 | R | Inver Grove Heights sewage-treatment plant |
| 818.0 | L | Cottage Grove sewage-treatment plant |
| 815.2 | – | Lock and Dam No. 2 |
| 814.0 | R | Hastings sewage-treatment plant |
| 811.3 | L | St. Croix River |
| 811.3 | L | U.S.G.S. gaging station, Mississippi River at Prescott, Wis. |
| | | **Minnesota River** |
| 39.4 | L | U.S.G.S. gaging station, Minnesota River near Jordan |
| 33.3 | R | Sand Creek |
| 32.0 | L | Carver Creek |
| 29.7 | L | Chaska Creek |
| 28.1 | L | East Chaska Creek |
| 28.0 | L | Chaska sewage-treatment plant |
| 22.3 | L | Riley Creek (Grass Lake outlet) |

Table 20. – River mileage of mouths of streams, points of withdrawal and outfall, locks and dams, and power plants on the Mississippi and Minnesota Rivers in the Twin Cities area. – Continued

| Location | | |
|---|---|---|
| Mile | Bank | Minnesota River (Cont.) |
| 19.1 | R | Blue Lake sewage-treatment plant |
| 18.2 | L | Purgatory Creek |
| 15.9 | R | Eagle Creek |
| 14.6 | R | Savage sewage-treatment plant |
| 13.4 | R | Credit River |
| 10.9 | L | Nine Mile Creek |
| 10.7 | R | Burnsville sewage-treatment plant |
| 10.7 | R | Black Dog steam-power plant intake |
| 8.8 | R | Black Dog steam-power plant |
| 7.6 | R | Black Dog steam-power plant outlet |
| 7.4 | R | Seneca sewage-treatment plant |
| 4.8 | R | Eagan sewage-treatment plant |
| 0 | | Mouth of Minnesota River at mile 844 on Mississippi River |

Mileage on the Mississippi River is measured upstream from the mouth of the Ohio River; for the Minnesota River it is measured upstream from the mouth.

Table 21. – Twin Cities area electric-power plants

**Steam Power**

| Name | Stream and mile* | | Rated capacity (megawatts) | Water+ demand (cfs) max. | Water+ demand (cfs) min. | 1970 use (cfs) |
|---|---|---|---|---|---|---|
| Riverside | Mississippi | 856.9 | 418 | 823 | 594 | 359 |
| Southeast Minneapolis | Mississippi | 853.5 | 30 | 84 | 71 | 18 |
| Island | Mississippi | 840.9 | 20 | 80 | 67 | 2.8 |
| High Bridge | Mississippi | 840.5 | 423 | 661 | 501 | 459 |
| Black Dog | Minnesota | 8.8 | 416 | 575 | 387 | 410 |
| Alan S. King | St. Croix | 21.5 | 550 | 624 | 468 | 433 |
| Total | | | 1,857 | 2,847 | 2,088 | 1,681.8 |

**Hydropower**

| Name | Stream and mile | | Head (ft) | Installed capacity hp | Installed capacity cfs | Installed capacity kw | 1970 use (cfs) |
|---|---|---|---|---|---|---|---|
| Coon Rapids | Mississippi | 866.2 | 20 | 11,040 | 6,075 | 8,240 | discontinued |
| Main Street | Mississippi | 853.75 | 49 | 2,000 | 450 | 960 | discontinued |
| Hennepin Island | Mississippi | 853.75 | 49 | 15,300 | 3,450 | 12,500 | 1,961 |
| Lower St. Anthony Falls | Mississippi | 853.36 | 24 | 11,680 | 5,000 | 8,000 | 3,259 |
| Ford Motor Co. | Mississippi | 847.7 | 34.5 | 18,700 | 5,960 | 13,930 | 4,251 |

* Mileage on the Mississippi River is measured upstream from the mouth of the Ohio River; for other streams it is given as miles upstream from the mouth.

\+ Maximum demand is water needed during high water temperature summer months; minimum demand is needed during low water temperature winter months, at peak generating capacity.

## Mississippi River Below St. Paul

The Island and High Bridge plants are downstream from the confluence of the Minnesota and Mississippi Rivers. The Island plant is a standby, but High Bridge is the largest single generating facility within the Twin Cities. Assuming that the distribution of returns and inflows is about right, there should be enough flow to satisfy peak demand (661 cfs). However, it is questionable whether temperature requirements can be met, especially if the water was used for cooling purposes at the Riverside and Black Dog plants. The temperature of the river water after cooling the High Bridge boilers would probably be high, considering that in July of 1967, with an average flow of 14,170 cfs in the Mississippi River at St. Paul, the average water temperature was about 75$^{O}$F; and, in the last week of that month, the average was over 80$^{O}$F, while the flows ranged from 7,970 to 5,220 cfs.

Temperature and quantity of flow becomes extremely important at the next critical point, the Metropolitan wastewater-treatment-plant outfall. A report by the Water Resources Coordinating Committee (1970, p. 149) indicates that minimum summer streamflows of 3,500 to 3,800 cfs (2,300-2,500 mgd) would be sufficient for water-quality low-flow purposes through the year 2020. Even so, with only about 24 percent of the flow necessary to dilute the sewage outfall (842 cfs vs 3,500 cfs) and that probably at a high temperature, the quality of the river water in the vicinity of the outfall and for some distance downstream could be seriously affected.

Although the 100-year drought is an extreme example, dry periods of less frequent occurrence will also cause shortages. For example, to satisfy minimum water demand in the reach from Anoka to the Minnesota River, the minimum flow at Anoka should be equal to water withdrawn for municipal supply plus water needed for cooling purposes. Under present development and neglecting returns, this would be 334 cfs plus 823 cfs, or 1,157 cfs. Drawing a straight line at this discharge across the frequency curves (Figure 30) for the Anoka station shows that this discharge will occur on 1 day in about every 6-1/2 years (on the average); for a 7-day period, about once every 7-1/2 years; and for a 90-day period, about once every 20 years.

To reiterate, the surface water resources of the Twin Cities metropolitan area are now being used to such an extent that a supply adequate to meet all demands will not be available during severe drought. Without increasing the quantity of water available (through storage, importation of water, or other means), the only apparent way to alleviate the deficient supply for power plant usage and sanitary sewage effluent assimilation would be to reduce the amount of water diverted from the Mississippi River by Minneapolis and St. Paul during the drought. The goal would be to insure adequate flows in the Mississippi River to meet the demands of the larger generating plants in order to avoid a power shortage because the Black Dog generating plant would either be operating far below capacity or would shut down. Also, if flows were this low, they would be inadequate to maintain the Mississippi River at anything approaching good quality below the Metropolitan wastewater-treatment plant, as mentioned previously.

One way to decrease the amount of water diverted from the Mississippi River would be for the city of St. Paul to use the stored water from the lake chains in its reservoir and supply system (Figure 55). Depending on climatic conditions, 10 to 35 percent of the total raw water required is supplied by two lake chains, the least lake water being used in the summer because of taste and odor problems associated with algae.

The Impounding Reservoir Lake System consists of Deep, Charles, Pleasant, Sucker, and Vadnais Lakes, with an available supply of 3,600 million gallons between optimum operating elevation and gravity-flow limits. An additional 5 billion gallons is in dead storage in this system. Two lakes in the Rice Creek chain of lakes, Peltier and Centerville, have been incorporated into the system. Flow is by gravity from Peltier to Centerville Lake, where a 40 mgd pumping station conveys water to Pleasant Lake. Available storage in the Rice Creek system is 2,300 million gallons, with another 340 million gallons in dead storage.

Although there would undoubtedly be some problems involved in using the available storage of 5,900 million gallons, it seems that this supply could be of value in mitigating the effects of a serious drought.

**Figure 54. – Location of selected gaging stations with 100-year 30-day low flow, some wastewater treatment plants, power plants and surface-water pumping station.**

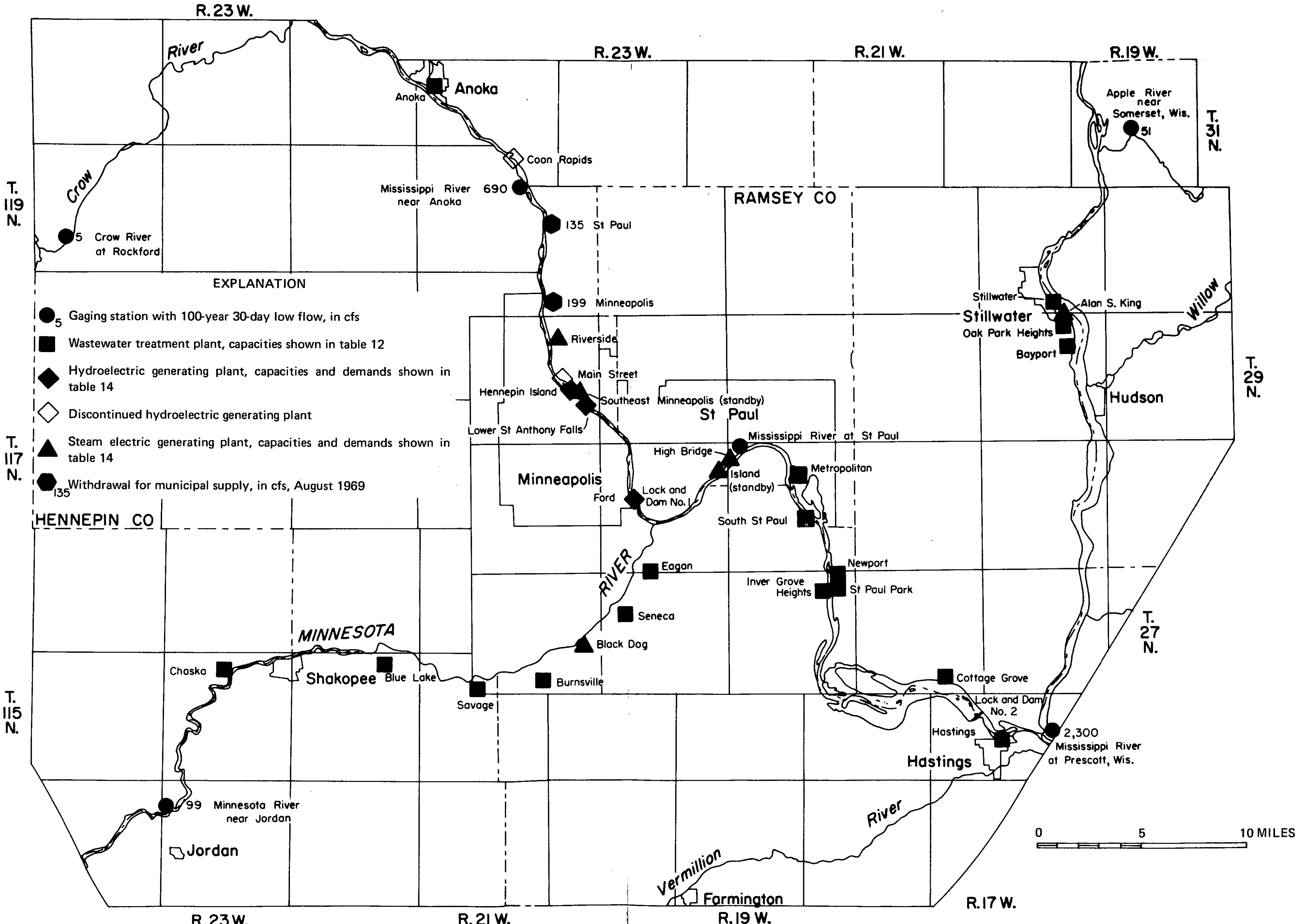



Figure 54. — Location of selected gaging stations with 100-year 3-day low flow, some wastewater treatment plants, power plants and surface-water pumping station.

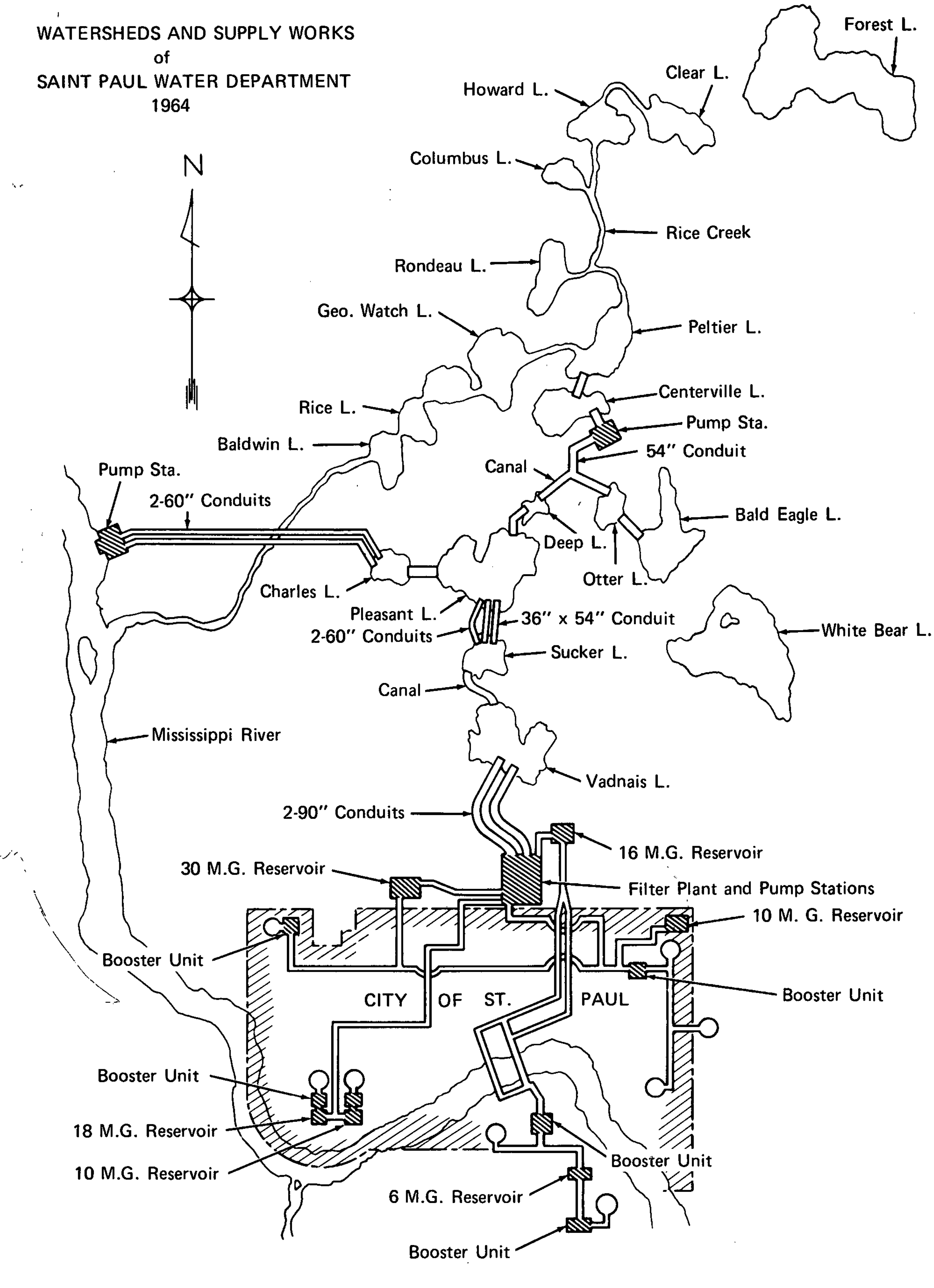



**Figure 55. – Schematic diagram of the St. Paul water-supply system.**

Minneapolis obtains all its water from the Mississippi River, and at present, has no alternate or supplementary source of supply. In the event of serious drought, the city might consider incorporating some of its lakes into the water-supply system, thus providing a supplementary or alternate source of water. One additional measure worth consideration would be to interconnect the water supply systems of the two cities. This might prove valuable not only during droughts but also if one intake were to become polluted.

Augmenting low flows on the Mississippi River has been considered in the past. The three methods given the most consideration have been: pumping from Lake Superior (about 130 miles northwest of Twin Cities), diversion from the St. Croix River, and releases from lakes and reservoirs on or tributary to the Mississippi River above the Twin Cities. The first two methods would give rise to political issues – Lake Superior is international water, whereas the St. Croix River is interstate. Socio-economic factors would weigh heavily in any plan to augment flows by releases from the headwater reservoirs (or Mille Lacs Lake, which was once considered), which are now regulated within narrow limits in order to meet the needs of lake-shore property owners. One possibility would be to increase ground-water use and decrease surface-water use, at least during extended periods of low flow. This would increase the quantity of water available for sewage dilution and cooling and would take better advantage of natural ground-water storage.

*Ground Water*

Quantitative evaluation of the sustained level of development that the major aquifers can withstand must be based, at present, on many assumptions, approximations, and hydrologic judgements. Thus, the results obtained must be considered only as approximations. In keeping with the above, the extent of the Prairie du Chien-Jordan aquifer in the metropolitan area is taken as 2,000 square miles, and the extent of the entire study area is taken as 6,000 square miles. These are the gross areas, unless otherwise indicated, upon which the following computations are based.

Ground-water use by municipalities in 1970 is shown in Table 12. The distribution of ground water in 1970 by category of use and by county is shown in Table 13. The derivation of the figures to make the latter table are explained in the "Present water use" section of this report. Although municipal pumpage is incorporated in Table 13, it is necessary to define the gross municipal pumpage within the metropolitan area to obtain the base daily and summer daily pumpage explained below. Thus, data from both the above tables were used to further distribute the 1970 pumpage in time and space.

Pumpage by aquifer is not readily available. However, in analyzing the well and water-level data for this study, it was possible to estimate total pumpage from the different aquifers. These estimates follow:

| Aquifer groupings | Percent | 1970 Annual pumpage (billion gallons) |
|---|---|---|
| Glacial drift, Platteville Limestone, St. Peter Sandstone | 7 | 5.0 |
| Prairie du Chien-Jordan | 75 | 53.2 |
| Ironton-Galesville, Mount Simon-Hinckley | 18 | 12.7 |
| Total | 100 | 70.9 |

In evaluating pumping effects quantitatively, it also is necessary to estimate the base daily and warm-weather or excess summer pumpage. Base daily pumpage is that pumpage that occurs throughout the year, regardless of seasonal conditions. It differs from the average daily pumpage (total annual pumpage divided by 365), and is derived by dividing the difference between total annual pumpage and excess summer pumpage by 365. Excess summer pumpage is that attributable to air conditioning, irrigation, and other summer only uses. It is superimposed on the base daily pumpage.

Because one purpose of this report is to provide a base for future comparison, the method used to estimate the base daily and summer pumpages follows by steps. For practical reasons, these pumpages were derived only for withdrawals from the Prairie du Chien-Jordan aquifer.

Step 1. Estimate total municipal pumpage within metropolitan area. Assume summer is 120 days.

a) Annual municipal pumpage (Table 12) . . . . . . 21,900 million gals.

b) Reports from selected municipalities show that about 50 percent of municipal use is in the 120 summer days and 50 percent of municipal use is in the remaining 245 days.

Then:

10,950 ÷ 120 = 91 mgd (summer)
10,950 ÷ 245 = 45 mgd (remainder)

c) Difference between summer and other municipal pumpage equals 46 mgd. Thus excess summer municipal pumpage equals 5,520 million gallons (120 x 46).

Step 2. Combine air-conditioning and irrigation use with municipal summer excess.

a) Municipal summer excess . . . . . . . . . . . . . . . 5,520

Air conditioning (derived from Table 13) 120 by 74.6 mgd . . . . . . . . 8,950 million gals.

Irrigation (from (Table 13) . . . . . . . 3,410 million gals.

Total 120-day excess . . 17,880 million gals.

b) Assume 85 percent (greater than yearly estimate of 75 percent) is from Prairie du Chien-Jordan to obtain total summer excess pumpage.

17,880 x 0.85 = 15,200 million gallons

c) The daily excess summer pumpage from Prairie du Chien-Jordan aquifer is 15,200 ÷ 120 = 127 mgd.

Step 3. Compute base daily pumpage from Prairie du Chien-Jordan aquifer.

a) 70.9 billion gallons x 0.75 = 53,175, or 53,200 million gallons –
53,200-15,200 = 38,000 million gallons
38,000 ÷ 365 = 104 mgd, base daily pumpage

b) Total summer daily pumpage is 104 + 127, or 231 mgd.

The base and summer daily pumpage values, as determined above, then are used to analyze the effects of pumping in, and to make predictions of potential yield from, the Prairie du Chien-Jordan aquifer.

For purposes of this study, the pumpage rate in the Mount Simon-Hinckley aquifer is considered to occur at an average daily rate. Annual pumpage from the aquifers below the Prairie du Chien-Jordan is estimated at 12.7 billion gallons, or 18 percent of the total pumpage in Table 13. Assuming 15 percent of the total annual pumpage is from the Mount Simon-Hinckley aquifer, then the average pumpage from this aquifer is 29 mgd.

*Areal and Volumetric Effects of Pumping*

Prairie du Chien-Jordan Aquifer

As previously mentioned, water levels in the Prairie du Chien-Jordan aquifer (Figures 45, 46, and 48) show little, if any, long-term permanent decline since about 1958, except for an area on the west side of Minneapolis. That is, winter water levels return to about the same altitude every year. Thus, it is assumed that the aquifer, at its present level of development, is near equilibrium; long-term discharge and recharge are in close balance, and the cone of depression is nearly stabilized. In effect, this means that the cone of depression has reached enough sources of recharge (including captured natural discharge) to supply the amount of water now being withdrawn annually at the base daily rate. The present extent of the annual cone now encompasses about 740 square miles and has a volume of 3.2 cubic miles. This area and volume were derived by superimposing the 1885 potentiometric-surface map of the Prairie du Chien-Jordan aquifer (Reeder, 1966) on the 1970 potentiometric-surface map (Figure 20) made in this study and obtaining the head differences. Some adjustments were made at places near the periphery of the area, where the early data were more doubtful and direct comparisons resulted in unusually large differences in head. The average head change in this cone of depression is 23 feet.

A similar procedure was followed to obtain the dimensions of the transitory cone of depression brought about annually by increased summer withdrawals. This summer cone encompasses about 770 square miles and has a volume of 1.2 cubic miles more than the annual cone. These values were derived from the water-level-change map shown in Figure 47. Note that this cone is brought about by a summer pumping rate of 127 mgd more than the base daily pumping rate of 104 mgd. Also, note that this cone is not stabilized; it is superimposed on the annual cone of depression; and it almost fully recovers after summer pumping ends. The average head change for the superimposed cone is 8 feet more than the annual cone. Combining the long-term and transitory-cone dimensions gives an overall unstable cone of depression whose approximate dimensions are 770 square miles in area, 4.4 cubic miles in volume, and whose average head change is 31 feet. The pumping rate causing this cone is 231 mgd for 120 days.

Using the above information, it is possible to compute the present unit yield from the Prairie du Chien-Jordan aquifer under both the base daily and summer pumping conditions.

The present long-term unit yield at the base daily pumping rate is computed as follows:

Area of influence . . . . . . . . . 740 sq. mi.

Base daily pumping rate . . . . . . . 104 mgd

Average head change (1885-winter 1970-71) . . . . . . . . . . . . . . 23 ft.

104 mgd ÷ 740 sq. mi. = 141,000 gpd per sq. mi.

0.141 mgd per sq. mi. ÷ 23 ft. =
6,100 gpd per sq. mi. per ft. of decline

The present short-term unit yield at the summer daily pumping rate is computed as follows:

Area of influence . . . . . . . . . 770 sq. mi.

Summer daily pumping rate (120 days) . . . . . . . . . . . . . 231 mgd

Average head change (1885-summer 1971) . . . . . . . . . . . . . . . . 31 ft.

231 mgd ÷ 770 sq. mi. = 300,000 gpd per sq. mi.

0.30 mgd ÷ 31 ft. =
9,700 gpd per sq. mi. per ft. of decline

### Mount Simon-Hinckley Aquifer

Hydrographs of wells completed in the Mount Simon-Hinckley aquifer are shown in Figure 22. Long-term declines in the aquifer continue at a rate of 7 to 10 feet per year. Thus, the cone of depression has not stabilized. In addition, historical water-level data compared with present data are not sufficient to obtain meaningful dimensional measurements of the long-term cone of depression in the aquifer. Therefore, the method applied above to obtain the approximate unit yield in the Prairie du Chien-Jordan aquifer is not used. The potential yield based on horizontal movement of water and vertical leakage to the aquifer, however, was estimated and is discussed in a following section of this report.

### Potential Level of Development

In order to estimate the potential yield from the major aquifers, it was necessary to determine 1) available head in the Prairie du Chien-Jordan aquifer; 2) available head in the Mount Simon-Hinckley aquifer; and 3) average head difference between the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers. The available head in the Prairie du Chien-Jordan aquifer, as of winter 1970-71, is shown in Figure 41. It was derived by overlaying the potentiometric-surface map (Figure 20) of the aquifer on the structure-contour map (Figure 12 and 14) of the aquifer and computing the differences. By planimetering the intervals of equal head and computing volumes, the area of available head was determined to be about 1,710 square miles, total volume of head was 35 cubic miles, and average head, throughout, was 110 feet.

The available head in the Mount Simon-Hinckley aquifer is shown in Figure 42. The available heads ranged from about 350 to more than 650 feet in the metropolitan area. The volume and average head were not determined because they were not needed in the computations that follow.

The head difference between the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers are shown in Figure 56. This map was derived by overlaying Figure 20 on Figure 21, the potentiometric-surface maps of the two aquifers, and by obtaining the differences in heads. The average head difference was about 110 feet throughout approximately 2,000 square miles. The above determinations of available areas and available head differences are used then to estimate the maximum potential yield from the two major aquifers.

In the computations and solutions that follow, it is assumed that all water pumped comes from recharge to the aquifers and not from storage. It can be shown that in these aquifers only a small part of the discharge is derived from storage, making this a reasonable assumption. Also, it is assumed that the unit yields derived above do not change as water-level drawdowns increase in the aquifers.

The available head, shown in Figure 41, ranges from 0 to more than 300 feet and averages 110 feet. Even with ideal well spacing and totally controlled pumping, it is not realistic to assume that the entire 110 feet of average available head can be obtained. Therefore, two thirds of the total or about 75 feet is estimated to be practical head obtainable in making the following determination of potential yield.

Potential yield of Prairie du Chien-Jordan aquifer is computed as follows:

Total available
area of influence . . . . . . . . 1,710 sq. mi.

Total available head . . . . . . . . . . 110 ft.

Total practical head (assume roughly
two-thirds of total
available) . . . . . . . . . . . . . . -75 ft.

Long-term unit yield
(p.121) . . . . . . 6,100 gpd per sq. mi. per ft.

Thus:

0.0061 mgd per sq. mi. per ft. x 1,710 sq. mi. x 75 ft. = 782 mgd, potential additional yield (regardless of source of recharge).

Total sustained yield, including present base use is 782 + 104 = 886 mgd.

Potential Yield – Mount Simon-Hinckley Aquifer

Estimates of potential yield from the Mount Simon-Hinckley aquifer are based on horizontal and vertical recharge into the aquifer. For practical purposes, it is assumed that the area affected by pumping in the Mount Simon-Hinckley underlies directly and is the same (740 sq. mi.) as that in the Prairie du Chien-Jordan aquifer.

Horizontal recharge to the aquifer was computed with data from the potentiometric surface map (Figure 21) applied to a variation of Darcy's Law, Q=TIL (Ferris and others, 1962), where

Q is recharge, in gallons per day

T is transmissivity, in gallons per day per ft.

I is hydraulic gradient, in ft. per mi.

L is width of flow section, in mi.

The 800-foot potentiometric contour line, on Figure 21, nearly coincides with the western and northern outer limits of the Prairie du Chien-Jordan aquifer. A 54-mile stretch of this line was selected as the line of section through which most of the horizontal recharge occurs to the Mount Simon-Hinckley in the metropolitan area. The average hydraulic gradient at the line is 13 feet per mile. The average transmissivity of the aquifer is about 616,000 gpd per foot. Therefore,

Q = 20,000 gpd per ft. x 13 ft. per mi. x 54 mi.

Q = 14 mgd, horizontal recharge

Vertical recharge to the aquifer was computed by the formula on page 109-110.

Using $A_c$ = 2,000 sq. mi.; P' = 5.5 x $10^{-5}$ gpd per $ft^2$; m' = 15 ft.; and $\Delta h$ = 110 ft.; then $Q_c$ equals about 23 mgd and $Q_c/A_c$ equals about 11,000 gpd per sq. mi. (at a head difference of 110 ft).

Because there is little direct information concerning vertical hydraulic conductivites in the metropolitan area, the value for P' is an approximation based on core analyses done by the Minneapolis Gas Co. in the Eau Claire Sandstone, several miles southwest of the metropolitan area. At that location, it was found that the least permeable part (shale beds) of that formation was about 15 feet thick (m') and had a vertical hydraulic conductivity (P') of less than 0.003 millidarcys (less than 5.5 x $10^{-5}$ gpd/$ft^2$). The assumption is made here that the shale beds of the Eau Claire Sandstone are of constant thickness, continuous to and throughout the metropolitan area, and retain similar hydrologic properties. No better source to obtain values for P' and m' is available at this time. (Note that the P' value used in this report for the Eau Claire confining bed is arbitrarily taken as 5.5 x $10^{-5}$ gpd/$ft^2$, but the values obtained in the core analyses may be considerably less.)

The $A_c$ value used above is for the approximate total extent of the Prairie du Chien-Jordan aquifer in the metropolitan area. Considering only the 740 square miles affected by present base daily pumpage, the vertical recharge to the Mount Simon-Hinckley equals:

740 sq. mi. x 11,000 gpd per sq. mi. = 8.1 mgd.

This amount, added to the present horizontal recharge, totals 22 mgd (14 mgd + 8 mgd). But, present pumpage from the aquifer is 29 mgd; thus, the aquifer is being overpumped by roughly 7 mgd – one apparent reason why water levels continue to decline.

Recharge to the Mount Simon-Hinckley aquifer can be increased by lowering the water levels in the aquifer, thereby increasing the $\Delta h$ for vertical recharge and increasing the I for horizontal recharge. The available head in the aquifer within the metropolitan area is greater than 350 feet, as shown in Figure 42. For practical purposes, it is assumed that 300 feet of this is obtainable. If the head in the Prairie du Chien-Jordan aquifer remains constant, then, by increased pumpage, the $\Delta h$ between the two aquifer units can be increased to at least 410 feet (110 ft. + 300 ft.), or about 3.7 times as much head as at present throughout about 2,000 square miles. Then vertical recharge to the aquifer should increase to 3.7 times 23 mgd, or 85 mgd over the 2,000 square miles. This lowering of water levels will steepen the horizontal gradient. Assuming that the ratio of horizontal to vertical recharge remains the same (14 to 8), horizontal recharge will be about 150 mgd. The total of the two sources of recharge will be 235 mgd. But present pumpage is about 29 mgd; thus, total potential increased pumpage from the aquifer is 206 mgd.

As stated above, this vertical recharge estimate assumes that the head in the Prairie du Chien-Jordan aquifer remains constant; however, the system is not that simple, and changes will occur in the upper aquifer as pumping demands increase. To illustrate, the effects of the summer cone of depression in the upper aquifer on vertical recharge to the lower aquifer were determined. Here, it is assumed that the head in the Mount Simon-Hinckley aquifer remains constant. Using the $Q_c/A_c$ equal to 11,000 gpd per square mile (p. 125) at a head difference of 110 feet, then:

11,000 gpd per sq. mi. x 8 ft./110 ft. =
800 gpd per sq. mi.

800 gpd per sq. mi. x 770 sq. mi. =
616,000 gpd

less recharge leaking to the Mount Simon-Hinckley aquifer during the summer pumping period. In 120 days, this is 74 million gallons of water, another probable reason why water levels continue to decline in the lower aquifer.

**Figure 56. – Difference in head between the Prairie du Chien-Jordan aquifer and the Mount Simon-Hinckley aquifer in Winter 1970-71 in the metropolitan area.**

EXPLANATION

— 150 — —

Line of equal head difference
Shows amount of difference between the potentiometric surface of Prairie du Chien-Jordan aquifer and Mount Simon-Hinckley aquifer. Dashed where approximately located.

— — — —

Geologic contact
Contact between the Jordan Sandstone and underlying rocks. Modified after Schwartz, (1936).

Boundary of study area

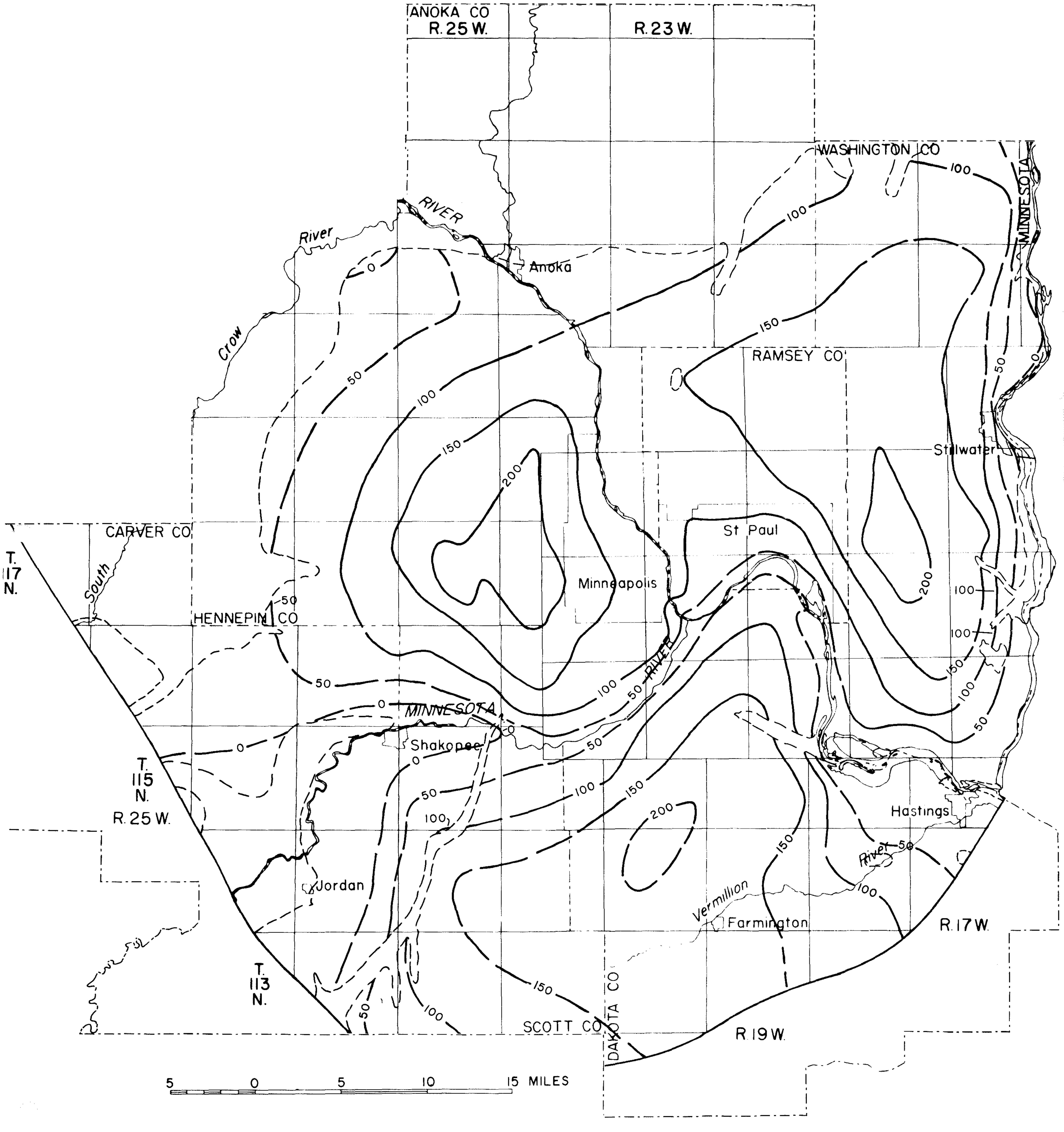



Figure 56. — Difference in head between the Prairie du Chien-Jordan aquifer and the Mount Simon-Hinckley aquifer in Winter 1970-71 in the Metropolitan Area.

If maximum withdrawal is made from the Prairie du Chien-Jordan aquifer at the same time that maximum stress is put on the Mount Simon-Hinckley, the head difference between the two aquifers will be 335 feet, in contrast to the 410 feet shown on page 165. Thus, the vertical recharge to the lower aquifer will be only 3 times 23 mgd, or about 70 mgd; and total potential recharge will be 220 mgd.

An additional 4,000 square miles within the study area is underlain by the Mount Simon-Hinckley aquifer. As a practical example, an estimate was made of the potential yield from 1,500 square miles of that area, using a hypothetical distribution of wells. Assuming that the overall average transmissivity of the Mount Simon-Hinckley aquifer is 20,000 gpd per foot, with a storage coefficient of $5 \times 10^{-4}$, then the specific capacities of 12-inch diameter wells completed in the aquifer can be estimated to be 10 gpm per foot of drawdown (Meyer, 1963). Thus, pumping at 1,000 gpm would create a drawdown of at least 100 feet in each well, more likely 150 feet over a long period of time. There is about 1,500 square miles north and west of the metropolitan area where the available head in the aquifer ranges from 150 to 350 feet. (See Figure 42.) Therefore, if one well were placed in every 10 square miles of this area, there would be 150 wells pumping 1,000 gpm, for a grand total of 150,000 gpm, or 216 mgd. This is more water than is presently pumped in the metropolitan area.

The preceding determinations provide estimates of the water-yielding capabilities of the two major aquifers without considering whether the water is available. Actually, the sustained level of development that can be attained is dependent on the available recharge to the hydrologic system, as inferred on page 140.

*Sources of Recharge*

Five sources of recharge to the major aquifers are: 1) precipitation; 2) induced recharge from streams and lakes; 3) water in storage in overlying aquifers, such as the glacial drift and the St. Peter Sandstone; 4) artificial recharge; and 5) recharge from incidental sources.

Precipitation

A large part of the maximum average annual amount of water available for pumping without reducing gross water in storage in the ground-water system is that part of the average annual precipitation that recharges the ground-water system. The measure of this, on a long-term basis, is the base-flow in streams owing to basin storage. Computed in the water budget (Table 5) for the Twin Cities area, this base-flow averages 5.24 inches annually and, for the entire area, 4.23 inches. This amounts to 183 billion gallons, or about 500 mgd, over the 2,000 square miles of the Twin Cities area in which the major aquifers occur and, over the 6,000 square miles of the study area, to 446 billion gallons per year, or 1,220 mgd.

Considering only the Twin Cities area, it is not practical to assume that all the 500 mgd of base-flow can be diverted to pumping wells. However, about three-fourths, or 375 mgd, is estimated to be obtainable because the streams are the main areas of aquifer discharge, they are centrally situated, and have valley bottoms filled with unconsolidated sediments that are conducive to capture of aquifer discharge by pumping wells.

Induced Recharge

Induced recharge from the Mississippi River alluvium and underlying glacial valley fill presently supplies a substantial part of the water pumped in the summer in the Twin Cities area. Seasonal cones of depression near the river, where potentiometric levels are 25 to 75 feet below river level, are shown in

Figure 47. Estimates of recharge from these cones can be made by the leakage formula (p. 109-110). Firm values for the necessary parameters are not obtainable for this area, but the following computation is made with approximate values. Using m' = 90 feet; P' = 1.31 gpd per ft.$^2$ $\Delta h$ = 50 ft., $A_c$ = 1.5 square miles (6 linear miles of river, estimated from closed contours near the Mississippi River in Figure 43, times an average 0.25-mile width of alluvium), then $Q_c$ = 30.6 mgd, or equivalent roughly to 13 percent of the total water pumped from the Prairie du Chien-Jordan aquifer during the summer. The value for P' used for the valley fill above is taken from Table 7, where it is the value for "Drift, sand and gravel, some clay and silt". Using the above values, the recharge rate, $Q_c/A_c$, is 20.4 mgd per square mile; and, for unit head loss, the rate is 0.4 mgd per square mile per foot, or 1.4 x $10^{-2}$ gpd per cubic foot.

As inferred, the 1.31 gpd per square foot value for P' is not substantiated by field testing, locally. (Norris and Fidler (1969) made a rather detailed study of vertical permeabilities in glacial outwash fill in the Scioto River valley, Ohio. They obtained an average coefficient of vertical permeability of 365 gpd per square foot for the valley fill and a value of 27 gpd per square foot for the streambed sediments. The streambed and valley-fill sediments in the Scioto River valley were largely sand and gravel with an absence of clay and silt. The unconsolidated sediments in the stream valleys in the Twin Cities area are generally sand and gravel with appreciable silt and clay fractions in some places. Also, the streambeds, especially in the regulated parts of the streams, become silty and mucky. High-velocity flood flows in the spring tend to scour out these soft sediments periodically, however. In addition, occasional dredging of the navigable parts of the streams helps to keep the streambeds clean. Although the P' value used in this report seems low in comparison with the Ohio value, it does not seem low when the grain size of the sediments is considered.)

There is more than 100 square miles of alluvium-covered valley fill (Figure 9) in the metropolitan area. If the head difference were lowered an average of 25 feet beneath the entire alluviated area, induced recharge, including captured natural discharge, would be roughly 1 billion gpd, or about 1,550 cfs. Baseflow from basin storage (Table 5) is about 900 cfs. Thus, if the head were lowered by 15 feet beneath the entire alluviated area, theoretically, a quantity of water equal to all natural discharge from the metropolitan area would be captured by pumping wells. Any lowering in excess of the 15 feet would capture water that ordinarily flows downstream beyond Hastings, assuming direct hydraulic connection of the stream channel with the alluvium; that is, no confining sediment in the stream bed. (See discussion of timeliness of withdrawals on p. 96.)

The above estimates of induced recharge are on an average annual basis. In practice, the situation is more complex. Summer withdrawals already create greater than 25-foot head differences in parts of the valley fill during periods when river flows are low. It would seem that as summer pumping rates increase induced recharge from the rivers will exceed demands on river water during seasonal low-flow periods. However, most of the initial induced water would come from storage in the valley fill. Also, this effect is dampened by the fact that much of the water pumped in the summer, especially that used for air conditioning, is discharged directly to the rivers through storm sewers.

The average discharge, based on flow records for calendar years 1935-69, of the Mississippi River at St. Paul is about 10,000 cfs (Figure 3). The alluvium-covered valley fill in the metropolitan area along just the Mississippi River is more than 50 square miles. Considering only the Mississippi River as a perennial source of induced water because of its high average discharge, increasing the head difference between the potentiometric surface in the major aquifer and the water level in the valley fill to 25 feet beneath the entire 50 square miles would result in induced recharge of 510 mgd. For practical purposes, it is estimated that water from induced recharge could amount to at least 350 mgd in the metropolitan area if the withdrawal wells were located in the proper places in a line parallel to the streams.

Leakage from Overlying Sediments

Few exposures of the Prairie du Chien-Jordan aquifer and none of the Mount Simon-Hinckley occur in the metropolitan area. Thus, most of the recharge to these aquifers must percolate through the overlying sediments, which consist largely of alluvial deposits, glacial drift, and St. Peter Sandstone. Recharge (leakage) rates are greatest where the Prairie du Chien-Jordan aquifer is in direct hydraulic connection with the glacial drift, about 1,350 square miles of the metropolitan area. (See Figure 45.) Significant lowering of the potentiometric surface in the major aquifer results in removal of water from the overlying sediments and a decline in the water table. The water table recovers each year when recharge, either from precipitation or induced from surface-water sources, is sufficient to supply pumping demands. However, where recharge is insufficient, the pumped water comes from storage in the overlying sediments, which results in long-term lowering of the water table. Short-term lowering of the water table in surficial sediments is indicated by the seasonal leakage of water from some of the lakes. Presently, hydrographs of historical changes in the water table in the glacial drift and in the St. Peter Sandstone are lacking. Therefore, it is not known how much, if any, storage water is being removed. A tremendous amount of water is stored in these sediments, however, and it is available for recharge to the major aquifer. Gross approximations of the total amount of water in storage follow. The parameters used in the computations are necessarily estimates.

*Alluvial Deposits and Valley Fill:*

| | |
|---|---|
| Area | 110 sq mi |
| Average saturated thickness | 90 ft |
| Storage coefficient | 0.10 |
| Water in storage, in billion gallons | 207 |

*Valley-Train Deposits:*

| | |
|---|---|
| Area | 200 sq mi |
| Average saturated thickness | 75 ft |
| Storage coefficient | 0.20 |
| Water in storage, in billion gallons | 628 |

*Glacial Till:*

| | |
|---|---|
| Area (overlying Prairie du Chien-Jordan aquifer). | 1,700 sq mi |
| Average saturated thickness | 50 ft |
| Storage coefficient | 0.05 |
| Water in storage, billion gallons | 890 |

*St. Peter Sandstone:*

| | |
|---|---|
| Area | 660 sq mi |
| Average saturated thickness | 100 ft |
| Storage coefficient | 0.01 |
| Water in storage, billion gallons | 138 |

Total water in storage in the sediments overlying the Prairie du Chien-Jordan aquifer is the sum of the above, or roughly 1.9 trillion gallons. Whether or not the potentiometric surface in the major aquifer is being sustained in places by leakage from storage in these shallow sediments is not known. When and if annual discharge from the major aquifer exceeds the annual recharge to the aquifer, resource planners may want to withdraw water from this storage "bank". These withdrawals will cause water-level declines in the shallow aquifers unless the withdrawals can be replaced with water from another source, most probably artificial recharge.

Artificial Recharge

Artificial recharge is the diversion of surface water to places where it can seep into the subsurface and add to the ground-water resources. It becomes feasible when, in time or space, ground-water levels in the major aquifers are in danger of falling below desired depths. The benefits to be derived from artificial recharge are dependent on the volume of water added to storage in the aquifer, the subsequent buildup in water levels, and the length of time the recharge water remains in storage at the particular place. Major elements to be considered in artificial recharging are 1) sources of recharge water; 2) conveyance to selected recharge sites; 3) chemistry of the recharge water and its compatibility with the ground water being recharged; and 4) means of getting recharge water into storage in the ground-water reservoirs.

Item 1 above poses no problem in this area because there are ample flood flows in the major streams in the early spring that could be diverted to selected places of recharge. Items 2 and 3 involve special studies of overriding importance. Item 4 can be done by either one or both of the two methods – direct injection into recharge wells or water-spreading in surface ponds or lakes.

The Geological Survey is now (1971) studying artificial recharge by injection through wells in dolomite in the Prairie du Chien Group in West St. Paul. The results of this study should prove valuable to water planners in the Twin Cities area, where carbonate rocks constitute major aquifers. Theoretically, a water well will take as much water as it will give. However, it is necessary that certain logistics of well recharge and well-maintenance problems be worked out before the injection method is used. Lakes are presently being recharged in this area. In 1969, roughly 1.5 billion gallons of water was pumped into Lake Calhoun from streams. (See Figure 50.) Part of this water must have seeped through the lake bottom to recharge the underlying aquifers. The major consideration in water spreading is the infiltration capacity of the subsurface sediments at the recharge sites. The bottom sediments of lakes are generally of low permeability, so that leakage is minimal. In recharge ponds, it is necessary to keep the surface "skin" as free as possible of the low permeability sediments carried in the recharge water, so as to facilitate rapid infiltration. This is done generally by scarification; in lakes, it may be done by dredging. The vertical hydraulic conductivity of the deposits between the surface "skin" and the top of the aquifer must, of course, be high, so that recharge can be significant. If these deposits are of low conductivity, the large size of the areas needed for ponding become a deterrent.

The vertical conductivity of the bulk of the deposits above the Prairie du Chien-Jordan aquifer can be estimated by rearranging the formula on page 109-110.

$$P' = Q_c m' / [A_c (2.8 \times 10^7) \Delta h]$$

Using the base daily pumping rate of $Q_c$ = 104 mgd, m' = 90 ft., $\Delta h$ = 50 feet, and $A_c$ = 740 square miles; then P' = 0.009 gpd per square foot. The lithology of these deposits would be classed as "Drift, clay and silt with some sand and gravel and dolomite" (Table 7). Using the summer pumping rate, or $Q_c$ = 231 mgd, m' = 90 feet, $\Delta h$ = 58 feet (50 + 8), and $A_c$ = 770 square miles; the P' = 0.017 gpd per square foot which would be classed as "Drift, clay and silt with some sand and gravel".

The leakage coefficients (Hantush, 1956) or the recharge rates per unit area per foot of head loss (P'/m') are $1.0 \times 10^{-4}$ gpd per cubic foot and $1.9 \times 10^{-4}$ gpd per cubic foot, respectively, for the two situations described above.

The leakage coefficient remains constant as long as the saturated thickness and vertical conductivity of the deposits through which recharge occurs does not change and the potentiometric surface does not decline below the base of the deposits. (See Walton, 1965, p. 33.) The two coefficients above differ then, not because of a change in saturated thickness, although some relatively slight reduction in thickness must have occurred during the summer pumping period, but because of a change in the bulk vertical conductivity. Summer drawdown cones near the river (Figure 47) have given more weight to the significance of the more highly permeable alluvial and valley-fill sediments, and, thus, the leakage coefficient for the bulk of the sediments has increased. At the higher coefficient of $1.9 \times 10^{-4}$ gpd per cubic foot and with a head change of 1 foot over a hypothetical 10 square miles, the recharge rate would be 53,200 gpd into the major aquifer. At the lower rate of $1.0 \times 10^{-4}$ gpd per cubic foot, the rate would be only 28,000 gpd. One foot of water ponded over 10 square miles is 2.1 billion gallons. One foot of head rise over 10 square miles in sediments having a storage coefficient of 0.10 takes 210 million gallons. Thus, where the leakage coefficient is low, the volume of water needed to produce 1 foot of head, the driving force, is excessive compared to the recharge benefits derived. Recharge into the major aquifer by water spreading would probably be slow unless the overlying sediments were composed entirely of drift of relatively high vertical conductivity. Ideal site selection would be imperative if immediate benefits are expected solely in the major aquifer. But, artificial recharge into the shallow aquifers at selected sites can be rapid. Large areas exist in the metropolitan area where the surficial sediments are valley-train and outwash deposits (Figure 9). Referring to Table 7, the lithology of these deposits could be classified as "Drift, sand and gravel, some clay and silt". Their leakage coefficients would probably range from 3.4 x $10^{-2}$ to 2.3 x $10^{-1}$ gpd per cubic foot. Using a leakage coefficient of 1.5 x $10^{-1}$ gpd per cubic foot, 1 foot of water ponded over 10 square miles would result in a recharge of 42 mgd. If ideal sites were selected, recharge could proceed at a rate of 64 mgd. Doubling the head will double the recharge, and so forth. Once the initial ponds are filled, water need only be added at the recharge rate plus losses due to evaporation, which would be large where spreading areas are large. Once in the subsurface, the water would move out laterally and, as head declines are increased in the potentiometric surface of the major aquifer by pumping, the recharge rate would increase substantially. Under good management, it seems reasonable to expect that artificial recharge could be carried on in this area at an average rate of at least 100 mgd, providing proper recharge sites are available. However, before any artificial recharge project is undertaken, extensive research into operational and experimental recharge projects would be extremely valuable.

Factors for consideration and information needed to carry on an artificial-recharge program in three broad parts of the study area are discussed in general below. No degree of accuracy is intended for the estimated parameter values used, for they are only for purposes of discussion – fieldwork is needed to obtain accurate values.

*Anoka Sand Plain:* The Anoka sand plain overlies an extensive, roughly fan-shaped sand body, largely to the north of the Twin Cities. This sand body could constitute an important source of recharge in the metropolitan area. Eng (1968), in a reconnaissance of roughly a 25-square mile area near Ham Lake on the sand plain, suggests that water from the surficial aquifers underlying the plain is recharging bedrock formation, which, in turn, are supplying water to the Twin Cities area. The potential for recharge to the underlying aquifers from the sand body certainly exists, but the magnitude and significance of this recharge is not fully known.

The Anoka sand plain covers about 850 square miles (Farnham, 1956), chiefly in Anoka, Isanti, Sherburne, and Chisago Counties. The surficial sand is dominantly poorly stratified and fine, and islands of gray clay till occur within the plain. Mechanical analyses by Farnham (1956, p. 60) show: 17.5 percent medium sand and coarser, 59.1 percent fine sand, and 23.4 percent very fine sand and finer. There is no indication of a decrease in particle size from west to east. The area is poorly drained and contains many lakes and swamps.

Where the sand is at the surface, it probably ranges in thickness from about 2 to 100 feet and averages about 45 feet. It is underlain at various places by gray clay till (Des Moines lobe) and red sandy till (Superior lobe). The water table is shallow, ranging in depth from 0 (in swamps) to about 20 feet below land surface. The surficial sand and underlying till is underlain by the Prairie du Chien-Jordan aquifer in the southern part of the plain; by the Ironton-Galesville aquifer in the central part, and by the Mount Simon-Hinckley aquifer in the northern part. Head differences between the water table and the potentiometric surfaces in the bedrock aquifers possibly average 15, 40, and 10 feet, respectively. At some places, especially in the northern part of the plain, the potentiometric surface in the Mount Simon-Hinckley and the water table in the sand may almost coincide.

The storage coefficient of the sand is estimated to be 0.2; therefore, each cubic foot of sand holds about 1.5 gallons of water. At an average saturated thickness of 45 feet and an area of 850 square miles, the total water in storage in the sand is about 1.6 x $10^{12}$ gallons.

Because of the many lakes and swamps and the shallow water table in the sand plain, maximum evapotranspiration is probably 22 inches of water per year. In places, the surficial aquifer is probably fully saturated, and much water, available annually for recharge, is rejected. Therefore, if it were to be artifically recharged, water levels in parts of the aquifer would have to be drawn down by pumping to make room for the additional recharge. This may pose a problem because it could be difficult to obtain large yields of water from conventional wells pumping from the predominantly fine sand. Excessive pumping from the underlying bedrock aquifers might serve a similar purpose, however.

The average vertical conductivity of the sand is estimated at 5 gpd per square foot. Thus, assuming the existence of no confining beds, the leakage rate through the sand for each foot of head differential is 3.3 mgd per square mile. However, assuming that the sand is underlain by 10 feet of gray clay till with a conductivity of 0.03 gpd per square foot, the leakage rate for each foot of head differential would be only about 84,000 gpd per square mile to the underlying aquifers. For 15 feet of head difference, leakage would be 1.26 mgd per square mile, the rate at which the Prairie du Chien-Jordan aquifer may be recharged at some places.

*Lake Minnetonka Area:* The Lake Minnetonka area is a major recharge area for the Prairie du Chien-Jordan aquifer. The land surface in the Minnetonka area is underlain by the Des Moines lobe and Superior lobe drift, ranging in thickness from about 80 to 300 feet. The composition of the drift is variable; sand and gravel occurs at the surface in places and clay or clay till at the surface in other places. The sand and gravel and till layers alternate in the subsurface in beds of varying thicknesses. Aquifers that subcrop in the area include the St. Peter and Prairie du Chien-Jordan. The altitude of the lake surface is about 930 feet, and it is assumed to represent that of the water table in the drift.

Harza Engineering Co. and others (1971) made a somewhat detailed study of the Lake Minnetonka watershed to formulate a program for preserving the quality of the lake water. As part of that study, a water budget for the lake was made, and it was estimated that 4 inches of water leaks annually from the watershed into the underlying aquifers, a reasonable approximation. The head difference between the potentiometric surface in the Prairie du Chien-Jordan aquifer and the water table in the glacial drift changes from 20 to 70 feet in this area. Assuming an average till thickness of 50 feet, an average head difference of 30 feet, and a leakage rate of 4 inches per year (191,000 gpd/sq. mi.), the average vertical hydraulic conductivity of the confining till layer(s) between the water table and the bedrock aquifers is 0.0114 gpd per square foot. And the potential leakage rate ranges from 127,000 to 447,000 gpd per square mile in places, or about 6,400 gpd per square mile per 1 foot of head difference. Roughly 15 square miles of the Prairie du Chien-Jordan aquifer is directly overlain by glacial drift and Lake Minnetonka proper. If the lake level is raised 1 foot, the leakage to the aquifer is increased by 96,000 gpd (6,400 gpd per sq. mi. x 15 sq. mi.). If the lake level is lowered 1 foot, the leakage is decreased by the same amount. Assuming the average head difference between the lake surface and the potentiometric surface in the aquifer to be 30 feet, the leakage from the lake into the aquifer is 191,000 gpd per square mile, or 2.9 mgd. However, the lake is as deep as 90 feet in a few places. Here the intervening drift layers between the lake and the aquifer may be thin or even absent, in which places, the unit leakage could be considerably greater than estimated above. Of course, a controlling factor, which is not known, is the permeability of the lake-bottom sediments.

The above attempts to determine the unit leakage in the Minnetonka area yield gross estimates and may be misleading. The hydrology and geology of the area are complex, and more data are needed for future hydrologic studies.

*Vermillion River Basin:* The Vermillion River basin includes 195 square miles in the southeast corner of the study area. Land-surface altitudes range from near 1,100 feet in the upper part of the basin to less than 700 feet in the flats, where the Vermillion River flows into the Mississippi. Surficial deposits are glacial drift composed largely of sand and gravel outwash of both the Des Moines and Superior lobes (Figure 9). At places, small mounds of St. Peter Sandstone and Prairie du Chien dolomite crop out. The drift ranges in thickness from a feather edge to more than 300 feet (Figure 8), and the entire drift section may be composed entirely of sand and gravel. The St. Peter and Prairie du Chien-Jordan aquifers directly underlie the surface deposits (Figure 45).

The water table in the basin ranges from 0 to more than 100 feet below land surface, getting progressively deeper in the downstream direction until it surfaces again to discharge into the Mississippi River.

An auger hole (114.17.5ccd) a few miles southwest of Hastings penetrated 70 feet of dry sand before hitting solid rock. The water levels in the St. Peter aquifer and in the drift aquifers are probably almost coincident in most places. The head difference between the water table and the potentiometric surface in the Prairie du Chien-Jordan aquifer probably ranges from a few feet in places in the headwaters region to more than 50 feet in places in the downstream part of the basin, before both surfaces come together to discharge into the Mississippi River. The hydraulic relationship between the water table and the potentiometric surface of water in the Prairie du Chien–Jordan aquifer is not known in the valley of the Vermillion River.

Average annual baseflow (ground-water runoff) in the basin is 31 cfs, assuming that the 60-percent point of the duration curve of the Vermillion River at Hastings (Figure 37) is representative of baseflow. This amounts to a unit yield of 0.16 cfsm, or about 100,000 gpd per square mile. Water available for development in the basin then amounts to 19.5 mgd, a more realistic figure being about two-thirds of this, or 13 mgd.

Data are not sufficient to determine optimum artificial recharge rates in this area. Surface infiltration and subsurface percolation rates are probably high in much of the area. Using the highest rate of vertical conductivity, 1.60 gpd per square foot, shown in Table 7; assuming an average head difference of 20 feet between the water table and the Prairie du Chien-Jordan aquifer; and an average drift thickness of 50 feet, the recharge rate would be 18 mgd per square mile, a rate close to the entire basin yield estimate above. This rate would be less where there is less permeable material in the subsurface. At the assumed large rate of percolation, it is understandable why thick sections of the surficial sand and gravel deposits are dry.

Although it seems possible that the water resources in this basin may be augmented with water from artificial recharge, other hydrologic aspects of the basin must be considered. That is, almost anyplace in the basin is close to a possible place of natural discharge, either the Vermillion River flow plain or the Mississippi River bottom lands. Thus, any buildup in water levels may be followed shortly by a corresponding increase in natural discharge. For this reason, it is necessary to make detailed hydrologic study of this or any other area where artificial recharge is seriously being considered.

### Incidental Recharge

Incidental recharge is water that passes through the present water-supply-dispersal system and percolates downward to the water table. It occurs generally as leakage from water mains; settling basins; sewer laterals, both storm and sanitary; and individual home drainage fields. The volume of water recharged throughout the metropolitan area in this manner is difficult to determine. Estimated losses and unaccounted for water in the Minneapolis and St. Paul systems alone amount to roughly 20 mgd. Not all of this percolates to the ground, however, for some is discharged overland and through sewers. Quantitatively, then, the inefficiencies of the dispersal systems are beneficial to the ground-water supply system. Qualitatively, however, especially as concerns sanitary sewers, these inefficiencies may not be beneficial. For purposes of this report, incidental recharge is estimated at 20 mgd.

## *Summary of Ground-Water Availability*

The availability of ground water for development is summarized as 1) potential sustained yields of aquifers and 2) water available from recharge. The latter is the controlling factor for the optimum sustained level of development in the metropolitan area because the aquifers are capable of yielding more water than is naturally recharged. Beyond the metropolitan area, however, natural recharge is more than enough to supply any needs for the foreseeable future.

### Potential Yields of Aquifers

The estimated present and potential additional yields obtainable from the Prairie du Chien-Jordan and the Mount Simon-Hinckley aquifers are shown in

Table 22. These yields are obtainable if, on the average, the heads in the above aquifers are drawn below the 1970 potentiometric levels (Figures 20 and 20) 75 and 300 feet, respectively, as shown in column (6). Also, these yields are obtainable only if recharge is equal to or greater than pumpage. Under maximum practical stress and good management, the two major aquifers may yield an additional 975 mgd in the metropolitan area. They can yield almost 1,200 mgd by extending well fields a relatively short distance west and north of the metropolitan area.

Note that the yield estimates made here are based on the gross response of the aquifers to present-day pumping and on reasonable assumptions in areas where data are lacking. The effects of both lateral and vertical boundaries on drawdowns in the hydrologic system were not considered in making these estimates.

Water Available from Recharge

As stated above, the water available from recharge is the controlling factor for the optimum level of ground-water development in the metropolitan area. The estimates of aquifer yields shown in Table 22 are valid only if recharge is equal to or greater than pumpage. The sources and estimates of practical recharge within the metropolitan area are as follows:

| Source of recharge | Approx. amt. in mgd |
|---|---|
| Precipitation (2,000 sq. mi.) | 375 |
| Induced from streams | 350 |
| Artificial | 100 |
| Incidental | 20 |
| Total | 845 |

Two thirds, or 4,000 square miles, of the study area falls outside the limits of the Prairie du Chien-Jordan aquifer. If 3.72 inches of basin-storage discharge, then 710 mgd is recharge from precipitation, and about two-thirds (less than the three-fourths in metropolitan area), or 475 mgd, is available to pumping wells. (The 3.72-inch factor was derived algebraically for 4,000 square miles by using the 4.23-inch determination in Table 5 for the entire 6,000-square-mile area and the 5.24-inch determination for the roughly 2,000-square-mile Twin Cities area within the entire area). For the 1,500 square miles in which the hypothetical pumping wells are located (p. 167), 265 mgd is recharged, and 175 mgd is available. Thus, slightly more than 1 billion gallons of water per day can be obtained by increasing pumpage in both the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers in and around 3,500 square miles of the metropolitan area and by using considerable management and planning. About 1.3 billion gallons per day can be pumped in the entire area.

*Aspects of Future Ground-Water Development*

The question now arises as to how much water is available if the growth of pumpage continues on its present course, that is, under a minimum of management controls. The answer to this can only be surmised. The Twin Cities are located in an ideal place of optimum use of ground water. Almost anywhere a well is drilled in the Prairie du Chien-Jordan aquifer is either near a place of natural discharge from the aquifer or near a place of natural recharge to the aquifer. (See Figure 20.) Thus, drawdown cones of pumping wells either capture natural discharge or induce natural recharge, thereby causing these cones to stabilize in a relatively short time. A possible exception to this is along the ridge in the potentiometric surface of the aquifer (Figure 20), midway between St. Paul and Hudson, Wisconsin. Drawdown here would have to be excessively deep to capture natural discharge; and the area for recharge is narrow, so danger of overdevelopment exists.

Summer pumpage in 1970 from the Prairie du Chien-Jordan aquifer was 231 mgd; the pumpage from all aquifers was less than 300 mgd. The major drawdown cones caused by summer pumpage are shown in Figure 47. As expected, the deepest cones are in the Minneapolis and St. Paul downtown areas, where pumping for air conditioning peaks and interference among wells is maximum. Overlaying Figure 47 on Figure 41 shows that, at peak drawdown in the summer, the residual head in the Prairie du Chien-Jordan aquifer is about 75 feet in Minneapolis and about zero in St. Paul. This is not alarming, however,

Table 22. – Present and potential additional yield of aquifers assuming infinite recharge available.

| Aquifer | Area (sq. mi.) | Approximate average daily 1970 pumpage (mgd) | Area affected by 1970 pumpage (sq. mi.) | Area affected by optimum pumpage (sq. mi.) | Estimated average practical head available (ft.) | Estimated potential additional yield (mgd) | Remarks |
|---|---|---|---|---|---|---|---|
| River alluvium and valley fill deposits | 110 | 14 | ID [1] | 110 | ID | ID | Area is for that part overlying the Prairie du Chien aquifer within the metropolitan area, in Minnesota |
| Valley train deposits | 200 | | ID | 200 | ID | ID | Area is for that part overlying the Prairie du Chien aquifer within the metropolitan area, in Minnesota |
| Undifferentiated glacial drift | 1700 | | ID | 1700 | ID | ID | Area is for that part overlying the Prairie du Chien aquifer within the metropolitan area, in Minnesota |
| St. Peter Sandstone | 660 | | ID | 660 | – | – | Area is for that part overlying the Prairie du Chien aquifer within the metropolitan area, in Minnesota |
| Prairie du Chien-Jordan | 2000 | 104 [2] | 740 [3] | 1710 [4] | 75 | 782 | 1970 summer pumpage is 231 mgd and affects an area of 770 sq. mi. Total estimated yield is about 886 mgd. |
| Ironton-Galesville | | 6 | ID | | – | – | |
| Mount Simon-Hinckley | 6000 | 29 | 740 [5] | 3500 | 300 | 1) 206<br>2) 191<br>3) 216 | 1) Only for 2,000 sq. mi.; assumes Prairie du Chien-Jordan head is stable<br>2) Only for 2,000 sq. mi.; assumes Prairie du Chien-Jordan head is dropped 75 feet overall<br>3) Yield from 1,500 sq. mi. beyond extent considered above. Assumes 150 wells each pumping 1,000 gpm |

[1] ID, insufficient data  [2] Base daily pumpage (p. 129)  [3] Area affected by base daily pumpage

[4] Only artesian part of aquifer in Minnesota is considered  [5] Assumed area

for these cones of depression almost fully recover in the fall, after the pumping stress is removed. If the intense summer pumpage were maintained year round, the cones would deepen and spread laterally.

Base daily pumpage in the Prairie du Chien-Jordan is about 104 mgd and, from all aquifers, probably less than 150 mgd. Placement of high-yield wells is critical. Closely spaced wells mutually withdrawing water from the same area, such as those in downtown Minneapolis and St. Paul, may create excessive drawdowns, which, in turn, create need for lowering drop pipes in wells. This increases the costs of pumping water and maximizes electric-power consumption for this purpose. When water levels fall below the tops of the aquifers, many of the wells in the downtown areas will have to be deepened. A large part of these recurring costs in pumping water can be deferred by planning and management.

It is not the purpose of this study to formulate plans for future development but to provide technical information. The information should prove useful if such plans are formulated. Maps in this report can be used to select well sites based on considerations of 1) aquifer, 2) depth needed for completion, 3) head availability, 4) location of natural recharge and discharge boundaries, and 5) distance from areas where overdevelopment is imminent. In addition, the potentiometric-surface maps of the different aquifers, especially those of the Prairie du Chien-Jordan, are bases for comparisons. Water-level-change maps (Figures 47 and 48) can be drawn for any period in the future by repeating the water-level measurements in the control wells used in this study. In turn, the water-level-change maps can be overlaid on the availability of head maps (Figures 41 and 42) to obtain estimates of total head depletion; thus, water managers can be forewarned where over-development of ground water is impending.

# CHAPTER SIX: WATER QUALITY

## GROUND WATER

The ground-water-quality data in Table 23 are compiled from 388 complete and partial chemical analyses collected by the Minnesota Department of Health and the U.S. Geological Survey. The samples were collected during 1951-70. The dissolved mineral concentrations and physical characteristics of water in the different aquifers in the study area are listed by range and median of values. The range of many of the constituents is large because of the different degree of intermixing of waters in different places. Intermixing of waters, especially in the metropolitan area, is intensified by the cones of influence of pumping wells inducing recharge from above, below, and laterally into the pumped aquifer. Some local intermixing may occur through uncased wells that penetrate more than one aquifer. Probably the lower values in each range are more representative of water in the different aquifers in the undisturbed natural state, except for water in glacial drift, which is widely variable in composition, depending on the type of drift. For example, historically, the Mount Simon-Hinckley aquifer is known to contain soft water, as indicated by the 54 mg/1 (milligrams per liter) value at the lowest end of its hardness range, yet the water is as hard or harder at the highest end of the range than some of the water in the other aquifers, which are expected to contain hard water. Where the aquifers are directly overlain by the glacial drift from which they derive much of their recharge, relatively high mineralization of the water can be expected.

Only a generalized appraisal of ground-water quality is intended in this report, but a few extremes in constituents shown in Table 23 warrant some explanation. For example, the highest sodium and sulfate values, 180 and 67 mg/1, respectively, for water in the Mount Simon-Hinckley aquifer were determined for water samples from well 118.23.3cacl at Howard Lake, near the extreme western boundary of the Hinckley Sandstone. (The boundary of the study area, as shown on the maps, should be extended about 1 mile westward at this place.) Here the sandstone is in close proximity to Cretaceous sediments, the water of which is generally high in sodium and sulfate. Apparently, water from the rock formations on the west moves into the Hinckley aquifer. Similarly, the highest sulfate, 89 mg/1, in the Jordan Sandstone is in water from well 115.26.14cbc at Norwood (Figure 57). This well is also close to the Cretaceous sediments, but here the aquifer is directly overlain by thick deposits of Des Moines lobe drift, which contains highly mineralized water free to percolate downward into the aquifer. The highest chloride concentration, 190 mg/1, of any other of the aquifers is in water from the Mount Simon-Hinckley aquifer in well 37.21.21aab2 at Rush City. Although this is below the 250 mg/1 limit recommended by the U.S. Public Health Service, it is anomalously high for the study area. There is no ready explanation for the high chloride at this location.

The extremes of nitrate concentration, an indicator of pollution, are in the glacial drift and the Prairie du Chien aquifers. The range in the other aquifers is slight in comparison. Pollution can occur easily in the surficial sand and gravel aquifers in the drift because of their shallowness. Pollution can also occur easily in the Prairie du Chien dolomites because of the secondary permeability in these rocks. Where the aquifer is overlain by thin drift, polluted water is filtered but little as it percolates downward into and through the joints and factures in the aquifer.

Generally, ground water in the study area is relatively good for most uses. Except for high nitrate concentrations in some wells, there are no extremes in constituent concentrations that might be considered alarming. Maderak (1965) made a somewhat detailed evaluation of the chemical quality of ground water in the metropolitan area. The conclusions from that work are repeated here as follows:

1. On the average the water from all the formations is the calcium bicarbonate type.

2. The average dissolved-solids content of the water from the major aquifers is highest in the glacial drift and lowest in the Jordan Sandstone.

3. The different materials that compose the reddish-brown (Superior lobe) and light-gray (Des

Table 23. – Summary of water-quality data in aquifers in the Minneapolis-St. Paul area. (Chemical constituents reported in milligrams per liter unless otherwise noted.)

| | Glacial Drift | | | St. Peter | | |
|---|---|---|---|---|---|---|
| Constituent | Range | Median | No. of Samples | Range | Median | No. of Samples |
| Silica ($SiO_2$) | 13-35 | 23 | 76 | 14-34 | 22 | 14 |
| Iron (Fe) | 0-9.6 | .18 | 115 | .01-8.82 | 0.51 | 17 |
| Manganese (Mn) | 0-2.5 | .15 | 115 | 0-.53 | .08 | 15 |
| Calcium (Ca) | 14-186 | 72 | 115 | 49-96 | 81 | 17 |
| Magnesium (Mg) | 3.6-57 | 24 | 114 | 15-51 | 30 | 17 |
| Sodium (Na) | 2-72 | 5.6 | 105 | 3.1-20 | 5.2 | 17 |
| Potassium (K) | .3-9.4 | 1.6 | 82 | 1.0-5.7 | 1.65 | 14 |
| Bicarbonate ($HCO_3$) | 46-645 | 304 | 150 | 217-452 | 366 | 17 |
| Sulfate ($SO_4$) | .1-157 | 15 | 114 | 1.5-81 | 13.5 | 17 |
| Chloride (Cl) | 0-88 | 2.9 | 115 | 0-33 | 4.0 | 17 |
| Fluoride (F) | 0-.5 | .2 | 110 | .1-.3 | .2 | 17 |
| Nitrate ($NO_3$) | 0-91 | <4.4 | 150 | 0-10.1 | .9 | 17 |
| Phosphorus (P) | .01-.26 | .06 | 77 | .03-.09 | – | 3 |
| Boron (B) | 0-.45 | .03 | 99 | .01-.05 | .04 | 13 |
| Dissolved solids (residue on evaporation at 180° C) | 109-782 | 326 | 99 | 229-457 | 349 | 13 |
| Hardness as $CaCO_3$: calcium, magnesium | 56-644 | 290 | 115 | 182-412 | 324 | 17 |
| Noncarbonate | 0-134 | 17 | 59 | 0-82 | 2 | 11 |
| Specific conductance (micromhos at 25° C) | 140-1160 | 553 | 120 | 362-738 | 570 | 14 |
| pH | 6.0-8.2 | 7.7 | 138 | 7.3-8.1 | 7.8 | 17 |
| Temperature (°F) | 47-60 | 53 | 91 | 49-68 | 52 | 11 |
| Detergents (as alkyl benzene sulfonate, ABS) | .01-.24 | .03 | 41 | .01-.02 | – | 2 |

Table 23. – Summary of water-quality data in aquifers in the Minneapolis-St. Paul area. (Chemical constituents reported in milligrams per liter unless otherwise noted.) – Continued

| | Prairie du Chien | | | Prairie du Chien-Jordan | | |
|---|---|---|---|---|---|---|
| **Constituent** | **Range** | **Median** | **No. of Samples** | **Range** | **Median** | **No. of Samples** |
| Silica ($SiO_2$) | 13-23 | 19 | 13 | 14-22 | 16 | 7 |
| Iron (Fe) | .01-2.5 | .33 | 14 | .02-7.5 | 0.39 | 45 |
| Manganese (Mn) | 0-.71 | .035 | 14 | 0-.31 | .04 | 43 |
| Calcium (Ca) | 47-101 | 70 | 14 | 38-108 | 69 | 45 |
| Magnesium (Mg) | 12-41 | 23 | 14 | 15-44 | 29 | 45 |
| Sodium (Na) | 2.6-31 | 5.4 | 14 | 0-63 | 6 | 43 |
| Potassium (K) | .8-6.7 | 1.4 | 13 | .6-3.4 | 2.1 | 9 |
| Bicarbonate ($HCO_3$) | 247-435 | 283 | 14 | 195-537 | 329 | 45 |
| Sulfate ($SO_4$) | 1.5-39 | 8.9 | 14 | .2-124 | 8.3 | 45 |
| Chloride (Cl) | 0-46 | 2.0 | 14 | .5-31 | 1.7 | 45 |
| Fluoride (F) | 0-.3 | .2 | 14 | 0-1.5 | .2 | 45 |
| Nitrate ($NO_3$) | 0-127 | <4.4 | 14 | 0-25 | 4.4 | 44 |
| Phosphorus (P) | .02-.06 | .02 | 4 | .09-.11 | – | 2 |
| Boron (B) | .01-.11 | .03 | 13 | 0-.09 | .06 | 6 |
| Dissolved solids (residue on evaporation at 180° C) | 222-496 | 305 | 12 | 198-564 | 295 | 26 |
| Hardness as $CaCO_3$: calcium, magnesium | 190-403 | 271 | 14 | 160-430 | 290 | 45 |
| Noncarbonate | 0-169 | 0.8 | 9 | 0-44 | 10 | 5 |
| Specific conductance (micromhos at 25° C) | 370-791 | 495 | 13 | 340-898 | 479 | 19 |
| pH | 6.9-8.0 | 7.6 | 14 | 6.9-8.1 | 7.5 | 43 |
| Temperature (°F) | 50-60 | 53.5 | 8 | 48-53 | 50 | 6 |
| Detergents (as alkyl benzene sulfonate, ABS) | .01-.03 | – | 2 | .02 | – | 1 |

Table 23. – Summary of water-quality data in aquifers in the Minneapolis-St. Paul area. (Chemical constituents reported in milligrams per liter unless otherwise noted.) – Continued

| | Jordan | | | Ironton-Galesville | | |
|---|---|---|---|---|---|---|
| Constituent | Range | Median | No. of Samples | Range | Median | No. of Samples |
| Silica ($SiO_2$) | 11-21 | 15 | 25 | 17-23 | 19 | 3 |
| Iron (Fe) | 0-4.2 | .29 | 97 | .03-1.2 | .75 | 6 |
| Manganese (Mn) | 0-.53 | .03 | 100 | 0-.35 | .04 | 6 |
| Calcium (Ca) | 27-104 | 64 | 99 | 43-61 | 52 | 6 |
| Magnesium (Mg) | 7.4-51 | 27 | 99 | 7.3-46 | 18.5 | 6 |
| Sodium (Na) | 0-44 | 4.5 | 91 | 3-16 | 5.75 | 5 |
| Potassium (K) | .8-4.0 | 1.75 | 28 | 1.2-2.0 | 1.3 | 4 |
| Bicarbonate ($HCO_3$) | 134-537 | 305 | 101 | 183-415 | 255 | 6 |
| Sulfate ($SO_4$) | <.1-89 | 7.5 | 99 | 3-31 | 5 | 6 |
| Chloride (Cl) | 0-37 | 1.6 | 99 | .7-10 | 1.8 | 6 |
| Fluoride (F) | <1-1.2 | .2 | 94 | .1-.3 | .2 | 6 |
| Nitrate ($NO_3$) | 0-26 | <4.4 | 99 | 0-8.8 | 2.4 | 6 |
| Phosphorus (P) | .03-.13 | .06 | 7 | – | – | – |
| Boron (B) | 0-.14 | .02 | 25 | 0.06 | 0.06 | 3 |
| Dissolved solids (Residue on evaporation at 180° C) | 136-640 | 275 | 64 | 180-400 | 2.54 | 6 |
| Hardness as $CaCO_3$: calcium, magnesium | 106-460 | 251 | 100 | 150-340 | 195 | 6 |
| Noncarbonate | 0-28 | 0 | 24 | 0 | 0 | 1 |
| Specific conductance (micromhos at 25° C) | 220-646 | 456 | 49 | 240-457 | 405 | 4 |
| pH | 6.6-8.2 | 7.6 | 97 | 7.0-7.6 | 7.4 | 6 |
| Temperature (°F) | 49-68 | 51 | 21 | 53 | 53 | 1 |
| Detergents (as alkyl benzene sulfonate, ABS) | 0-.04 | .02 | 6 | – | – | – |

Table 23. – Summary of water-quality data in aquifers in the Minneapolis-St. Paul area. (Chemical constituents reported in milligrams per liter unless otherwise noted.) – Continued

| | Mount Simon-Hinckley | | | Recommended limits for drinking water (U.S. Public Health Service, 1962) |
|---|---|---|---|---|
| Constituent | Range | Median | No. of Samples | Concentrations in mg/1 |
| Silica ($SiO_2$) | 7.3-32 | 19 | 19 | – |
| Iron (Fe) | .02-.83 | .76 | 55 | 0.3 |
| Manganese (Mn) | 0-1.1 | .07 | 54 | .05 |
| Calcium (Ca) | 11-100 | 54 | 55 | – |
| Magnesium (Mg) | 6.4-53 | 20 | 55 | – |
| Sodium (Na) | 0-180 | 10.5 | 48 | – |
| Potassium (K) | 1-6.8 | 2 | 25 | – |
| Bicarbonate ($HCO_3$) | 61-537 | 268 | 55 | – |
| Sulfate ($SO_4$) | .3-67 | 5 | 52 | 250 |
| Chloride (Cl) | <.5-190 | 5.1 | 54 | 250 |
| Fluoride (F) | 0-1.6 | .25 | 50 | 1.5 1/ |
| Nitrate ($NO_3$) | 0-13.6 | <4.4 | 52 | 45 |
| Phosphorus (P) | .01-.18 | .07 | 10 | – |
| Boron (B) | 0-.77 | .07 | 24 | – |
| Dissolved solids (residue on evaporation at 180° C) | 79-660 | 273 | 39 | 500 2/ |
| Hardness as $CaCO_3$: calcium, magnesium | 54-430 | 220 | 55 | – |
| Noncarbonate | 0-19 | 0 | 9 | – |
| Specific conductance (micromhos at 25° C) | 230-797 | 446 | 28 | – |
| pH | 6.2-8.0 | 7.6 | 54 | – |
| Temperature (°F) | 45-56 | 50 | 15 | – |
| Detergents (as alkyl benzene sulfonate, ABS) | 0-.05 | .02 | 4 | .5 |

1/ Based on annual average of maximum daily air temperature of 54.6°F at St. Paul
2/ Total dissolved solids

Moines lobe) drifts have little effect on the average percentage composition of constituents in the water, but they do have a significant effect on the median dissolved solids in the water.

4. Except for recharge areas, dissolved solids are lowest in the eastern or northeastern part of the area and highest in the western or southern part.

5. Prediction of the quality of water likely to be obtained from the major aquifers in the basin is possible with the use of isocon (lines of equal concentration of dissolved solids) maps, a system of curves, and bar graphs.

6. The natural change in the quality of water in the major aquifers from 1899 to 1963 has been minor.

7. Pollution, as indicated by nitrate concentrations, of the ground water is fairly widespread in the Richfield and Brooklyn Park communities.

8. Contamination of drift aquifers in recharge areas could affect the quality of water in the Jordan Sandstone.

9. Excessive concentrations of iron and manganese and of hardness necessitate treatment of the water used in most industries (and in several municipal water systems).

10. The quality of the water from all major aquifers in most of the basin is suitable for municipal and domestic supplies (with appropriate treatment).

For an explanation of the interpretation of the chemical characteristics of natural water, see Hem (1970).

## SURFACE WATER

Surface-water-quality samples are collected on some streams by the Minneapolis and St. Paul water departments, by the U.S. Geological Survey, and by the Metropolitan Sewer Board. The Twin Cities water departments analyze samples of water at their respective water-supply intakes on the Mississippi River at Columbia Heights and Fridley. The results of these analyses are published by the Water Works of the Minneapolis Department of Public Works and by the Board of Water Commissioners of the city of St. Paul in their respective annual report series. An example of the analyses made in 1970 by the St. Paul Water Department is shown in Table 24.

The Geological Survey presently maintains only one station, Minnesota River near Jordan; complete chemical analyses of water samples from this station are made monthly. Continuous temperature records are collected of Mississippi River water at St. Paul and at Lock and Dam No. 3 near Red Wing, 13 miles southeast of the study area. At least one complete chemical analysis is available for 33 other sites on various streams (Table 3). Individual quality-of-water determinations, such as specific conductance and suspended sediment load, also are available for many streams in the files of the Geological Survey; they are not included in published reports.

Chemical analyses made during water year 1968-69 for stations on the Minnesota and Mississippi Rivers are shown in Table 25. Examination of the analyses show an appreciable range in most of the constituents throughout the period of sampling. Time and volume of discharge must be considered when interpreting the analyses. For example, most individual constituent concentrations and thus dissolved solids, excluding the determination in tons per day, are generally least at the highest discharge rates and most at the lowest rates. This is because, at high discharge rates, streamflow is largely overland runoff made up of snowmelt and rainwater of low mineralization; whereas, at low discharge rates, streamflow is almost wholly made up of more highly mineralized ground-water runoff (baseflow). In direct contrast, concentration of nitrate increases during the high-flow periods. This is because the overland runoff flushes fertilizer and nitrogenous wastes directly from the land surface and into the streams.

Comparison of the analyses at Jordan with those near Anoka show that Minnesota River water is more than twice as mineralized as Mississippi River water except during high flow. The Minnesota River above

Table 24. – Chemical Analysis of water – Mississippi River (Fridley) – 1970 as determined from monthly composite samples (From St. Paul Board of Water Commissioners 89th Annual Report)

| Month | Temperature °C. | Odor at 60° C. | Turbidity | Color | Alkalinity Total ppm | Alkalinity Phen. ppm | Hydrogen Ion-pH | Oxygen Dissolved | Orthophosphates | Surfactants | Ammonia Nitrogen-N | Albuminoid-Ammonia-N | Nitrites-N | Nitrates-N | Total Nitrogen |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 0 | 6 | 1 | 25 | 180 | 0 | 7.9 | 11.5 | 0.05 | 0.05 | 0.064 | 0.432 | 0.012 | 0.090 | 0.598 |
| February | 0 | 6 | 1 | 25 | 180 | 0 | 7.7 | 11.5 | 0.03 | 0.02 | 0.064 | 0.451 | 0.020 | 0.085 | 0.620 |
| March | 1 | 6 | 5 | 20 | 176 | 0 | 7.9 | 12.3 | 0.02 | 0.03 | 0.064 | 0.451 | 0.029 | 0.075 | 0.619 |
| April | 5 | 5 | 9 | 33 | 134 | 0 | 8.2 | 12.4 | 0.02 | 0.02 | 0.080 | 0.536 | 0.008 | 0.090 | 0.714 |
| May | 14 | 5 | 9 | 50 | 116 | 1 | 8.3 | 9.4 | 0.01 | 0.03 | 0.056 | 0.528 | 0.005 | 0.090 | 0.679 |
| June | 22 | 5 | 10 | 43 | 148 | 3 | 8.4 | 8.2 | 0.02 | 0.03 | 0.032 | 0.560 | 0.012 | 0.085 | 0.689 |
| July | 24 | 6 | 12 | 38 | 160 | 10 | 8.8 | 8.7 | 0.03 | 0.04 | 0.005 | 0.325 | 0.004 | 0.095 | 0.429 |
| August | 22 | 6 | 12 | 35 | 168 | 10 | 8.8 | 8.3 | 0.04 | 0.03 | 0.020 | 0.480 | 0.015 | 0.085 | 0.600 |
| September | 17 | 6 | 9 | 30 | 168 | 6 | 8.7 | 9.8 | 0.03 | 0.03 | 0.080 | 0.490 | 0.008 | 0.195 | 0.773 |
| October | 10 | 6 | 8 | 25 | 176 | 6 | 8.7 | 10.9 | 0.03 | 0.03 | 0.060 | 0.416 | 0.014 | 0.085 | 0.575 |
| November | 3 | 6 | 8 | 31 | 152 | 2 | 8.4 | 12.9 | 0.03 | 0.03 | 0.048 | 0.582 | 0.008 | 0.182 | 0.820 |
| December | 2 | 5 | 5 | 30 | 169 | 0 | 8.1 | 13.1 | 0.04 | 0.03 | 0.016 | 0.451 | 0.010 | 0.147 | 0.624 |
| Average | 10 | 6 | 7 | 32 | 151 | 3 | 8.3 | 10.8 | 0.03 | 0.03 | 0.049 | 0.475 | 0.012 | 0.109 | 0.645 |

Table 24. – Chemical Analysis of water – Mississippi River – 1970. – Continued

| Month | Residue on Evaporation | Loss on Ignition | Non Volatile Salts | Silicon-Si | Fluorine-F | Manganese-Mn | Iron-Fe | Aluminum-Al | Chlorides-Cl | Calcium-Ca | Magnesium-Mg | Sulphur-S | Sodium and Potassium as Na | Carbonate Hardness | Non Carbonate Hardness | Total Hardness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 300 | 119 | 181 | 4.97 | 0.50 | 0.03 | 0.28 | 0.32 | 6.0 | 48.1 | 16.4 | 3.58 | 4.41 | 180 | 10 | 190 |
| February | 233 | 107 | 126 | 5.10 | 0.50 | 0.05 | 0.18 | 0.23 | 5.5 | 47.8 | 16.5 | 3.68 | 4.82 | 180 | 9 | 189 |
| March | 244 | 123 | 121 | 5.40 | 0.66 | 0.02 | 0.30 | 0.09 | 10.0 | 47.7 | 16.0 | 3.70 | 7.03 | 176 | 10 | 186 |
| April | 197 | 97 | 100 | 4.03 | 0.22 | 0.03 | 1.10 | 0.00 | 5.5 | 37.4 | 13.5 | 4.32 | 2.70 | 134 | 15 | 149 |
| May | 188 | 99 | 89 | 2.20 | 0.68 | 0.00 | 0.35 | 0.11 | 7.5 | 33.8 | 10.9 | 3.80 | 3.67 | 116 | 14 | 130 |
| June | 212 | 108 | 104 | 3.92 | 0.14 | 0.00 | 0.20 | 0.54 | 5.0 | 40.8 | 13.0 | 3.97 | 3.92 | 148 | 11 | 159 |
| July | 213 | 105 | 108 | 5.00 | 0.40 | 0.10 | 0.10 | 0.00 | 6.0 | 43.8 | 15.3 | 5.00 | 5.16 | 160 | 13 | 173 |
| August | 247 | 119 | 128 | 4.40 | 0.20 | 0.15 | 0.18 | 0.50 | 7.0 | 43.3 | 17.0 | 4.56 | 5.19 | 168 | 13 | 181 |
| September | 278 | 165 | 113 | 3.13 | 0.54 | 0.02 | 0.12 | 0.44 | 7.5 | 44.7 | 17.2 | 5.06 | 8.75 | 168 | 18 | 186 |
| October | 220 | 119 | 101 | 2.76 | 0.36 | 0.20 | 0.30 | 0.09 | 8.0 | 48.2 | 17.6 | 6.13 | 5.64 | 176 | 18 | 194 |
| November | 239 | 116 | 123 | 5.80 | 0.42 | 0.07 | 0.35 | 0.05 | 10.0 | 45.8 | 16.2 | 9.10 | 7.30 | 152 | 27 | 179 |
| December | 310 | 176 | 134 | 5.38 | 0.24 | 0.07 | 0.30 | 0.20 | 7.0 | 47.6 | 15.7 | 6.54 | 6.30 | 169 | 17 | 186 |
| Average | 240 | 121 | 119 | 4.34 | 0.41 | 0.06 | 0.31 | 0.22 | 6.9 | 44.1 | 15.4 | 4.95 | 5.41 | 151 | 15 | 166 |

Table 25. – Chemical analyses for stations on the Mississippi and Minnesota Rivers, water year 1968-1969.

| Date | Discharge (cfs) | Silica ($SiO_2$) (mg/l) | Dissolved Aluminum (Al) (ug/l) | Dissolved Iron (Fe) (ug/l) | Dissolved Manganese (Mn) (ug/l) | Calcium (Ca) (mg/l) | Magnesium (Mg) (mg/l) | Sodium (Na) (mg/l) | Potassium (K) (mg/l) | Bicarbonate ($HCO_3$) (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| Minnesota River near Jordan (05330000) | | | | | | | | | | |
| Oct. 03 | 6920 | 26 | 200 | 0 | 0 | 108 | 37 | 14 | 4.6 | 327 |
| Nov. 13 | 6420 | 23 | 300 | 50 | 100 | 118 | 44 | 17 | 4.1 | 359 |
| Dec. 11 | 3310 | 21 | 200 | 50 | 120 | 81 | 50 | 21 | 4.3 | 253 |
| Jan. 06 | 1160 | 21 | 100 | 60 | 210 | 113 | 44 | 24 | 4.3 | 385 |
| Feb. 28 | 1460 | 23 | 1900 | 110 | 400 | 109 | 47 | 28 | 3.7 | 385 |
| Mar. 19 | 19400 | 15 | 700 | 60 | 0 | 53 | 14 | 6.1 | 5.7 | 154 |
| Apr. 14 | 83800 | 15 | 2200 | 20 | 0 | 48 | 13 | 4.9 | 4.9 | 145 |
| May 12 | 16000 | 8.1 | 400 | 40 | 30 | 78 | 35 | 14 | 5.4 | 238 |
| July 10 | 10500 | 23 | 472 | 94 | 20 | 104 | 40 | 17 | 4.4 | 299 |
| Mississippi River near Anoka (05288500) | | | | | | | | | | |
| Oct. 01 | 7630 | 9.8 | 100 | – | 0 | 37 | 13 | 5.9 | 2.6 | 170 |
| Nov. 12 | 9930 | 13 | 400 | – | 100 | 50 | 18 | 6.6 | 3.6 | 208 |
| Dec. 12 | 7080 | 12 | 200 | – | 0 | 58 | 22 | 8.3 | 3.9 | 244 |
| Jan. 07 | 5700 | 14 | 200 | – | 20 | 56 | 21 | 9.1 | 3.4 | 260 |
| Feb. 11 | 6000 | 14 | 700 | 110 | 30 | 47 | 18 | 9.0 | 2.8 | 239 |
| Apr. 01 | 11800 | 13 | 900 | 120 | 70 | 50 | 17 | 7.5 | 5.1 | 215 |
| 10 | 54700 | 12 | 800 | 160 | 0 | 32 | 9.4 | 4.6 | 3.5 | 132 |
| 13 | 72100 | 9.5 | – | – | – | 32 | 12 | 3.2 | 3.7 | 126 |
| June 06 | 9860 | 10 | 500 | 60 | 10 | 47 | 16 | 5.8 | 2.8 | 209 |
| July 09 | 5920 | 9.3 | 228 | 94 | 10 | 44 | 17 | 6.1 | 2.3 | 210 |
| Mississippi River at St. Paul (0533100) | | | | | | | | | | |
| Nov. 12 | 14800 | 15 | 200 | 100 | 20 | 70 | 24 | 9.3 | 3.4 | 239 |
| June 04 | 18900 | 14 | 400 | 70 | 20 | 67 | 27 | 12 | 4.0 | 248 |

Table 25. – Chemical analyses for stations on the Mississippi and Minnesota Rivers, water year 1968-1969. – Continued

| Date | Carbonate ($CO_3$) (mg/l) | Alkalinity as $CaCO_3$ (mg/l) | Sulfate ($SO_4$) (mg/l) | Chloride (Cl) (mg/l) | Fluoride (F) (mg/l) | Nitrate (N) (mg/l) | Nitrate ($NO_3$) (mg/l) | Phosphate ($PO_4$) (mg/l) | Ortho Phosphate ($PO_4$) (mg/l) | Dissolved Phosphorus (P) (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|
| Minnesota River near Jordan | | | | | | | | | | |
| Oct. 03 | 0 | 268 | 140 | 15 | .5 | – | 27 | .64 | .60 | – |
| Nov. 13 | 0 | 294 | 177 | 17 | .5 | – | 25 | .57 | .41 | – |
| Dec. 11 | 0 | 207 | 195 | 19 | .3 | – | 25 | – | .34 | .12 |
| Jan. 06 | 0 | 316 | 156 | 28 | .3 | – | 16 | – | .27 | .09 |
| Feb. 28 | 0 | 316 | 190 | 24 | .4 | .10 | .4 | – | .15 | .07 |
| Mar. 19 | 0 | 126 | 63 | 7.8 | .4 | 3.8 | 17 | – | .34 | .15 |
| Apr. 14 | 0 | 119 | 48 | 6.9 | .3 | 3.5 | 15 | – | .19 | .06 |
| May 12 | 0 | 195 | 155 | 11 | .5 | 2.2 | 9.8 | – | .02 | .02 |
| July 10 | 0 | 245 | 182 | 14 | .7 | 4.7 | 21 | – | .36 | .13 |
| Mississippi River near Anoka | | | | | | | | | | |
| Oct. 01 | 0 | 139 | 17 | 5.1 | .3 | – | .3 | .41 | .23 | – |
| Nov. 12 | 0 | 170 | 38 | 7.2 | .3 | – | 3.4 | .25 | .25 | – |
| Dec. 12 | 0 | 200 | 39 | 7.4 | .2 | – | 3.6 | – | .17 | .08 |
| Jan. 07 | 0 | 213 | 27 | 7.2 | .2 | – | 1.3 | – | .19 | .08 |
| Feb. 11 | 0 | 196 | 19 | 7.8 | .2 | .00 | .2 | – | .13 | .06 |
| Apr. 01 | 0 | 177 | 27 | 9.6 | .2 | 1.9 | 8.2 | – | .40 | .23 |
| 10 | 0 | 108 | 14 | 4.0 | .1 | 1.4 | 6.4 | – | .13 | .08 |
| 13 | 0 | 103 | 20 | 4.1 | .1 | .90 | 4.0 | – | .03 | .02 |
| June 06 | 0 | 171 | 19 | 5.5 | .3 | .50 | 2.1 | – | .07 | .03 |
| July 09 | 0 | 172 | 21 | 5.2 | .3 | .00 | .1 | – | .12 | .08 |
| Mississippi River at St. Paul | | | | | | | | | | |
| Nov. 12 | 0 | 196 | 74 | 9.2 | .7 | – | 8.9 | .29 | .28 | – |
| June 04 | 0 | 203 | 90 | 9.8 | .5 | 1.0 | 4.6 | – | .18 | .07 |

Table 25. – Chemical analyses for stations on the Mississippi and Minnesota Rivers, water year 1968-1969. – Continued

| Date | Boron (B) (ug/1) | Dissolved solids (residue at 180 C) (mg/1) | Dissolved solids (sum of constituents) (mg/1) | Dissolved solids (tons per ac-ft) | Dissolved solids (tons per day) | Hardness (Ca, Mg) (mg/1) | Non-carbonate hardness (mg/1) | Percent sodium | Sodium adsorption ratio |
|---|---|---|---|---|---|---|---|---|---|
| Minnesota River near Jordan | | | | | | | | | |
| Oct. | | | | | | | | | |
| 03 | 70 | 546 | 532 | .74 | 10200 | 419 | 152 | 7 | .3 |
| Nov. | | | | | | | | | |
| 13 | 60 | 635 | 601 | .86 | 11000 | 472 | 178 | 7 | .3 |
| Dec. | | | | | | | | | |
| 11 | 90 | 576 | 541 | .78 | 5150 | 406 | 199 | 10 | .5 |
| Jan. | | | | | | | | | |
| 06 | 100 | 620 | 596 | .84 | 1940 | 460 | 144 | 10 | .5 |
| Feb. | | | | | | | | | |
| 28 | 160 | 660 | 618 | .90 | 2600 | 464 | 149 | 11 | .6 |
| Mar. | | | | | | | | | |
| 19 | 60 | 316 | 259 | .43 | 16600 | 191 | 65 | 6 | .2 |
| Apr. | | | | | | | | | |
| 14 | 0 | 273 | 230 | .37 | 61800 | 173 | 54 | 6 | .2 |
| May | | | | | | | | | |
| 12 | 70 | 451 | 434 | .61 | 19500 | 337 | 142 | 8 | .3 |
| July | | | | | | | | | |
| 10 | 121 | 568 | 554 | .77 | 16100 | 424 | 179 | 8 | .4 |
| Mississippi River near Anoka | | | | | | | | | |
| Oct. | | | | | | | | | |
| 01 | 40 | 186 | 175 | .25 | 3830 | 146 | 6 | 8 | .2 |
| Nov. | | | | | | | | | |
| 12 | 40 | 270 | 242 | .37 | 7240 | 200 | 29 | 7 | .2 |
| Dec. | | | | | | | | | |
| 12 | 50 | 291 | 275 | .40 | 5560 | 235 | 35 | 7 | .2 |
| Jan. | | | | | | | | | |
| 07 | 50 | 285 | 268 | .39 | 4390 | 227 | 14 | 8 | .3 |
| Feb. | | | | | | | | | |
| 11 | 70 | 246 | 237 | .33 | 3990 | 191 | 0 | 9 | .3 |
| Apr. | | | | | | | | | |
| 01 | 0 | 261 | 245 | .35 | 8320 | 195 | 18 | 7 | .2 |
| 10 | 40 | 158 | 152 | .21 | 23300 | 119 | 10 | 8 | .2 |
| 13 | 40 | 180 | 150 | .24 | 35000 | 127 | 24 | 5 | .1 |
| June | | | | | | | | | |
| 06 | 30 | 219 | 212 | .30 | 5830 | 185 | 14 | 6 | .2 |
| July | | | | | | | | | |
| 09 | 54 | 212 | 208 | .29 | 3390 | 179 | 7 | 7 | .2 |
| Mississippi River at St. Paul | | | | | | | | | |
| Nov. | | | | | | | | | |
| 12 | 60 | 347 | 334 | .47 | 13900 | 274 | 78 | 7 | .2 |
| June | | | | | | | | | |
| 04 | 60 | 373 | 352 | .51 | 19000 | 278 | 75 | 8 | .3 |

Table 25. – Chemical analyses for stations on the Mississippi and Minnesota Rivers, water year 1968-1969. – Continued

| Date | Specific conductance (micromhos) | pH (units) | Temperature (deg C) | Color (platinum cobalt units) |
|---|---|---|---|---|
| Minnesota River near Jordan | | | | |
| Oct. | | | | |
| 03 | 803 | 7.6 | 14 | 17 |
| Nov. | | | | |
| 13 | 888 | 8.1 | 3 | 11 |
| Dec. | | | | |
| 11 | 818 | 8.0 | 1 | 3 |
| Jan. | | | | |
| 06 | 909 | 8.1 | 0 | 4 |
| Feb. | | | | |
| 28 | 946 | 7.8 | 1 | 3 |
| Mar. | | | | |
| 19 | 360 | 8.1 | 1 | 12 |
| Apr. | | | | |
| 14 | 367 | 7.9 | 9 | 18 |
| May | | | | |
| 12 | 671 | 7.7 | 14 | 12 |
| July | | | | |
| 10 | 807 | 7.7 | 22 | 15 |
| Mississippi River near Anoka | | | | |
| Oct. | | | | |
| 01 | 310 | 7.3 | 16 | 22 |
| Nov. | | | | |
| 12 | 407 | 7.8 | 2 | 33 |
| Dec. | | | | |
| 12 | 468 | 8.1 | 1 | 18 |
| Jan. | | | | |
| 07 | 457 | 8.1 | 0 | 15 |
| Feb. | | | | |
| 11 | 399 | 7.6 | 0 | 7 |
| Apr. | | | | |
| 01 | 394 | 8.3 | 1 | 17 |
| 10 | 251 | 8.0 | 5 | 13 |
| 13 | 246 | 7.4 | 7 | 16 |
| June | | | | |
| 06 | 360 | 7.7 | 19 | 15 |
| July | | | | |
| 09 | 364 | 7.7 | 21 | 15 |
| Mississippi River at St. Paul | | | | |
| Nov. | | | | |
| 12 | 531 | 7.4 | 4 | 23 |
| June | | | | |
| 04 | 557 | 7.8 | 18 | 17 |

Jordan drains a prairie region whose subsurface is composed of thick deposits of calcareous drift and Cretaceous sedimentary rocks of siltstone and shale. This area contains some of the most highly mineralized ground water in the State. Whereas, the Mississippi River above Anoka drains a forested area of lakes and swamps, where the drift deposits are not so calcareous or thick and the bedrock is largely crystalline, imparting less mineralization to the ground water and, thusly, to the baseflow in the streams. The effects of the joining of the two rivers above the gaging station at St. Paul is clearly shown by the appreciable increase in the dissolved-solids content of the Mississippi River water at this station.

Concentrations of heavy minerals in river water are shown in Table 26. These are determined because of the low tolerance biotic organisms have for some of the minerals. Strontium seems to be the most abundant heavy mineral in the streams, but no standard limits have been placed on its concentration (Water Pollution Control Commission, 1967). These constituents in the table are listed in ug/l (micrograms per liter), which is one millionth of a gram, or equivalent to about one part in a billion parts of water.

Aspects related to the pollution of the major streams in the metropolitan area are monitored by the Metropolitan Sewer Board. The Sewer Board makes monthly analyses of water collected at several sites throughout the area. Pollution is a recognized problem in the rivers that flow through the Twin Cities, and plans are underway to minimize the problem wherever possible. Stream and effluent-quality standards for the waters of Minnesota have been or shortly will be established by the Minnesota Water Pollution Control Agency. These standards are in the form of water pollution control (WPC) regulations and are printed and distributed by the Documents Section, Department of Administration of the State of Minnesota.

## WATER AND WASTE TREATMENT FACILITIES

The general locations and sources of the municipal water-supply systems along with the treatment employed for municipal water supply and sewage are summarized in Figure 52. Surface water is used for public supply only in those communities connected to the Minneapolis and St. Paul systems. All other communities are supplied with water pumped from wells.

The locations of the waste-water treatment plants that discharge into the major streams in the metro-

Table 26. – Dissolved heavy metals in river water for water year 1968-69. Constituents measured in micrograms per liter (ug/1). 1/

| Station | Date | Arsenic (As) | Copper (Cu) | Lithium (Li) | Moly-bdenum (Mo) | Selenium (Se) | Strontium (Sr) | Vana-dium (V) | Zinc (Zn) |
|---|---|---|---|---|---|---|---|---|---|
| Minnesota River near Jordan | Oct. 3 | 0 | 0 | 0 | 2 | 0 | 360 | 3 | 0 |
| | May 12 | 0 | 0 | 40 | 0 | 10 | 390 | 0 | 0 |
| Mississippi River near Anoka | Oct. 1 | 0 | 0 | 0 | 0 | 0 | 160 | 1 | 0 |
| | June 6 | 0 | 10 | 0 | 0 | 0 | 200 | 0 | 0 |
| Mississippi River at St. Paul | Nov. 12 | 0 | 0 | 0 | 8 | 0 | 280 | 0 | 0 |
| | June 4 | 10 | 10 | 30 | 0 | 10 | 340 | 1 | 1 |

1/ Other metals tested for which zero (0) concentrations were recorded include cadmium (Cd), chromium (Cr), cobalt (Co), lead (Pb), and nickel (Ni).

politan area are shown in Figure 54. The present capacity of each of the plants and the surface-water body into which its effluent is discharged are listed in Table 19. Where immediate plant-expansion programs are known, the proposed capacity of the plants are shown in parentheses in the table. The present (1971) total average daily capacity of Metropolitan Sewer Board waste-water plants in the metropolitan area is about 250 mgd.

# CHAPTER SEVEN: WATER RESOURCES OF PARTS OF CARVER, SCOTT, AND DAKOTA COUNTIES

Eleven percent of the seven-county metropolitan area was excluded from the major part of this study, but a brief description of the geohydrology of parts of three counties extending beyond the major area of study is included herein.

The extended areas of study are shown in Figure 57. The map segment on the right side of the figures is of part of Dakota County and the segment on the left side is of parts of Carver and Scott Counties. Land-surface altitudes in the area on the east range from near 1,070 feet, atop hills structurally controlled by the Platteville Limestone, in the central part to less than 700 feet on the flood plain of the Mississippi River on the northeast edge. The area has relatively few upland swamps and is fairly well drained by the Cannon River on the south and by tributaries to the Vermillion and Mississippi Rivers on the north. Altitudes on the west range from near 1,040 feet 2-1/2 miles northeast of Norwood to less than 700 feet along the bottom lands of the Minnesota River, where it flows northeastward out of the area. Most of the upland is relatively flat rolling, ranging in altitude from 940 to 1,000 feet. The area is poorly drained, having many upland lakes and swamps. Drainage is largely to tributaries of the Minnesota River in the south and to tributaries of the Crow River in the north.

The population (1970) of the extended areas is roughly 9,000. The land is mostly used for farming, and the economy is, with the exception of gravel-pit operations, almost wholly based on agricultural products.

## HYDROGEOLOGIC UNITS

Bedrock and surficial geologic maps are shown in Figures 57 and 58, respectively. The sequence, description, and water-bearing characteristics of the lithologic units are the same or similar to those described in Table 2. Where the uppermost bedrock units (Figure 57) are shown to be the Platteville Limestone and Glenwood Shale, all the underlying bedrock aquifers and most or all of the strata listed in the geologic column in Table 2 are present in the subsurface. Similarly, all or most of the underlying strata are present where the St. Peter Sandstone is the uppermost unit, and so forth. The St. Peter Sandstone aquifer is widespread in the eastern area but totally absent in the western. In the eastern area, where the uppermost bedrock unit is mapped as "undifferentiated Cambrian," the Jordan Sandstone aquifer may or may not be present, but the Ironton-Galesville and the Mount Simon-Hinckley aquifers probably are present. In the western area enough data were available to map probable extents of the Jordan Sandstone aquifer, but in that part mapped as "undifferentiated Cambrian" only the two underlying aquifers mentioned above are probably present.

The bedrock geology in the western area is dominated by the Belle Plaine fault, which trends northeast-southwest. The trace of this fault is altered somewhat from that mapped on the Geologic Map of Minnesota, St. Paul Sheet (1966). The fault trace was revised through work by H.W. Anderson of the U.S. Geological Survey (oral communication, March 1972). On the upthrown (northeast) side of the fault the older Cambrian rocks are nearer the land surface, and in a small area north of the Minnesota River near Belle Plaine, the uppermost bedrock unit is Precambrian rock. On the downthrown (southwest) side of the fault, the younger Cambrian rocks are nearer the land surface. The overall effects of the fault on the hydrology of the area are unknown, although it seems significant enough in extent to disrupt ground-water movement in the bedrock from one side of the fault to the other.

The surficial geology (Figure 58) in the eastern and western areas is similar to that in the major area of study, and the discussions in the major part of this report pertaining to the hydrology of the glacial deposits apply here. In the eastern area, deposits of both the Des Moines and Superior lobes occur, whereas, in the western area, only deposits of the Des Moines lobe occur. In the western area, the surficial deposits are largely clay till of low permeability. Any aquifers in this till would probably be buried outwash sand and gravel and could be delineated only by extensive test drilling or perhaps in some places by electrical resistivity methods. The only drift aquifers with surficial expression are the valley-train and alluvial deposits associated with the larger streams. Belle Plaine obtains its water supply from two wells, 280 feet deep, completed in sand and gravel. The static water level in these wells in August 1971 was 134 feet below land surface. The wells are within 100 feet of each other, yet interference between them is small. Pumping records show that the specific capacity of the well designated No. 1 (113.24.6cadl) is about 50 gpm per foot of drawdown while pumping 660 gpm for 20 hours. The transmissivity of this aquifer, then, is estimated to be 100,000 gpd per foot. The aquifer could support considerably more development, as could probably all the glacial sand and gravel deposits associated with the Minnesota River valley.

In the eastern area, the outwash and valley-train deposits associated with the Mississippi River valley may be thick. A well in the NE1/4SW1/4SE1/4 sec. 13, T.114N., R.17W. penetrated 298 feet of unconsolidated drift deposits before entering the underlying St. Lawrence Formation. The outwash deposits associated with the Cannon River are not so thick. A well drilled in the NW1/4SW1/4SW1/4 sec. 6, T.112N., R.19W. penetrated only 33 feet of glacial sand and gravel before entering the underlying Prairie du Chien dolomite. Few data are available, but the bedrock aquifers seem to be the best source of water supply for larger yielding wells in the eastern area.

Enough data were available to extend the potentiometric-surface map (Figure 20) of the Prairie du Chien-Jordan aquifer into the eastern area, as shown in Figure 59. Water movement in this part of the aquifer is locally toward the Cannon River and regionally toward the Mississippi River. Data were not available to define the potentiometric surfaces in the other bedorck aquifers or the water table in the glacial drift.

More data are necessary to evaluate the potential value of the water resources in both the western and eastern parts of the extended areas.

**Figure 57. – Bedrock geology of parts of Carver, Scott and Dakota Counties outside of major study area.**

**Figure 58. – Surficial geology of parts of Carver, Scott, and Dakota Counties outside of major study area.**

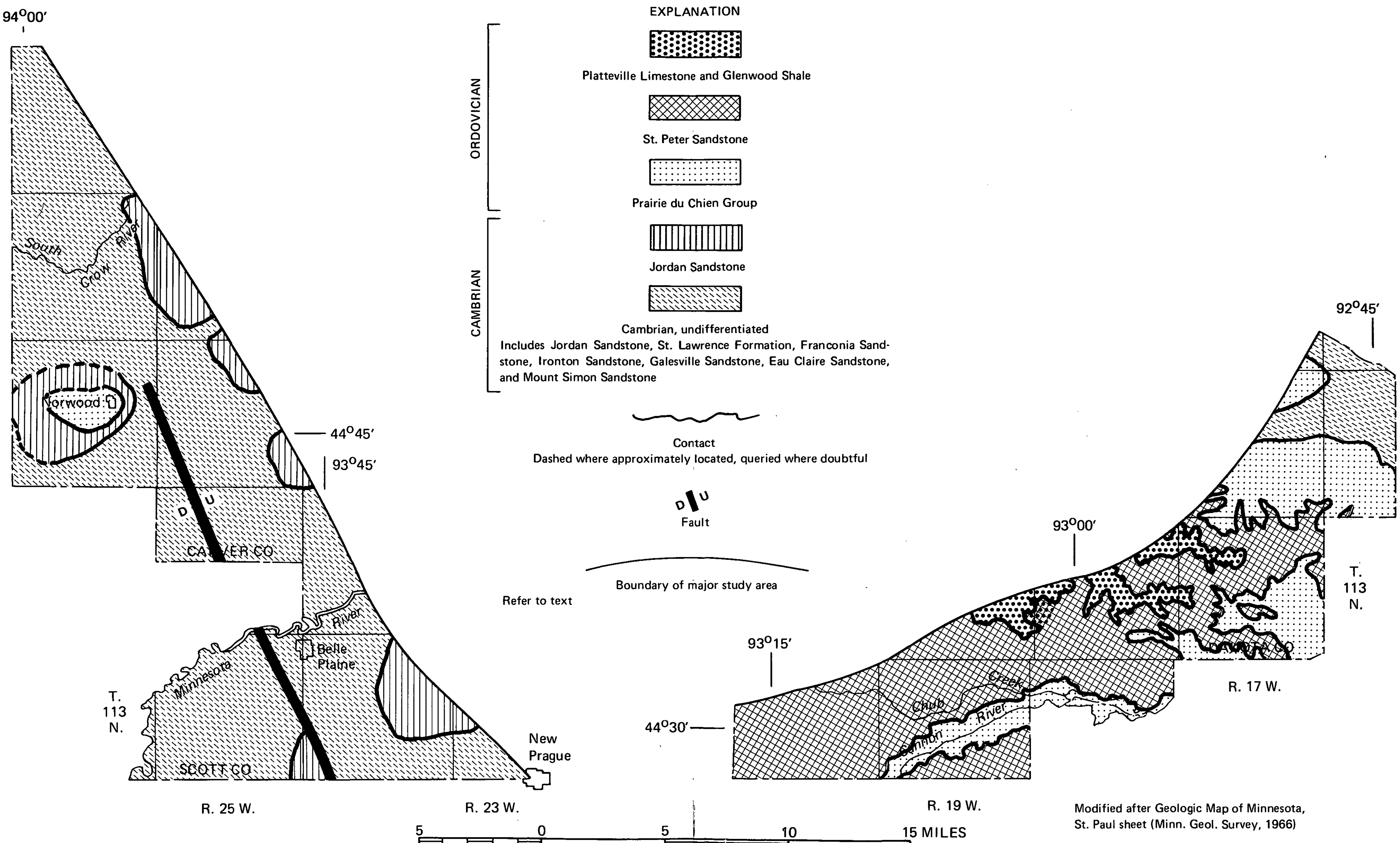



**Figure 57. — Bedrock geology of parts of Carver, Scott and Dakota Counties outside of major study area**

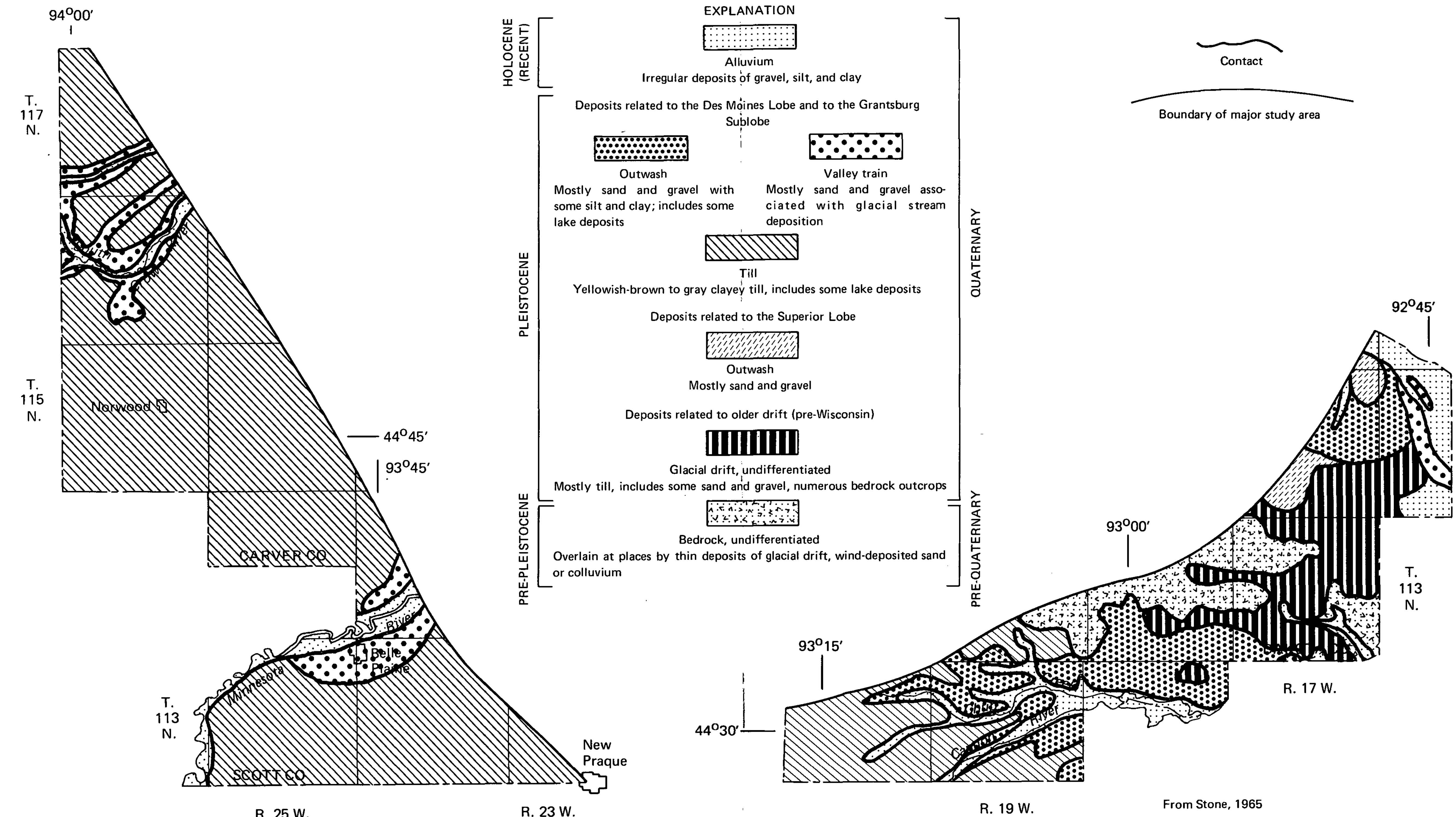



**Figure 58. — Surficial geology of parts of Carver, Scott and Dakota Counties outside of major study area.**

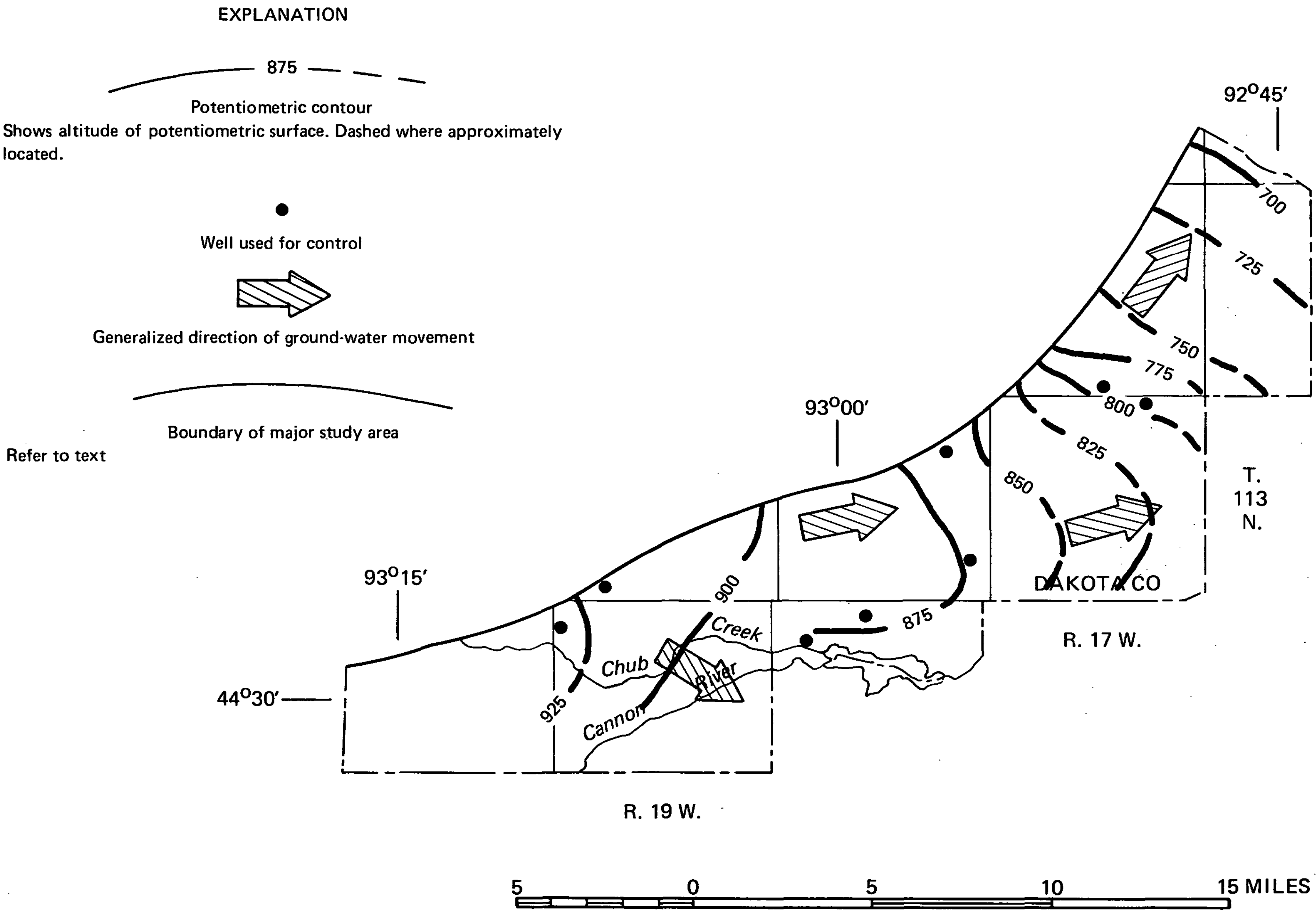



Figure 59. — Potentiometric surface of water in the Prairie du Chien-Jordan aquifer in Winter 1970-71 in part of Dakota County, Minnesota.

# CHAPTER EIGHT: SUMMARY

The area of study, about 6,000 square miles, is bounded by the extent of the Hinckley Sandstone, as it relates to the hydrology of the Minneapolis – St. Paul metropolitan area. Within this boundary, the geohydrology is described in general and, within the area underlain by the Prairie du Chien-Jordan aquifer (about 2,000 square miles), in greater detail.

In 1970, water use in the seven-county metropolitan area, plus a part of Wright County totalled 119.3 billion gallons or 327 mgd (million gallons per day). Of this, 48.4 billion gallons (133 mgd) was raw Mississippi River water pumped by the Minneapolis and St. Paul water-supply systems, and 70.9 billion gallons (194 mgd) was water pumped from wells. About 1,022,000 people (1970) are served by the Minneapolis and St. Paul supplies, 623,000 are served with ground water from municipal supplies, and 220,000 are self supplied with water from individual wells. Many industries also have their own ground-water supplies.

Streamflow available to the Twin Cities metropolitan area from the Mississippi River is 672 mgd (Table 17), based on the 7-day 10-year low flow. About 1,460 mgd would be available, using the combined supply from the Mississippi, Minnesota and St. Croix Rivers.

The surface-water resources of the Twin Cities metropolitan area are used to such an extent that a supply adequate to meet needs, such as power-plant demands and sanitary effluent assimilation will not be available during severe drought. The prolonged drought in the 1930's seems to have a recurrence interval of 100 years and upon recurrence would greatly curtail the operation of the utilities mentioned above.

Water is obtained from six aquifer systems: 1) glacial drift, 2) Platteville Limestone, 3) St. Peter Sandstone, 4) Prairie du Chien Group and Jordan Sandstone, 5) Ironton and Galesville Sandstones, and 6) Mount Simon and Hinckley Sandstones. In 1970, the first three supplied about 7 percent of the ground water; the fourth, about 75 percent; and the last two, about 18 percent.

Industry uses the greatest amount of ground water, accounting for 45.3 percent of the total annual pumpage in 1970. Domestic, air conditioning, commercial, irrigation, and other uses account for the remainder – 24.9, 14.4, 5.9, 4.8, and 4.7 percent, respectively.

Withdrawing water from closely spaced wells in the same area (resulting in well interference) in the Prairie du Chien-Jordan aquifer locally causes large cones of depression in the summer, resulting in increased costs of pumping water in some places. The largest seasonal drawdown cones are in the downtown areas of Minneapolis and St. Paul, in the west Minneapolis suburbs of Edina and St. Louis Park, and in South St. Paul.

Base daily pumpage (pumpage on a perennial basis not related to seasonal factors) from the Prairie du Chien-Jordan aquifer is 104 million gallons and, from all aquifers, less than 150 million gallons. Summer pumpage from the Prairie du Chien-Jordan aquifers is 231 mgd and from all aquifers less than 300 mgd. If pumpage increases significantly, the local cones of depression will grow larger. A wider distribution of high-yield wells would decrease the size of the local cones of depression.

For all practical purposes, the level of ground-water development that can be sustained under natural conditions, excluding recharge induced from surface sources by drawdowns due to heavy well pumping, is equal to the basin-storage discharge in the reaches of the three major streams in the area. This discharge, in that part of the metropolitan area underlain by the Prairie du Chien-Jordan aquifer, is about 500 mgd. Three-fourths, or 375 mgd, of this is estimated to be available to pumping wells.

The total amount of ground water in storage in the sediments (includes river alluvium, glacial drift, and St. Peter Sandstone) overlying the Prairie du Chien-Jordan aquifer in the metropolitan area is roughly 1.9 trillion gallons. If long-term ground-water pumpage greatly exceeds the 375 mgd of available recharge from precipitation large volumes of water will be withdrawn from this storage "bank" and water levels in wells completed in the shallow aquifers will decline.

The greatest amount of recharge to the bedrock aquifers occurs in parts of their subcrop areas that are directly overlain by glacial drift. The extents of these parts of the Prairie du Chien-Jordan and St. Peter aquifers in the metropolitan part of the study area are about 1,350 and 450 square miles, respectively.

Water available from recharge is the controlling factor for the sustained practical level of ground-water development because the aquifers are capable of yielding more water than is naturally supplied by recharge. The probable level of development that can be sustained by the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers in the metropolitan area alone, assuming recharge is available, is about 1,100 mgd (see Table 22). Available recharge to the aquifers in the metropolitan area (about 2,000 sq. mi.) derived from precipitation, streamflow induction, artificial and incidental sources is about 845 mgd. In a 1,500-square-mile area west and north of the Twin Cities, additional recharge of about 175 mgd is available. Thus, slightly more than 1,000 mgd of ground water (instead of the 1,100 mgd above) could be obtained by increasing pumpage in both the Prairie du Chien-Jordan and Mount Simon-Hinckley aquifers in and around 3,500 square miles of the metropolitan area. Considerable management and planning, however, would be needed to sustain this level of development.

Maps in this report can be used to select general well-field locations based on considerations of 1) aquifer, 2) depth needed for completion, 3) head availability, 4) location of natural recharge and discharge boundaries, and 5) distance from areas where overdevelopment of ground-water resources is imminent.

Yields given in the report are based on the gross response of the aquifers to present-day (1970) pumping and on estimates where data are lacking. The effects of both lateral and vertical hydrologic boundaries on water-level declines were not considered in making estimates, as they are beyond the scope of this study. A more intensive study incorporating the use of a hydrologic system model would be necessary to refine the yield estimates and to determine the effects of boundary interaction between the different aquifers.

Future detailed studies might include elaboration on some of the topics described in this report and the acquisition and interpretation of new data. Major items on which future work might focus are 1) data collection, 2) geohydrologic mapping, 3) hydraulic characteristics of subsurface geohydrologic units, 4) hydrology of lakes, and 5) hydrologic systems modeling.

# CHAPTER NINE: CONCLUSIONS

1. Ground-water sources alone could be developed to provide for the increasing water needs (exclusive of power plant usage and sanitary sewage efferent assimulation) of the metropolitan area for at least the next 30 years (see page 147-148 and Table 15). To sustain this level of development, however, good planning and controlled management would be necessary.

2. Although surface-water sources of supply under average flow conditions are adequate, they are inadequate under low-flow conditions (see page 156). Present demands during the summer could reduce low-flows in the Mississippi River to less than the once in 10-year, 7-consecutive day low flow considered necessary for waste-effluent assimilation.

3. Recurrence of a drought of similar magnitude to that of the 1930's could greatly curtail power-plant operations, detrimentally affect the water quality of the rivers, and place a stress on public-supply systems that are dependent on surface water under present development.

4. Water wells tied into the surface-water supply systems but located where they would not significantly affect base flow in the rivers during critical periods could be used to supplement surface supplies. The wells would greatly enlarge the reserve capacity of water systems, especially the Minneapolis system, for the ground-water reservoirs hold more water than could ever be stored on the surface in this highly urbanized area.

5. At the present level of ground-water development, the Prairie du Chien-Jordan aquifer system is nearly at equilibrium: that is, recharge to and discharge from the system are in near balance, and water is not being removed from storage over the long term. This balance exists because water that formerly discharged into the Mississippi River is now captured by pumping wells. Cones of short-term water-level decline in the aquifer, brought about by heavy summer pumping, recover almost wholly to their former state after the summer pumping stress is removed.

6. At the present level of ground-water development, withdrawals from the Mount Simon-Hinckley aquifer exceed recharge. Water levels are declining at a rate of about 10 feet per year. Withdrawals from this aquifer seem to have decreased in recent years, and the system may be tending toward a state of balance.

7. Summer water-level declines in downtown Minneapolis and St. Paul are becoming severe. These declines are due to mutually interferring wells. Additional wells in these areas may in time lower the ground water to undesirable levels locally. Excessive drawdowns create needs for lowering drop pipes and deepening wells, increase the cost of pumping water, and increase electric-power usage. The problems can be alleviated and deferred by good planning and management. If pumpage increases significantly the local cones of depression will grow larger. A wider distribution of high-yield wells would decrease the size of the local cones of depression.

8. There are essentially three hydrologic provinces, which include the Prairie du Chien-Jordan and overlying aquifers in the metropolitan area. These provinces emanate from three highs in the potentiometric surface of the Prairie du Chien-Jordan aquifer and end at major stream boundaries. The highs are in the northeast in the area of White Bear and Forest Lakes, in the west in the Lake Minnetonka area, and in the south in the Vermillion River headwaters area.

9. Because of the above provinces, the Twin Cities metropolitan area is located in an ideal place of optimum use of the Prairie du Chien-Jordan aquifer. Almost anywhere a well is located in this aquifer is either near a place of natural discharge from or recharge to the aquifer. Newly created drawdown cones on an annual basis in this aquifer will tend to stabilize in a relatively short time. A possible exception to this is in a narrow strip of the aquifer between St. Paul and Hudson, Wisconsin, where drawdowns would have to be great in order to capture natural discharge from the aquifer or to induce recharge from the streams.

10. The available head (feet of water above the top of aquifer) in the Prairie du Chien-Jordan aquifer ranges from 0 to more than 300 feet and averages about 125 feet in the metropolitan area. The available head in the Mount Simon-Hinckley aquifer ranges from 350 to more than 650 feet and averages about 500 feet. This information should aid in the proper placement of high-yielding wells in these aquifers.

11. Roughly 1.9 trillion gallons of water is in storage in the sediments overlying the Prairie du Chien-Jordan aquifer. Downward leakage of water from these sediments may, in part, be the reason for the near stabilization of water levels in the Prairie du Chien-Jordan aquifer.

12. The bedrock aquifers are recharged for the greater part in their subcrop areas. The subcrop of the Prairie du Chien-Jordan aquifer that is directly overlain by drift surrounds the Twin Cities in a broad band in much of the metropolitan area (see Figure 45). Its subcrop extent here is about 1,350 square miles. The subcrop extent of the St. Peter aquifer in direct contact with the drift is about 450 square miles in the metropolitan part of the report area.

13. The present observation-well network operated by the U.S. Geological Survey in cooperation with the Minnesota Department of Natural Resources is not sufficient to monitor water-level fluctuations in the metropolitan and outlying areas effectively. Re-evaluation and revision of the observation-well program is, thus, indicated.

14. Future quantitative evaluations of the water resources and definition of the flow system could be facilitated by hydrologic models.

# CHAPTER TEN: NEEDS FOR FUTURE STUDY

The objective of this study is to provide a first approximation of the total water resource. As in any study, where data are relied upon, results can benefit by additional and better data. Thus, future study would include elaboration on some of the topics described herein and the acquisition and interpretation of new data. Major study items might be 1) data collection, 2) geohydrologic mapping, 3) hydraulic characteristics of subsurface geohydrologic units, 4) hydrology of lakes, and 5) hydrologic-systems modeling.

## DATA COLLECTION

### Ground-Water-Level Monitoring

Of the five aquifers supplying water in the metropolitan area, the Prairie du Chien-Jordan and Mount Simon-Hinckley are the only two having water-level records of sufficient length and frequency of measurement to show changes in ground-water usage. But the observation wells from which these records are collected are too few to evaluate changes in even these major aquifers. As annual ground-water withdrawals approach annual natural recharge to the ground-water system, water levels in parts of the different aquifers may begin to decline at increasingly rapid rates. Even now, in places, appreciable amounts of water are probably being withdrawn from storage in the aquifers overlying the Prairie du Chien-Jordan aquifer. Few observation wells monitor the presently densely populated areas at the periphery, where future expansion is imminent. In addition, at no place are the water levels in all five aquifers being observed simultaneously, so that interaction between aquifers can be studied. Reevaluation and revision of the observation well program in the metropolitan area is indicated.

One difficulty in establishing an observation-well network is the convenience of using abandoned or little used wells for data collection. These wells are not always ideally situated or finished properly for monitoring. Drilling wells whose specific purpose is to monitor water-level fluctuations in all significant aquifers at any one place, however, is entirely feasible. This could be done by drilling a well through the entire geologic section into the Hinckley Sandstone and by installing individual piezometers in each aquifer penetrated. The head of this well, at the surface, would contain a nest of piezometer pipes, each one enabling measurement of water levels at a different depth and in a different aquifer. Hydrographs of water-level fluctuations in these wells could be published periodically and thus would provide warning of ground-water overdevelopment.

There are, in essence, three hydrologic provinces above and including the Prairie du Chien-Jordan aquifer in the metropolitan area. These provinces emanate from three potentiometric highs and end at the major streams, as shown on the potentiometric-surface map in Figure 21. Therefore, an efficient revised observation-well program would include a minimum of three multi-piezometer observation wells – one strategically located in each province. Several individual-aquifer observation wells could be selected to fill out and complete the network.

### Automatic Data Processing Needs

An appreciable amount of time in this study was spent compiling the quantitative pumpage data in Tables 13 and 14. Thousands of annual records, sent by water users to the Director of the Division of Waters, Soils, and Minerals of the Minnesota Department of Natural Resources, as required by Minnesota Statutes 105.41, were handled individually to arrive at the totals shown in Table 14. Additional data obtained from questionnaires were used in conjunction with the 1970 pumpage records to obtain the totals shown in Table 13. Despite this manipulation of data, the determinations of the percentages of water pumped from the different aquifers remain based on gross estimates.

The Minnesota Statutes require all persons and firms to obtain a permit for water use. The permit request includes a form titled "Statement on appropriation of water." Part of this form requires the location of the water source, the depth of the well used, and the intended use of the water. In addition, data are compiled on most of the wells belonging to the large water users in the State. With a concerted effort, data on the location of each well, aquifer, water use, and the annual volume of water withdrawn could be punched on cards for ADP storage and retrieval. Once the system is set up, little effort would be needed, as new data were acquired to keep it current. A program can be written to retrieve the data concerning location, aquifer, pumpage, and type of usage on an annual basis and, perhaps in the future, even on a monthly basis.

One deterrent to ideal programs, however, is the lack of really valid data. Some of the well locations in the present ADP programs are in error. Therefore, field checking those wells whose locations may be doubtful would be necessary. Also, the pumpage records sent annually to the State are sometimes difficult to interpret. The form states that pumpage be reported in either gallons or cubic feet, yet reports are sent in where this distinction is not made or where decimal points are not clear. For example, an individual may read his water meter directly, when a multiplication factor of 10 or 100 is involved.

### Central Data Collection and Storage

Much time in this study was used to collect and compile geohydrologic data. These data were in various files and pertained to well information, geologic logs, hydraulics of aquifers, water usage, water-level fluctuations, and water quality. Although the interpretations made in this report are based on a large amount of information, more, undoubtedly, is available. However, had all the data been found and used, this report may have benefited.

If all presently disseminated basic data pertaining to ground-water hydrology were collected and filed for storage and retrieval on a continuing basis at one central place, or, if the data were categorized and collected at a few central places for storage and retrieval, the data banks could be made available to any agency, firm, or individual working in the water field. Thus, time now spent collecting and assembling data could be used in interpreting data.

## GEOHYDROLOGIC MAPPING

### Surficial and Subsurface Drift

The glacial drift, blanketing most of the study area, not only transmits recharge to the underlying bedrock aquifers but also contains large aquifers not yet fully developed in places. Despite its importance to the water resources, its physical extent and internal makeup is little known. The surficial geology map (Figure 9) is, at best, a compilation of reconnaissance maps. Although the surficial map indicates the location of some of the potential drift aquifers, it does not indicate their subsurface configurations. The approximate thickness of the drift as a whole is shown on the drift-thickness map (Figure 18), but this does not differentiate between the sand and gravel parts, which constitute the aquifers, and the till parts, which generally constitute the confining beds. Detailed mapping of the drift at the surface and in the subsurface, at least over the entire subcrop area of the Prairie du Chien-Jordan aquifer and the Anoka sand plain, would aid considerably in developing the aquifers.

Drilling logs of bedrock wells generally lump the glacial drift into a unit. Some logs, however, are more detailed, especially those for wells in the drift, and they offer a starting point for subsurface mapping. More data are available than ever before on the structure of the surficial deposits, and they can now be assimilated with the ADP readout capabilities at the Minnesota Geological Survey.

### Delineation and Configuration of Erosional Valleys

The hydrologic system is greatly complicated by the subsurface erosional valleys, some showing surface expression and some not. The ideal layer-cake geology, as depicted by the cross sections in Figure 8, is breached, in places, by these valleys, offering conduits for flow of water. The significance of these valleys in the hydrologic system can only be surmised. Their lateral and vertical extents are little defined; although their approximate extents, inferred from drift-thickness data, are shown on some of the maps (Figures 10-15, and 18) in this report. Recently, a map showing the inferred extent of some of these valleys was made by Lindholm, Helgesen, and Mossler (1972). The internal composition of the valleys has not been defined. They are filled with glacial drift, but whether stratified sand and gravel, clay, or till predominates is not known.

The valleys are numerous and deep enough to affect ground-water flow significantly, so a more detailed study of their occurrence may be warranted. Study and mapping might include 1) the lateral and vertical extent of the valleys, 2) the relation of the valleys to the bedrock formations, 3) the physical and hydrologic properties of the valley fill, and 4) the potentiometric differences between water in the valley sediments and water in the adjacent bedrock aquifers. If the larger valleys are found to have little effect on ground-water hydrology, further mapping of the valleys would not be warranted. If the effect is significant, however, detailed mapping of all valleys might be warranted.

### Potentiometric-Surface Mapping

Potentiometric-surface maps of the St. Peter (Figure 19), Prairie du Chien-Jordan (Figures 20 and 43), and Mount Simon-Hinckley (Figure 21) aquifers were made as a part of this study. Although the number of wells used to draw the potentiometric surface of the Prairie du Chien-Jordan was appreciable (192), the definition can be refined by more control points (wells) around the periphery, especially in the southwest part. Similarly, the potentiometric surfaces of the St. Peter and Mount Simon-Hinckley aquifers can be refined considerably by more control points. Sufficient data were not available to draw similar maps for other aquifers.

Construction of potentiometric maps for the different aquifers would require much expenditure of time and manpower. First, well schedules have to be scanned to select wells completed only in certain aquifers and with sufficient areal distribution. Second, water levels in the wells must be measurable, and the measurements must be made within a relatively short time (about 2 weeks), so that they are comparable to one another. The best time is in late fall or early winter when water levels in the urban and suburban areas are most stable. Mass water-level measurements also are necessary for further time comparability. Four men were needed to make the mass measurements used in this study. Also, not only is the time required to make the water-level measurements appreciable, but much time is also needed to find the wells and to gain permission for measurement. Therefore, if all five aquifers in the metropolitan area were to be measured, many more wells, and many more men would be needed for the task.

A water-table map of the glacial drift and potentiometric-surface maps of water in the four bedrock aquifers would be necessary if the water resources were to be fully appraised. (There may not be enough wells completed in the Irontin-Galesville to define the water surface in that aquifer.) The maps could be used to determine the direction and volume of water exchange between the different aquifers and to draw available-head maps and, thus, estimate the pumpage the aquifers may withstand before water levels are drawn down below their tops.

## HYDRAULIC CHARACTERISTICS OF GEOHYDROLOGIC UNITS

Some of the most uncertain hydraulic parameters and probably the hardest to obtain are the transmissivity and storage coefficients of the aquifers and vertical conductivities of the confining beds. Close determination of these parameters is necessary to evaluate the hydrologic system as a whole. Some transmissivity and storage coefficients are available (Table 9) now, but they are not numerous or widely enough distributed to assign values throughout the system. Determinations for vertical conductivity of the confining beds are almost absent. Data necessary to obtain these parameters are generally obtained by field aquifer tests or by laboratory analyses of rock samples. Although the interpretations made from aquifer-test data may be good, there are some difficulties in acquiring information by this method. 1) Costs can be extremely high. A pumping well and one or more observation wells are needed to run a suitable aquifer test. If wells are drilled specifically for this purpose, some may have to be drilled more than 1,000 feet to penetrate the Hinckley Sandstone. If the same set of wells were used to test each successive aquifer, additional and elaborate modifications would be required. Several of these test wells would have to be drilled to obtain sufficient data for areally representative coverage. 2) It is necessary to test aquifers in the field in places where external pumping or recharge effects do not interfere with the test pumping or where the external pumping or recharge can be controlled. In urban areas, external pumping may be great and virtually impossible to control, resulting in inconclusive tests. For this reason valid aquifer tests can be made only in areas away from pumping or recharge centers, where interference is minimal. 3) Pumping tests in some areas may be resented by local residents, as the noise of drilling and pumping machines may be considerable. Removal of discharged water may also be a problem, especially in the winter.

Hydraulic conductivity determined by laboratory analyses of rock samples can be used to estimate transmissivity, but laboratory analyses can be used to determine storage coefficients for aquifers only under water-table conditions. Storage coefficients of artesian aquifers, however, may be estimated with fair accuracy.

Recently developed coring methods can be used to obtain suitable samples both of consolidated and nonconsolidated rocks. Thus, although a drilling program is required for laboratory determination of aquifer tests, manpower requirements, problems to be overcome, and overall costs may be less than those for aquifer testing. Other methods that may be tried to obtain values of hydraulic characteristics include flow-net analysis and trial-and-error modeling approaches.

## HYDROLOGY OF LAKES

Although Minnesota has 15,292, 10-acre lakes or larger (Minn. Dept. Of Natural Resources, 1968), their hydrology has begun to be studied only in the last few years. These studies were begun because of the threat of accelerated eutrophication caused by greater influx of sewage. The U.S. Geological Survey, in cooperation with the Environmental Protection Agency, is presently involved in three such lake studies, all of which are outside this study area. One rather comprehensive study was made for preserving the quality of Lake Minnetonka by Harza Engineering Co. (1971) in close association with Barr Engineering Co., Eugene A. Hickok and Associates, and the Limnological Research Center of the University of Minnesota. That study resulted in some quantitative estimates of the ground-surface-water exchange in the lake basin.

Definitive studies of the hydrology of different lake regimens could be begun by selecting lakes representative of alluvial flood plains, glacial-outwash aprons, glacial-till plains, terminal moraines, and glacial-tunnel valleys. The studies would require definition of the 1) water budget of the lake, 2) head differences between lake and aquifer water, 3) permeability of the lake-bottom sediments, and 4) chemical and biological quality of the lake, adjacent ground water, and bottom sediments. The information gained in the representative lake studies would have transfer value to other lakes in similar topographic and geologic settings.

## SIMULATION MODELING OF THE HYDROLOGIC SYSTEM

The physical characteristics and functioning of the hydrologic system in the study area is described herein in as much detail as possible. The size and complexity of the system are of such magnitude that it is virtually impossible to describe in greater detail without the use of a simulation model. Two common simulation techniques now used in hydrologic analyses involve digital and analog-model computers. The digital model is in some respects the more versatile of the two; however, its present use is largely restricted to systems having three or less layers. A model of the study area may require as many as 9 or more layers, each layer representing either an aquifer or a confining bed. The two techniques may be combined, so that the hydrologic system can be simulated as an analog model, while solutions to problems are obtained as digital readouts. Thus, advantages from each of the methods can be realized. Analog and digital models have served as tools for use in planning and development of ground-water resources and in the combined development of both ground water and surface water and for management of the water resources within specified physical, economic, and social constraints.

The following discussion on the steps leading to the modeling of a hydrologic system is largely from a talk presented at the Missouri Basin Inter-Agency Committee meeting (June 23, 1971) by John E. Moore, of the U.S. Geological Survey. The title of the presentation was "Integrating the use of ground water into water-resources planning":

The data requirements for ground-water planning depend upon many factors, such as hydrologic complexity, types of water problems, and size of area. Some planning studies would need sophisticated large-scale model analyses, whereas others would require only an evaluation of existing hydrologic data. A summary of the major steps in an intensive study of a ground-water system are:

1. Collect and interpret data needed to describe geology, hydrology, and historical development of water supplies (much of this is completed in the Twin Cities area).

2. Develop a model, analog or digital, of the hydrologic system.

3. Calibrate model.

4. Use model to evaluate water problems and to predict future changes.

The first phase of a ground-water study consists of evaluating available hydrologic and hydrogeologic data necessary to define the ground-water system. This evaluation is used to develop a conceptual model of the system, to guide the data-collection program, and to identify major water-supply deficiencies or problems. The field data collection includes information on the hydrogeology and operation of the aquifers, well locations and withdrawals, surface-water diversions, precipitation, and stream-flow. Supplementary data are obtainable by test drilling, new observation wells and gaging stations, geophysical logging, pumping tests, and water-quality analyses. The field data may then be summarized and interpreted to provide a description of the water resources and an evaluation of the historical development of the water supply.

If a more intensive study is indicated, the next phase might include a model (analog-digital) of the system. A model is essential for many projects to simplify integrating and analyzing large quantities of data. The model at first is used principally as a tool to synthesize data and to test hypotheses of the functioning of the hydrologic system. The results of a model analysis are as reliable as the basic-data input. Most model studies require a team approach, for accuracy of model calibration and prediction, normally consisting of specialists in geohydrology and geochemistry. Some may require additional specialists in law, economics, ecology, soil science, or other disciplines.

Hydrologic and hydrogeologic information relating to the aquifer, streamflow, recharge, and discharge are built into the model. Information needed to build a model include field data to define the physical framework and to delineate hydrologic stress on the system. A summary of general data requirements for a prediction model is given in Table 27.

After the elements of the hydrologic system are described and simulated, the model is calibrated by comparing actual system response with model predictions and adjusting differences. If the differences are too great to reconcile, it may be necessary to collect additional field data before calibration can continue.

When the model is properly calibrated and simulates the real system, it can be used to evaluate water problems and to predict future changes. Major constraints that affect water-management planning, such as water costs, legal controls on water use, water quality, and environmental effects of changed water use ordinarily modify model decisions. Mathematical and dynamic programming can then be used to arrive at an optimum compromise between model decisions and constraints.

**Twin Cities Area Model**

A model of the Twin Cities area could be of a modest scale (node spacing 1 mile or more) and objectives. Five aquifers, starting with the Mount

Table 27. – Data requirements for prediction model

**Physical Framework**

1. Hydrogeologic map showing areal extent and boundaries of all aquifers.
2. Topographic map showing surface-water bodies.
3. Water-table, bedrock-configuration, and saturated-thickness maps.
4. Transmissivity maps showing aquifers and their boundaries.
5. Maps showing variation in storage coefficient of aquifers.
6. Relation of saturated thickness to transmissivity.
7. Relation of streams and aquifers (hydraulic connection).
8. Maps showing available head in artesian aquifers.

**Hydrologic Stress**

1. Type and extent of recharge areas (irrigated areas, recharge basins, recharge wells, etc.).
2. Surface-water diversions.
3. Ground-water pumpage (distribution in time and space).
4. Depth-to-water map, keyed to evapotranspiration rate.
5. Tributary inflow (distribution in time and space).
6. Ground-water inflow and outflow.
7. Precipitation.
8. Areal distribution of water quality in aquifer.
9. Streamflow quality (distribution in time and space).

**Model Calibration**

1. Water-level-change maps and hydrographs.
2. Streamflow (including gain and loss measurements).

**Prediction and Optimization Analysis**

1. Economic information on water supply.
2. Legal and administrative rules.
3. Environmental factors.

Simon-Hinckley as the lowermost and extending to the unconsolidated glacial drift as the uppermost (water table) would be simulated. Definition of the five aquifers and the four intervening confining beds would be based on information now available. The principal goal would be to approximate the gross flow system and the hydrologic controls to allow evaluation of the effects of pumping and the sensitivity of the system response to changes in transmissivity, leakage, or recharge. The model would provide answers, gross, but the best available, and could serve as a starting point for more detailed analysis when more specific problems are identified and greater resolution is required. The model could, inferentially, indicate the additional data required for solution of the problems and could satisfy many immediate requirements of water planners and would help in planning future hydrologic analyses.

## ACKNOWLEDGMENTS

The success of any water-resources study is dependent on the cooperation of many individuals and groups, both public and private. The authors are grateful to those who allowed repeated measurements of water levels in their wells and those who answered questionnaires concerning water supply and usage. Water managers throughout the metropolitan area were extremely helpful in providing water-department personnel to aid in measuring water levels in municipal wells. A list would include almost every community in the metropolitan area. Well drillers and consulting firms aided in providing well-log information upon request.

Most of the geologic, hydrologic, quality-of-water, and water-use data in this study were supplied by the Minnesota Department of Natural Resources, the Minnesota Geological Survey, the Minnesota Department of Health, and the Metropolitan Sewer Board. Data concerning vertical-flow characteristics of some of the bedrock formations were obtained from deep drilling records furnished by the Minneapolis Gas Company. The Northern States Power Company provided information on power plant operations. The Minneapolis Park Department and the Ramsey County Board of Commissioners contributed lake-level data.

Dr. D. G. Baker of the University of Minnesota supplied information on the radiation balance that led to the evapotranspiration determination used in this study. Precipitation analyses by the Thiessen net method and evapotranspiration graphs by the Thornthwaite method were made by Miss Dana Larson and Miss Kay Smith during interim projects for Macalester College. Miss Larson, under Geological Survey supervision, also constructed the vertical flow sections while on a research grant from the college. The authors extend sincere appreciation for this help and for all the other help so kindly given to them in this work.

## REFERENCES CITED


Baker, Donald G., Haines, Donald A., and Strub, Joseph H., Jr., 1967, Climate of Minnesota Part V precipitation, facts, normals, and extremes: Univ. of Minnesota – Ag. Exp. Station Tech. Bull. 254, 43 p.

Bass, Frederic, Meyer, A. F., and Norling, S. A., 1932, Report of the Minneapolis Water Supply Commission to the City Council, Minneapolis, Minn. [mimeographed.]

Bean, E. F., 1939, Geologic map of Wisconsin: Wisconsin Geological and Natural History Survey.

Blad, Blaine L., and Baker, Donald G., 1971, A three-year study of net radiation at St. Paul, Minnesota: Jour. Applied Meteorology, vol. 10, p. 820-824.

Brown, Russell H., 1963, Estimating the transmissibility of an artesian aquifer from the specific capacity of a well in Bentall, Ray, Methods of determining permeability, transmissibility and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 336-338.

Cruff, R. W., and Thompson, T. H., 1967, A comparison of methods of estimating potential evapotranspiration from climatological data in arid and subhumid environments: U.S. Geol. Survey Water-Supply Paper 1839-M, 28 p.

Division of Waters, Soils, and Minerals, 1968, An inventory of Minnesota Lakes: Minnesota Conservation Department, 498 p.

Eng, Morris T., 1968, Ground water conditions at the Ham Lake airport site – Anoka County in Minnesota Conservation Department, Water resource and wildlife study of the proposed Ham Lake airport site, Anoka County: Minnesota Cons. Dept. [mimeographed.]

Franham, R. S., 1956, Geology of the Anoka Sand Plain in Schwartz, George M. (ed.), Glacial geology, eastern Minnesota: Geol. Soc. America Guidebook Series, p. 53-64.

Fenneman, N. M., 1938, Physiography of eastern United States: New York, McGraw-Hill Book Co., 714 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U.S. Geol. Survey Water-Supply Paper 1536-E, 174 p.

Hantush, Mahdi S., 1956, Analysis of data from pumping tests in leaky aquifers: Am. Geophys. Union Trans., v. 37, no. 6.

, 1964, Hydraulics of wells in Chow, Ven Te (Ed.), Advances in hydroscience: New York, Academic Press, p. 281-432.

Hantush, Mahdi S., and Jacob, C. E., 1955, Non-steady radial flow in an infinite leaky aquifer: Am. Geophys. Union Trans., v. 36, no. 1, p.95-100.

Harza Engineering Co., Barr Engineering Co., Eugene A. Hickok and Associates, and Limnological Research Center, Univ. of Minn., 1971, A program for preserving the quality of Lake Minnetonka: State of Minnesota Pollution Control Agency.

Hem, John D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 2nd ed., 363 p.

Johnson, Edward E., Inc., 1966, Ground water and wells: Edward E. Johnson, Inc. (St. Paul, Minn.), 440 p.

Kunkle, G. R., 1962, The baseflow-duration curve, a technique for the study of groundwater discharge from a drainage basin: Jour. Geophys. Research, v. 67, no. 4, p. 1543-1554.

Lang, S. M., and Leonard, A. R., 1967, Instructions for using the punchcard system for the storage and retrieval of ground-water data: U.S. Geol. Survey open-file report, 93 p.

Leverett, Frank, 1932, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geol. Survey Prof. Paper 161, 149 p., 5 pl.

Leverett, Frank, and Sardeson, F. W., 1932, Map of Minnesota showing surficial deposits in Leverett, Frank, Quaternary geology of Minnesota and parts of adjacent States: U.S. Geol. Survey Prof. Paper 161.

Lindholm, G. F., Helgeson, J. O., and Mossler, J. H., Bedrock topography of east-central Minnesota: Minnesota Geol. Survey Misc. Map Series (in prep.)

Maclay, R. W., Winter, T. C., and Bidwell, L. E., 1971, Water Resources of the Red River of the North drainage basin in Minnesota: U.S. Geol. Survey open-file report.

Maderak, M. L., 1965, Chemical quality of ground water in the Minneapolis-St. Paul area, Minnesota: Minnesota Div. of Waters Bull. 23, 44 p.

Mann, W. B. IV, and Collier, C. R., 1970, A proposed streamflow data program for Minnesota: U.S. Geol. Survey open-file report, 75 p. [mimeographed].

McNellis, J. M., and Morgan, C. O., 1967, A digital computer program for analyzing lithologic log data: Administrative Report, State Geol. Survey of Kansas, 73 p.

Metcalf and Eddy, Inc., 1968, Sewerage and water planning report: Metropolitan Council of the Twin Cities area, Minnesota, 197 p.

Meyboom, Peter, van Everdingen, R. O., and Freeze, R. A., 1966, Patterns of groundwater flow in seven discharge areas in Saskatchewan and Manitoba: Geol. Survey of Canada, Bull. 147, 57 p.

Meyer, Adolf A., 1933, The flow of underground water and the field of artesian wells in Bass, Frederic, Meyer, A. F., and Norling, S. A., Supplementary report of the Minneapolis Water Supply Commission to the City Council, Mar. 1933 [mimeographed].

Meyer, Rex, R., 1963, A chart relating well diameter, specific capacity, and the coefficients of transmissibility and storage in Bentall, Ray, Methods of determining permeability, transmissibility and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 338-340.

Miller, W. A., and Straka, G. C., 1969, Graphs of ground water levels in Minnesota 1962-66: U.S. Geol. Survey open-file report, 54 p.

Minneapolis Water Works, 1970, Annual report of the Minneapolis water department (year ending Dec. 31, 1969): Dept. of Public Works, 48 p.

Minnesota Department of Agriculture, 1971, Minnesota Agricultural Statistics: Minn. Dept. Agr., St. Paul, 96 p.

Minnesota Department of Health, 1971, Public water supply data: State of Minnesota, 170 p.

Minnesota Division of Waters, 1961, Water resources of the Minneapolis-St. Paul metropolitan area: Minnesota Div. of Waters Bull. 11, 52 p.

Minnesota Geological Survey, 1966, Geologic map of Minnesota, St. Paul sheet: University of Minnesota (Minneapolis).

Mossler, John, Winter, T. C., and Tufford, Sarah, 1971, Instructions for using the Minnesota system for storage and retrieval of geologic log data: Minn. Geol. Survey Inf. Circ. 9, 32 p.

Norris, Stanley E., and Fidler, Richard E., 1969, Hydrogeology of the Scioto River Valley near Piketon, south-central Ohio: U.S. Geol. Survey Water-Supply Paper 1872, 70 p.

Reeder, H. O., 1966, Fourteen maps of parts of the ground-water reservoir in the Minneapolis-St. Paul metropolitan area: U.S. Geol. Survey open-file maps.

St. Paul Water Department, 1970, The 89th annual report: Board of Water Commissioners (St. Paul), 110 p.

Schwartz, G. M., 1936, The geology of the Minneapolis-St. Paul metropolitan area: Minnesota Geol. Survey Bull. 27, 267 p.

Sellers, William D., 1965, Physical climatology: University of Chicago Press, Chicago, 272 p.

Sims, P. K., and Zietz, Isadore, 1967, Aeromagnetic and inferred Precambrian paleogeologic map of east-central Minnesota and part of Wisconsin: U.S. Geol. Survey Geophy. Inv. Map GP-563.

Stone, John E., 1965, Status of urban geology in the Minneapolis-St. Paul area: Minnesota Geol. Survey, Reprint Series – 2, p. 13.

Straka, G. C., and Miller, W. A., 1963, Graphs of ground-water levels in Minnesota 1957-1961: Minnesota Div. of Waters Bull. 18, 58 p.

Straka, G. C., and Schnieder, Robert, 1957, Graphs of ground-water levels in Minnesota through 1956: Minnesota Div. of Waters Bull. 9, 42 p.

Tanner, C. B., 1960, Energy balance approach to evapotranspiration from crops: Soil Sci. Soc. Amer. Proc., 24, p. 1-9.

Theis, C. V., 1938, The significance and nature of the cone of depression in ground-water bodies: Econ. Geology, V. 33, no. 8, p. 889-902.

, 1963, Estimating the transmissibility of a water-table aquifer from the specific capacity of a well in Bentall, Ray, Methods of determining permeability, transmissibility and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 332-336.

Thiessen, A. H., 1911, Precipitation for large areas: Monthly Weather Rev., vol. 39, p. 1082-1084.

Thornthwaite, C. W., and Mather, J. R., 1957, Instructions and tables for computing potential evapotranspiration and the water balance: Drexel Institute of Technology, Publications in Climatology, vol. X, no. 3, 311 p.

U.S. Geological Survey, 1959, Compilation of records of surface waters of the United States through September 1950, Part 5. Hudson Bay and upper Mississippi River basins: U.S. Geol. Survey Water-Supply Paper 1308, 708 p.

, 1968, Compilation of records of surface waters of the United States, October 1950 to September 1960, Part 5. Hudson Bay and upper Mississippi River basins: U.S. Geol. Survey Water-Supply Paper 1728, 576 p.

, 1971, Surface water supply of the United States 1961-65, Part 5. Hudson Bay and upper Mississippi River basins: U.S. Geol. Survey Water-Supply Paper 1914, vol. 2, 750 p.

U.S. Public Health Service, 1962, Public Health Service drinking water standards – 1962: Public Health Service Pub. 956, U.S. Govt. Printing Office, 61 p.

Walton, William C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey, Bull. 49, 81 p.

, 1965, Ground water recharge and runoff in Illinois: Illinois State Water Survey, Rept. of Inv. 48, 55 p.

, 1970, Groundwater resource evaluation: McGraw-Hill Book Co., 664 p.

Water Pollution Control Commission, 1967, Water quality standards for the interstate waters of Minnesota: Minn. Water Pollution Control Comm., 174 p.

Water Resources Coordinating Committee, 1970, Minnesota water and related land resources – first assessment: State Planning Agency, 396 p.

Water Resources Research Center, 1967, Ground-water resource investigation and research needs in the Minneapolis-St. Paul area, Minnesota: Univ. of Minnesota Water Resources Research Center, Info. Circ. No. 76, 23 p. [mimeographed].

Weeks, Edwin P., 1969, Determining the ratio of horizontal to vertical permeability by aquifer-test analysis: Water Resources Research, vol. 5, no. 1, p. 196-214.

Winchell, N. W., 1886, Revision of the stratigraphy of the Cambrian in Minnesota: Minnesota Geol. Nat. Hist. Survey, 14th Ann. Rept., p. 336-337.

Wright, H. E., Jr., and Ruhe, R. V., 1965, Glaciation of Minnesota and Iowa in Wright, H. E., Jr., and Frey, D. G. (eds.), The Quaternary of the United States: Princeton, New Jersey, Princeton University Press.

## GLOSSARY

**Appropriated water user** – an individual, organization, or municipality that has been assigned an appropriation number by the State Department of Natural Resources for the purpose of withdrawing water for use in Minnesota.

**Aquifer** – a geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

**Available head** – as used in this report, the height of a column of water, measured in feet, above the top of the aquifer supported by the hydrostatic pressure at a given point. It is the drawdown available to a pumping well before drawing the water level below the top of the aquifer.

**Average discharge** – in this report and the annual series of the Geological Survey's reports on surface-water supply, the arithmetic average of all complete water years of record, whether or not they are consecutive (except when a period is specified such as 1935-69).

**Bank storage** – the water that is absorbed into the banks of a stream channel when stream stages rise above the water table in the bank formations. This water returns to the channel when stages fall below the water table.

**Baseflow** – that part of the flow in a stream contributed by ground-water discharge.

**Basin-storage discharge** – that part of runoff attributable solely to effluent discharge from the zone of saturation.

**Biochemical oxygen demand (BOD)** – the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions.

**Climatic year** – in this report, the continuous 12-month period beginning April 1 and ending March 31. The beginning and ending dates were selected so as to encompass the entire low-flow cycle during a 1-year period.

**Consumptive use** – the quantity of water discharged to the atmosphere or used in vegetal growth, food processing, or industrial production.

**Cubic feet per second (cfs)** – a unit expressing rate of discharge. One cubic foot per second is equal to the discharge of a stream of rectangular cross section, 1 foot wide and 1 foot deep, with water flowing at an average velocity of 1 foot per second.

**Cubic feet per second per square mile (cfsm)** – the average number of cubic feet of water per second flowing from each square mile of area drained by a stream, assuming that the runoff is distributed uniformly in time and area.

**Direct surface runoff** – the runoff entering stream channels promptly after rainfall or snowmelt. The bulk of this water flows over the surface, although some part of its travel to the stream may be in perched ground-water bodies.

**Evapotranspiration** – water withdrawn from a land area by evaporation from water surfaces and moist soil and plant transpiration.

**Gallons per day** – gpd.

**Head, static** – the height above a standard datum of the surface of a column of water that can be supported by the static pressure at a given point.

**Hydraulic conductivity (K)** – capacity of a rock to transmit water under pressure. As used in this report, it is the rate of flow of water at the prevailing kinematic (moving) viscosity passing through a unit section of area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path.

**Isocline** – line of equal water-level decline.

**Isopotential line** – line connecting points of equal static head in an aquifer. (Head is a measure of the potential.)

**Langley (ly)** – measurement of solar radiation in energy per unit area. One langley equals 1 calorie per 1 square centimeter.

**Million gallons per day** – mgd.

**Milligrams per liter (mg/l)** – a unit for expressing the concentration of chemical constituents in solution. Milligrams per liter represents the weight of solute per unit volume of water. It is equivalent to parts per million (ppm) in water with a density of 1.000 g/ml.

**Piezometer** – a small diameter pipe placed in the ground in such a way that the water level in the pipe represents the total head at the very point in the flow field where the piezometer terminates.

**Porosity** – property of a rock of containing interstices or voids; may be expressed quantitatively as the ratio of the volume of its interstices to its total volume (Meinzer, 1923, p. 19); may be expressed as a decimal fraction or a percentage.

**Potential evapotranspiration (PE)** – water loss that will occur from a vegetation-covered soil surface that is supplied at all times with sufficient moisture so that there is never any deficit of water for use of vegetation.

**Potentiometric surface** – a surface that represents the static head in an aquifer, as defined by the levels to which water will rise in tightly cased wells.

**Raw water** – water, as yet untreated, pumped from surface-water sources for use in the Minneapolis and St. Paul public supply systems.

**Runoff** – that part of precipitation that appears in streams. Runoff is classified as follows for this report:

Direct surface runoff – (see above)
Bank-storage runoff – (see bank storage)
Ground-water runoff – (see basin-storage discharge)

**Saturation, zone of** – that part of the subsurface where all pore spaces and voids in the rocks are filled with water. The water table is the upper surface of the zone of saturation.

**Specific yield (Sy)** – the ratio of the volume of water that a volume of rock or soil, after being saturated, will yield by gravity to its own volume.

**Storage coefficient (S)** – the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head.

**Storm seepage** – that part of precipitation that infiltrates the surface soil and moves toward a stream as ephemeral, shallow, perched ground water above the main water table. Storm seepage is usually part of the direct runoff.

**Subcrop** – as used in this report, the subsurface extent of the bedrock aquifers where they are directly overlain by glacial drift.

**Transmissivity (T)** – the rate at which water at the prevailing kinematic (moving) viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

**Transpiration** – the process by which subsurface water is discharged into the atmosphere by plants.

**Underfit stream** – a stream that seems too small to have eroded the valley in which it flows.

**Water year** – in this report and Geological Survey reports dealing with surface-water supply, the 12-month period beginning October 1 and ending September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1970, is called the 1970 water year.

**Well field** – as used in this report, any combination of wells withdrawing water from the same area and in close enough proximity to cause mutual drawdown effects.

## APPENDIX A

## CHRONOLOGICAL ANNOTATED LIST OF SELECTED PUBLICATIONS AND REPORTS PERTAINING TO THE WATER RESOURCES OF THE MINNEAPOLIS-ST. PAUL AREA

Examination of the following chronological list of reports and publications reflects the steady advances made in the hydro-sciences. None of the past work done in this area has made use of the latest developments made in the water field, nor are these latest developments used in this present study. The compilation of this list was adapted and updated from a list made by the Water Resources Research Center (1967) of the University of Minnesota.

### 1971

Hogberg, R. K., Environmental Geology of the Twin Cities metropolitan area: Minnesota Geol. Survey, Educational Series-5, 64 p. A lay reader report discussing geology, mineral resources, and points of interest in the metropolitan area.

### 1970

Anonymous, Minnesota water and related land resources-first assessment: Water Resources Coordinating Committee, State Planning Agency, St. Paul, Minnesota, 396 p. A comprehensive assessment that uses existing information to establish water supply and use in 1969 and projects general trends throughout the State to 2020.

### 1967

Anonymous, Groundwater resource investigation and research needs in the Minneapolis-St. Paul area, Minnesota: University of Minnesota Water Resources Research Center, Info. Circ. No. 76, 23 p. A report by a task group of the consulting council of the Water Resources Research Council briefly describing the hydrogeologic framework of the Twin Cities artesian basin and stating the status and deficiencies of available information, needed investigations and research, and recommendations for future studies.

Stone, J. E., Geologic, hydrologic, and engineering data: New Brighton quadrangel, Minnesota: Minn. Geol. Survey Information Circular IC-3, Approximately 100 p. To be released in 1967. Consolidates the data available for one 54-square-mile area in the Twin Cities.

### 1966

Reeder, H. O., 1966, Fourteen maps of parts of the ground-water reservoir in the Minneapolis-St. Paul metropolitan area. U.S. Geol. Survey open-file maps. Available in rm. 1033 P. O. Bldg., St. Paul, Minn.

1. Piezometric surface of the Prairie du Chien-Jordan aquifer zone in 1885.

2. Piezometric surface of the Prairie du Chien-Jordan aquifer zone in 1949.

3. Piezometric surface of the Prairie du Chien-Jordan aquifer zone in 1959.

4. Piezometric surface of the Prairie du Chien-Jordan aquifer zone in 1965.

5. Piezometric surface of the Mt. Simon-Hinckley aquifer zone in 1885.

6. Piezometric surface of the Mt. Simon-Hinckley aquifer zone in 1949.

7. Piezometric surface of the Mt. Simon-Hinckley aquifer zone in 1959.

8. Piezometric surface of the Mt. Simon-Hinckley aquifer zone in 1965.

9. Change of piezometric surface of the Prairie du Chien-Jordan aquifer zone 1885-1949.

10. Change of piezometric surface of the Prairie du Chien-Jordan aquifer zone 1885-1959.

11. Change of piezometric surface of the Prairie du Chien-Jordan aquifer zone 1885-1965.

12. Change of piezometric surface of the Mt. Simon-Hinckley aquifer zone 1885-1949.

13. Change of piezometric surface of the Mt. Simon-Hinckley aquifer 1885-1959.

14. Change of piezometric surface of the Mt. Simon-Hinckley aquifer 1885-1965.

Sloan, R. E., and Austin, G. S., Geologic map of Minnesota, St. Paul sheet, bedrock geology: Minn. Geol. Survey, $2.00. First sheet of the revised bedrock geologic mâp of Minnesota. Covers the southeastern part of the state, including the southern half of the Twin Cities area. Scale, 1:250,000.

Stone, J. E., The status of urban geology in the Minneapolis-St. Paul area: Reprint Series – 2 from Proceedings of the 13th Annual Conference on Soil Mechanics and Foundation Engineering, University of Minnesota (April 15, 1965). Available from Minn. Geol. Survey. Summarizes the geology of the Twin Cities area, the utility of urban geology, the geologic work now being done, and the practical implications of recent geologic discoveries. Also discusses reasons geologic studies of the area should be accelerated. The need to accelerate geologic mapping.

Stone, J. E., Goelogic units and aquifers of the Minneapolis-St. Paul area: unumbered chart of the Minn. Geol. Survey. Includes graphic log and brief descriptions of geologic units. Geologic units are divided into aquifers and aquicludes.

Stone, J. E., Surficial geology of the New Brighton quadrangle, Minnesota: Minn. Geol. Survey Map Series GM-2, University of Minnesota Press, 39 p., 3 plates (in pocket). The only quadrangle in the Twin Cities area for which there is a comprehensive, detailed, up-to-date geologic report. Shows typical three-dimensional relationships of glacial and bedrock formations.

## 1965

Maderak, M. L., Chemical quality of ground water in the Minneapolis-St. Paul area, Minnesota: Minn. Dept. of Conservation, Bull. 23, 44 p.

Payne, C. M., Bedrock geologic map of Minneapolis, St. Paul, and vicinity: Minn. Geol. Survey Miscellaneous Map M-1. Map at 1:24,000 of the bedrock geology and bedrock topography of the central part of the Twin Cities metropolitan area. Shows what the bedrock surface would look like if the glacial deposits were removed.

Stone, J. E., Reconnaissance map of the surficial geology of the Minneapolis-St. Paul area: Minn. Geol. Survey open-file map. Covers 6500 square miles at a scale of 1:250,000. Can be used as an overlay to parts of the Stillwater and St. Paul AMS sheets, which provide culture and topography for this preliminary map.

Wright, H. E., and Ruhe, R. V., Glaciation in Minnesota and Iowa in Wright and Frey (eds.), the Quaternary of the United States: Princeton University Press, Princeton, New Jersey. Summarizes the movements of Wisconsin ice sheets in Minnesota. Two of these ice sheets affected the Twin Cities area.

## 1963

Anonymous, Water resources study, Mississippi River headwaters reservoirs, Minnesota: U.S. Dept. of Health, Education, and Welfare, Public Health Service, Region VI, Kansas City, Missouri. Comprehensive study of the future needs for municipal, industrial, and quality-control purposes in the upper Mississippi drainage basin, including the Twin Cities area.

## 1962

Anonymous, Water resources of Minnesota, a study guide: Minn. Dept. of Conservation, Div. of Waters Bull. 16.

Anonymous, Natural resources of Minnesota, 1962: Minn. Natural Resources Council, 64 p. Important summary report on all the natural resources of Minnesota. Emphasizes the need for water studies in the State and especially in the Twin Cities area.

Anonymous, Report on the needs and location of water supply for the city of St. Paul, Minnesota: Report for the St. Paul Water Dept. by Toltz, King, Duvall, Anderson, and Associates, Inc., Consulting Engineers, St. Paul, Minn.

**1961**

Anonymous, Water supply and sewage disposal in the Minneapolis-St. Paul metropolitan area: Minn. Dept. of Health.

Minnesota Division of Waters, Water resources of the Minneapolis-St. Paul metropolitan area: Minn. Dept. of Conservation, Div. of Waters Bull. 11, 52 p. A comprehensive assessment of the surface-water and ground-water resources of the Twin Cities area. Emphasizes the need for a comprehensive study of the ground-water resources of the area.

Leisch, B. A., Geohydrology of the Jordan aquifer in the Minneapolis-St. Paul area, Minnesota: Minn. Dept. of Conservation, Div. of Waters Tech. Paper 2. A comprehensive description of the Jordan aquifer.

Woodward, F. L., Ground-water contamination in the Minneapolis-St. Paul suburbs: Reprint from Proceedings of the 1961 Symposium on Ground-Water contamination, Robert A. Taft Sanitary Engineering Center Tech. Rept. W61-5. Summarizes ground-water contaimination in the Twin Cities area.

**1960**

Anonymous, Metropolitan water study, pt. 1: Twin Cities Metropolitan Planning Comm. Rpt. No. 3.

Anonymous, Metropolitan water study, pt. 2: Twin Cities Metropolitan Planning Comm. Rept. No. 6. Discussion of organizational, legal, and economic aspects of water supply as related to the Twin Cities. Points out the need for comprehensive study of the groundwater resources of the area.

**1959**

Minnesota Division of Waters, Hydrologic atlas of Minnesota: Minn. Dept. of Conservation, Div. of Waters Bull. 10, 182 p.

**1953**

Prior, C. H., Schneider, Robert, and Durum, W. H., 1953, Water resources of the Minneapolis-St. Paul area, Minnesota: U. S. Geological Survey Circular 274, 49 p. Summarizes the water resources of the Twin Cities area. Points out the potential of ground water in the area and dramatizes the need for a comprehensive study of the ground-water resources.

**1952**

Frellsen, S. A., An estimate of the total water use in Minnesota for 1950 and 1975: Minn. Dept. of Conservation, Div. of Waters Bull. 7.

**1950**

Anonymous, Proceedings of Minnesota Conference on underground waters: Minn. Dept. of Conservation, Div. of Waters Bull. 2.

**1949**

Bradley, Edward, Report on the artesian water supply of the Twin Cities Basin: Minn. Geol. Survey (Mimeographed), 18 p. Gives water level measurements on many wells in Minneapolis and St. Paul and outlying areas. Includes an addendum by George M. Schwartz recommending 1) acquisition of yearly production figures on all producing wells in the city (Mpls.), 2) continuous records of static water levels be kept in key wells, and 3) a study be made of the efficiency of water use in cooling systems.

**1944**

Thiel, G. A., Geology and underground waters of southern Minnesota: Minn. Geol. Survey Bull. 31. Generalized information on the hydrogeology of an area that includes the Twin Cities. Includes basic data.

**1942**

Meyer, A. F., Evaporation from Lakes, St. Paul, Minnesota: Minn. Resources Comm., 167 p.

1941

Stauffer, C. R., and Thiel, G. A., 1941, The Paleozoic and related rocks of southeastern Minnesota: Minn. Geol. Survey Bull. 29, 261 p. Summarizes the bedrock geology of an area that includes the Twin Cities. Includes basic data.

1937

Anonymous, Water Survey made by the Engineering Department of the Minneapolis-St. Paul Sanitary District.

1936

Chase, E. Sherman, Memorandum report regarding water supply for the Twin Cities, Minneapolis and St. Paul, Minnesota, 18 p. (Presented to W. W. Horner, water consultant, National Resources Board). A brief but all encompassing appraisal of present water supplies, prospective future sources, and recommendations for future development.

Schwartz, G. M., The geology of the Minneapolis-St. Paul metropolitan area: Minn. Geol. Survey Bull. 27, 267 p. A pioneering volume on urban geology. Includes many basic data.

1935

Cooper, W. S., The history of the upper Mississippi River in the late Wisconsin and postglacial time: Minn. Geol. Survey Bull. 26, 116 p. Out-of-date in some respects, but generally an accurate and interesting account of the history of the Mississippi River in the Minneapolis-St. Paul area. Includes considerable information about the surficial geology of part of the area.

1933

Anonymous, Supplementary report on artesian water for Minneapolis, Minnesota: Report of Layne-Northwest Company and Pillsbury Engineering Company to the City Council.

Bass, Frederic, Meyer, A. F., and Norling, S. A., Supplementary report of the Minneapolis Water Supply Commission to the City Council. Includes some of the earliest estimates of hydraulic characteristics for the Jordan Sandstone underlying Minneapolis and a description of artesian city wells in St. Paul.

1932

Anonymous, Artesian water for Minneapolis, Minnesota: Rept. of Layne-Northwest Company to the City Council. Engineering and economic evaluation of the ground water in the Twin Cities area.

Bass, Frederic, Meyer, A. F., and Norling, S. A., Report of the Water-Supply Commission to the City Council of Minneapolis, Minnesota (Mimeographed), 207 p. Comprehensive discussion covering most aspects of water supply in Minneapolis as of 1932. Includes basic data, description of operations, and economics.

1911

Hall, C. W., Material conditions of a municipal water supply: Science, v. 33, p. 468-69.

Hall, C. W., Meinzer, O. E., and Fuller, M. L., Geology and underground waters of southern Minnesota: U.S. Geol. Survey Water-Supply Paper 256. Includes basic data and generalized evaluations of ground-water resources in an area that includes the Twin Cities area.

1905

Winchell, N. H., Deep wells as a source of water supply for Minneapolis: Am. Geologist, v. 35, p. 266-91.

An early recognition of the potential of ground water in the Twin Cities area.

1904

Hall, C. W., Contribution to the hydrology of eastern United States: U.S. Geol. Survey Water Supply Paper 102, p. 441-88.

**1896**

Winchell, N. H., Notes on some deep wells in Minnesota: 14th Annual Rept. of the Geol. and Nat. Hist. Survey of Minnesota, p. 11-16, 348-53.

**1895**

Winchell, N. H., Notes on artesian wells in Mendota, Hastings, etc.: 13th Annual Rept. of the Geol. and Nat. Hist. Survey of Minnesota, p. 55-64.

**1894**

Mead, D. W., The hydro-geology of the Upper Mississippi Valley and some of the adjoining territory: Am. Eng. Soc. Jour., v. 13, p. 339-96.

**1889**

Hall, C. W., The geological conditions which control artesian well borings in Minnesota: Bull. Minn. Acad. of Nat. Sciences, v. 3, p. 111-124.

Hewitt, C. N., The water of artesian wells: its quality and the possibility of its becoming a source of supply in Minnesota. Minn. Acad. of Science, v. 3, p. 125-27. An early recognition of the potential of ground water in the Twin Cities area.