Appraisal of Ground Water for Irrigation in the Little Falls Area, Morrison County, Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2009-D

Prepared in cooperation with the Morrison County Soil and Water Conservation District and the Minnesota Department of Natural Resources, Division of Waters, Soils, and Minerals

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1973

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress catalog-card No. 72-600298

For sale by the Superintendent of Documents
U.S. Government Printing Office, Washington, D.C. 20402
Price: Paper cover—$1.25 domestic postpaid, or $1 GPO Bookstore
Stock Number 2401–00270

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APPRAISAL OF GROUND WATER FOR IRRIGATION IN THE LITTLE FALLS AREA, MORRISON COUNTY, MINNESOTA

By JOHN O. HELGESEN

ABSTRACT

Anticipated irrigation on sandy soils has prompted evaluation of ground-water-supply potential in the Little Falls area. Geologic conditions cause ground-water availability to vary widely in the area. The largest and most readily available ground-water source is the glacial outwash sand and gravel from which the soils were derived.

Test augering shows that the saturated surficial outwash is as much as 50–100 feet thick in the area where the outwash fills a probable former meltwater channel and that it is also this thick in smaller areas elsewhere. Transmissivity of the thicker parts of the aquifer approaches or exceeds 100,000 gallons per day per foot, and probable well yields should exceed 1,000 gallons per minute. In about two-thirds of the study area, a saturated thickness of less than 40 feet generally limits well yields to less than 300 gallons per minute.

Recharge to the surficial aquifer is obtained primarily from precipitation. Most discharge occurs as evapotranspiration, base flow to the Mississippi River, and base flow to other streams and to lakes.

Possible future response to pumping was studied through electric analog analyses by stressing the modeled aquifer system in accordance with areal variations in expected well yields. The model interpretation indicates most of the sustained pumpage would be obtained from intercepted base flow and evapotranspiration. Simulated withdrawals totaling 18,000 acre-feet of water per year for 10 years resulted in little adverse effect on the aquifer system. Simulated larger withdrawals, assumed to represent denser well spacing, caused greater depletion of aquifer storage, streamflow, and lake volumes, excessively so in some areas. Results of model analyses provide a guide for ground-water development by identifying the capability of all parts of the aquifer system to support sustained pumping for irrigation.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

This report appraises the capability of the ground-water system in the Little Falls area, Minnesota, to provide water for irrigation. Presently (1971), no extensive development of ground water has begun in the area. Increasing awareness of the need for irrigation has stemmed from the combination of unreliable precipitation during the growing season and soils of low water-holding capacity. Average annual precipitation in the area is about 25 inches. Though about two-thirds of this falls during the growing season, its distribution during this period is often unfavorable. Soils are mainly sands and loamy sands developed from glacial outwash. Being typically well drained, the soils commonly show a moisture deficit for optimum plant growth in the summer, particularly during July and August. Irrigation would be important to the Little Falls area by supplementing natural precipitation and thereby increasing the productivity of the soils.

Several geologic units, each with distinct hydrologic characteristics, underlie the area. Although each is described here generally, the uppermost unit is described more thoroughly. This deposit of glacial outwash sand and gravel is the largest and most readily available source of ground water. To evaluate its overall water-supply potential, the surficial outwash was studied to determine its extent and thickness, appraise its water-yielding capability, and estimate possible effects that pumping may have on the natural water system. In addition, chemical characteristics of the water are described in terms of suitability for irrigation. The results of this study are intended to contribute toward a better understanding and therefore optimum development of the ground-water resources of the area.

LOCATION AND DESCRIPTION OF AREA

The study area consists of about 180 square miles in Morrison County, central Minnesota (fig. 1). It is limited chiefly by the extent of surficial outwash, partly by county boundaries, and partly by Camp Ripley Military Reservation boundaries.

The study area is relatively low lying, is flat to moderately undulating, and drains generally southward. It forms part of the Mississippi-Sauk watershed unit, as designated by the Minnesota Department of Conservation (Minnesota Division of Waters, 1959). The Mississippi River flows through the study area and is regulated at two locations by dams, one at Little Falls and one northwest of Royalton (Blanchard Dam). Most of the eastern part of the area is drained by the Platte River, which joins the Mississippi River near the southernmost edge of Morrison County.

Agriculture is the principal economic activity of the region, although much land is presently out of production. The major crops produced are hay, corn, and oats. A small part of the study area is wooded, and a small part consists of lakes and swamps.

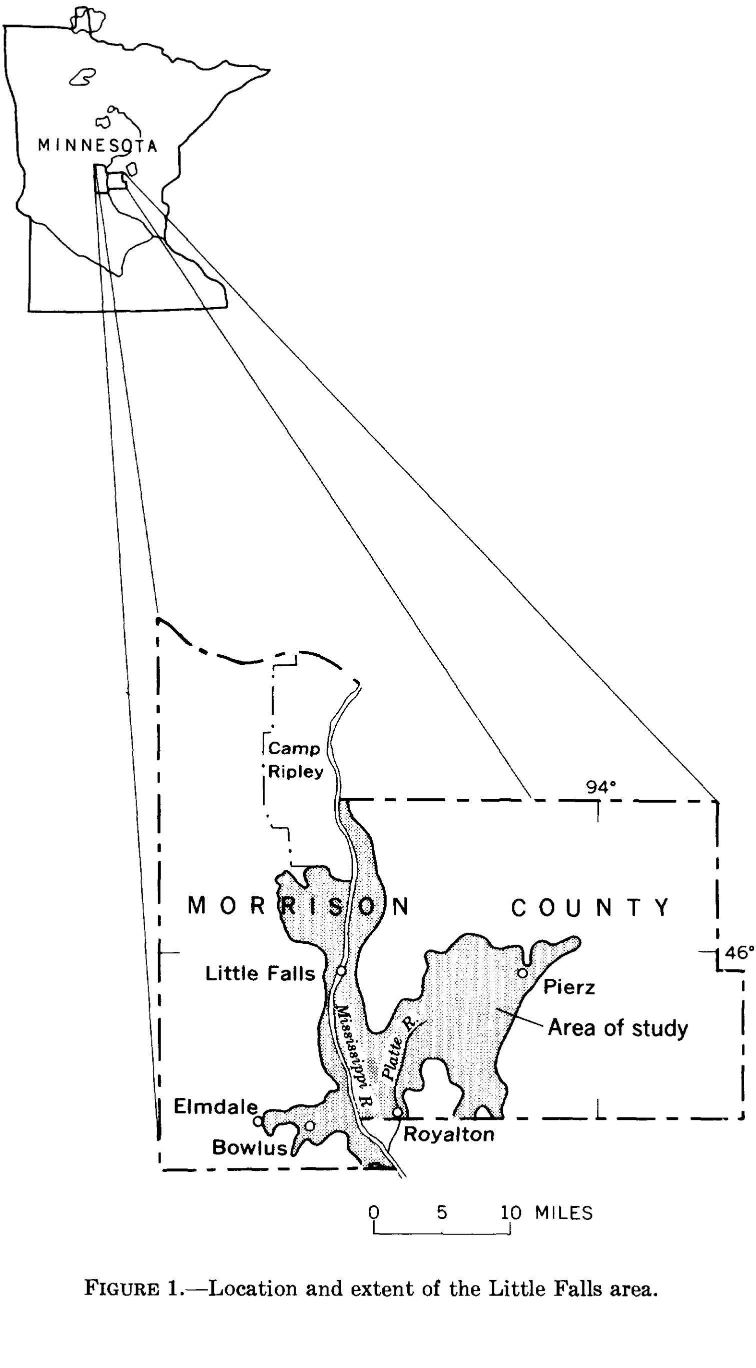

FIGURE 1.—Location and extent of the Little Falls area.

PREVIOUS INVESTIGATIONS

The earliest geologic work in Morrison County was by Upham (1888). Allison (1932) described very generally the geology and water resources of western Morrison County, and the work of Leverett (1932) included the description and interpretation of the main glacial features in the region. Schneider (1961) mapped in detail the glacial geology of the Randall area, about 20 square miles of which lies within the northwestern part of the present study area. Intensive ground-water exploration in the southern part of Camp Ripley Military Reservation, using test drilling and electrical resistivity, was carried out by Jones, Akin, and Schneider (1963).

METHODS OF INVESTIGATION

Data for this study were collected and analyzed during the 3-year period beginning in July 1968.

Published literature, aerial-photograph interpretation, and field mapping defined the surficial geology. Subsurface information was obtained primarily from 166 test holes which were drilled in the study area by the U.S. Geological Survey. Samples of materials were collected during drilling and analyzed for textural and hydraulic properties. Drillers, farmers, officials of municipalities, and others supplemented the test-drilling results by providing information pertaining to about 200 other drill holes in and near the study area.

Six aquifer tests were made in and near the study area to determine hydraulic properties of the outwash. The results provided a guide in estimating these properties at other points of test-drilling control. Three series of streamflow measurements obtained at times of low flow (Nov. 4–7, 1968; Aug. 20–22, 1969; and Aug. 17–20, 1970) provided a measure of the ground-water discharge to streams within the study area. Water-table fluctuations were monitored in 17 wells: five were recorded continuously, one taped weekly, and 11 taped monthly.

Water samples collected from 12 wells completed in the outwash were chemically analyzed by the U.S. Geological Survey.

Study of the hydrologic system was aided by data obtained from an electric analog model. The model, which is an approximate electrical simulation of the surficial aquifer, was used to estimate effects on the aquifer system that might arise from future ground-water development.

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. That part of the study area east of the Mississippi River is in the fourth principal meridian and base-line system. That part west of the river is in the fifth principal meridan 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 located. The lowercase letters a, b, c, and d, following the section number, represent the location of the well in the section. The first letter denotes the 160-acre tract, the second denotes the 40-acre tract, and the third denotes the 10-acre tract. The letters are assigned in a counterclockwise direction beginning in the northeast quarter. Consecutive numbers beginning with 1 are added as suffixes to distinguish wells within one 10-acre tract. Figure 2 illustrates the method of numbering. Thus, the

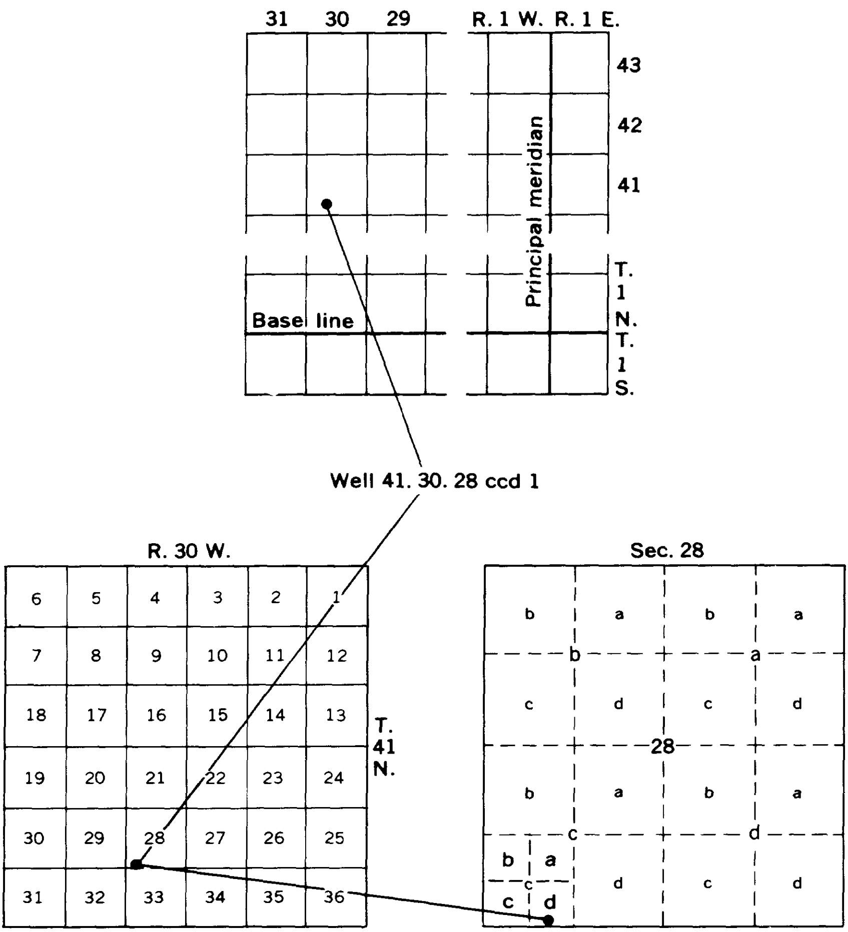

FIGURE 2.—Well and test-hole numbering system.

number 41.30.28 ccd1 identifies the first well or test hole located in the SE¼SW¼SW¼ sec. 28, T. 41 N., R.30 W.

DEFINITIONS

The geologic and hydrologic terms pertinent to this report are defined as follows:

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells or springs.

Base flow. Sustained streamflow, composed largely of ground-water discharge.

Evapotranspiration. Water withdrawn by evaporation from water surfaces and moist soil and by plant transpiration.

Glacial drift. All deposits resulting from glacial activity.

Ground water. That part of subsurface water that is in the saturated zone.

Hydraulic conductivity. The rate of flow of water in gallons per day through a porous medium of cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at the prevailing kinematic viscosity.

Outwash. Sorted, stratified drift deposited beyond the ice front by meltwater streams.

Saturated zone. Zone in which all voids are ideally filled with water. The water table is the upper limit of this zone, and the water in it is under pressure equal to or greater than atmospheric.

Specific yield. The ratio of (1) the volume of water which a saturated rock or soil will yield by gravity to (2) its own volume.

Storage coefficient. The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an unconfined aquifer, it is virtually equal to the specific yield.

Till. Unsorted, unstratified drift deposited directly by the ice.

Transmissivity. The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient.

Water table. That surface in an unconfined water body at which the pressure is atmospheric.

ACKNOWLEDGMENTS

This investigation was conducted in cooperation with the Morrison County Soil and Water Conservation District and the Minnesota Department of Natural Resources, Division of Waters, Soils, and Minerals. The writer is grateful for much useful information provided by property owners and well drillers. Special thanks are also

extended to those who permitted the drilling of test holes and the installation of observation wells on their land, and to those who allowed the use of their wells for aquifer tests.

GEOLOGY

PRECAMBRIAN ROCKS

The entire study area is underlain by rocks of Precambrian age (Goldich and others, 1961; Sims and Zietz, 1967). Metamorphosed sedimentary rocks, chiefly slate, phyllite, schist, and metagraywacke, underlie all of the area except the eastern part (fig. 3). They occur at or near the land surface at several places, mostly along the Mississippi River. Weathered sections of the metamorphosed sedimentary rocks, usually grayish, micaceous, and in places over 10 feet thick, were penetrated during test drilling.

Igneous intrusives, mainly quartz monzonite and tonalite, underlie the eastern part of the area (fig. 3) and local areas elsewhere. They crop out at points within and just north and east of the study area.

Figure 3 shows variations in altitude of the bedrock surface. The surface, which in places is quite irregular, slopes generally southward.

CRETACEOUS ROCKS

The only definite evidence of deposition after Precambrian time, other than glacial drift, is an outcrop of Cretaceous rocks east of Bowlus in the southern part of the study area (fig. 3). Allison (1932) described this outcrop as gray, sandy, calcareous clay and shale. Parham (1970), who described the exact location of the outcrop, identified it as 1 foot of light-gray clay. Extent of the Cretaceous rocks in the area is presumably very small. However, possible Cretaceous shale was found in two test holes in the extreme southern tip of the study area. The shale(?) occurs at a depth of about 95 feet at 127.29.26 cba and 127.29.27 bac.

GLACIAL DRIFT

Except where bedrock is exposed, the study area is mantled by glacial drift deposits left by ice advances of the most recent glaciation, the Wisconsin. In places these deposits are as much as 150 feet thick (fig. 4). The following discussion of the glacial history of the area is based on the report of Wright and Ruhe (1965). The Wadena Lobe, which is the earliest ice advance for which evidence remains, moved into the area from the northwest. It deposited gray to buff sandy calcareous till. As the ice front retreated to the northwest, the Pierz Sublobe of the Rainy Lobe advanced from the east and overrode the till of the Wadena Lobe. The till left by the Pierz Sublobe is brown to

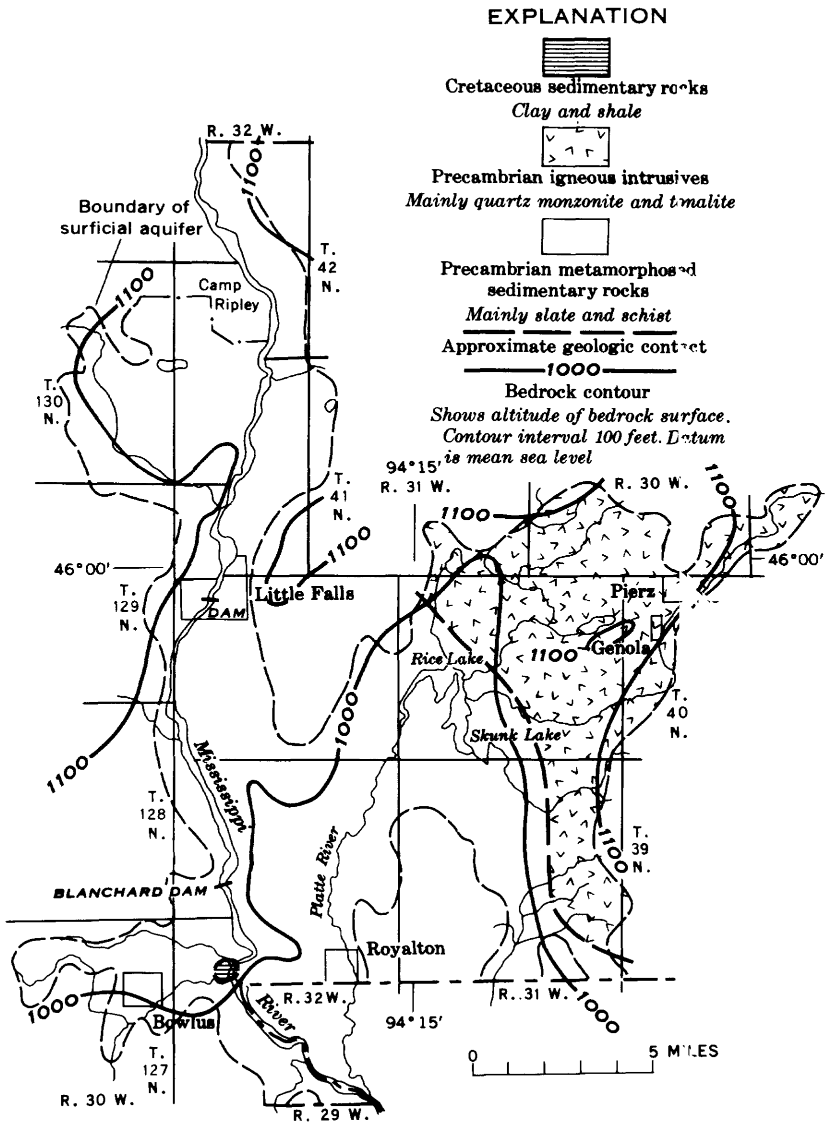

FIGURE 3.—Bedrock geology and bedrock topography. Geology adapted from Goldich, Nier, Baadsgaard, Hoffman, and Krueger (1961) and Sims and Zietz (1967).

reddish brown and sandy. A contemporaneous advance from the northeast, the Brainerd Sublobe of the Rainy Lobe, stopped just north of the study area. Most of the present landscape surrounding the study area is a till plain formed by the Pierz Sublobe. Southeast of Pierz,

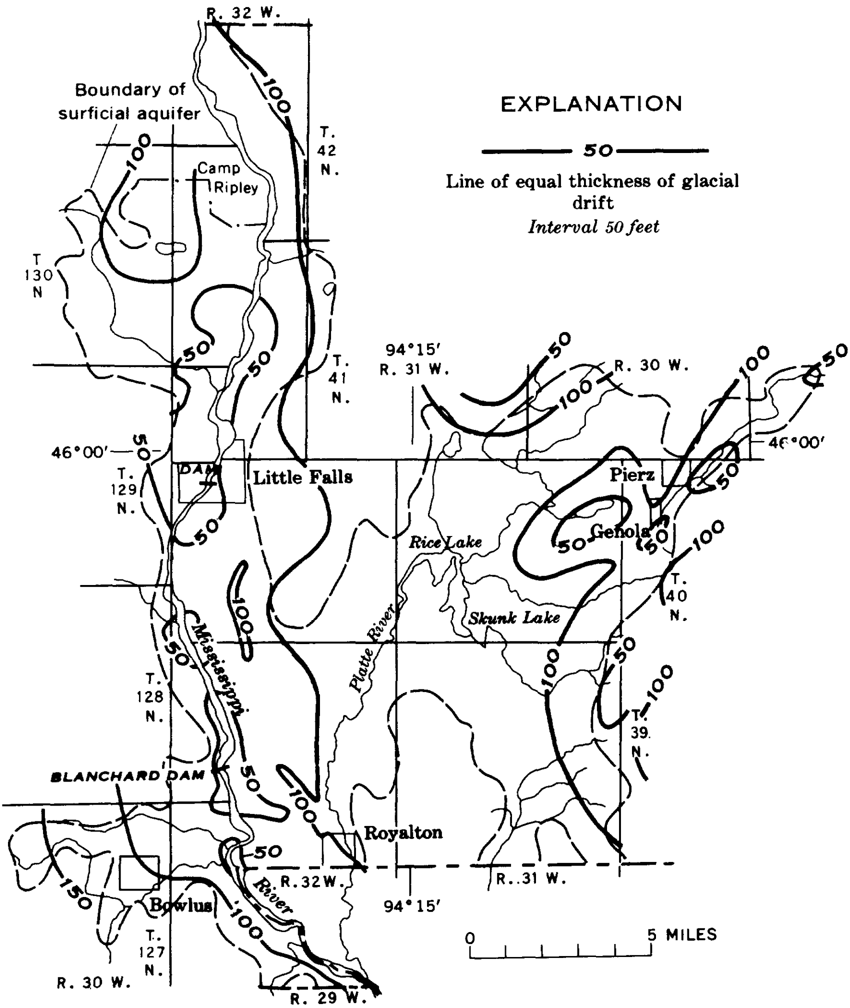

FIGURE 4.—Thickness of glacial drift.

the plain is in the form of a drumlin field, a group of many elongated hills of till whose long axes are parallel to the direction of ice movement. The topographically high area a few miles east and southeast of Little Falls consists mostly of brown drift and is probably a recessional moraine of the Pierz Sublobe, a deposit built up during a pause in the retreat of the ice front.

Meltwaters from the ice were a major cause of the distribution and thickness of the glacial deposits found today in the study area. Waters from the Brainerd Sublobe and the Wadena Lobe were introduced from the north, and wastage of the Pierz Sublobe contributed melt-

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waters from the east (Schneider, 1961, p. 105, 109). Although the gray till and the overlying brown till probably remain below the surficial outwash in most of the study area, meltwaters in some places eroded one or both units before depositing their debris. One erosion channel, which occurs near and roughly parallel to the present Mississippi River, is traceable through the entire study area. It was cut through the till and into bedrock along its deepest part. The channel was probably a major glacial drainageway, possibly cut by the waters from glacial Lake Wadena, which was about 10 miles northwest of the study area. Southward drainage of that glacial lake, which occurred rather suddenly upon recession of the Brainerd Sublobe (Cooper, 1935, p. 9; Schneider, 1961, p. 105, 109), presumably provided the rates of flow necessary to erode such a large channel.

After their erosive energy was dissipated, the meltwaters deposited the extensive outwash which now occurs at the surface in the study area (fig. 5). Total thickness of these stratified sands and gravels ranges from 0 to 50 feet over much of the area and exceeds 100 feet in places. The most extensive thick section of outwash, that part filling the previously mentioned bedrock channel, is reflected by the north-south linear trend of the thickness lines in figure 5.

Much of the outwash occupying the buried bedrock channel is gray, suggestive of drift carried by the Wadena Lobe. Gray outwash is found elsewhere in the study area, although the brown color of most of the outwash indicates its derivation from an eastern drift source. The main constituents of the outwash are sand and gravel, although some zones of clay, silt, or till are included. Grain size varies both laterally and vertically, but medium and coarse sand (Wentworth scale) are predominant in many sections. The materials are typically moderately to well sorted.

The outwash adjacent to the Mississippi River in Morrison County is part of a "valley train" deposit which extends from Brainerd to Minneapolis (Cooper, 1935, p. 9–11). The present Mississippi River is entrenched into this deposit to a depth in the study area of usually 20–50 feet.

HOLOCENE DEPOSITS

Holocene stream deposits occur along the Mississippi River (Schneider, 1961, p. 98) and, to a lesser extent, in other stream valleys. Because of the small extent of these sediments, they are not mapped separately in this report.

Wind deposits are also not differentiated from the surficial outwash. Wind-deposited sands occur locally at the surface in and adjacent to the study area (Cooper, 1935, p. 94–95).

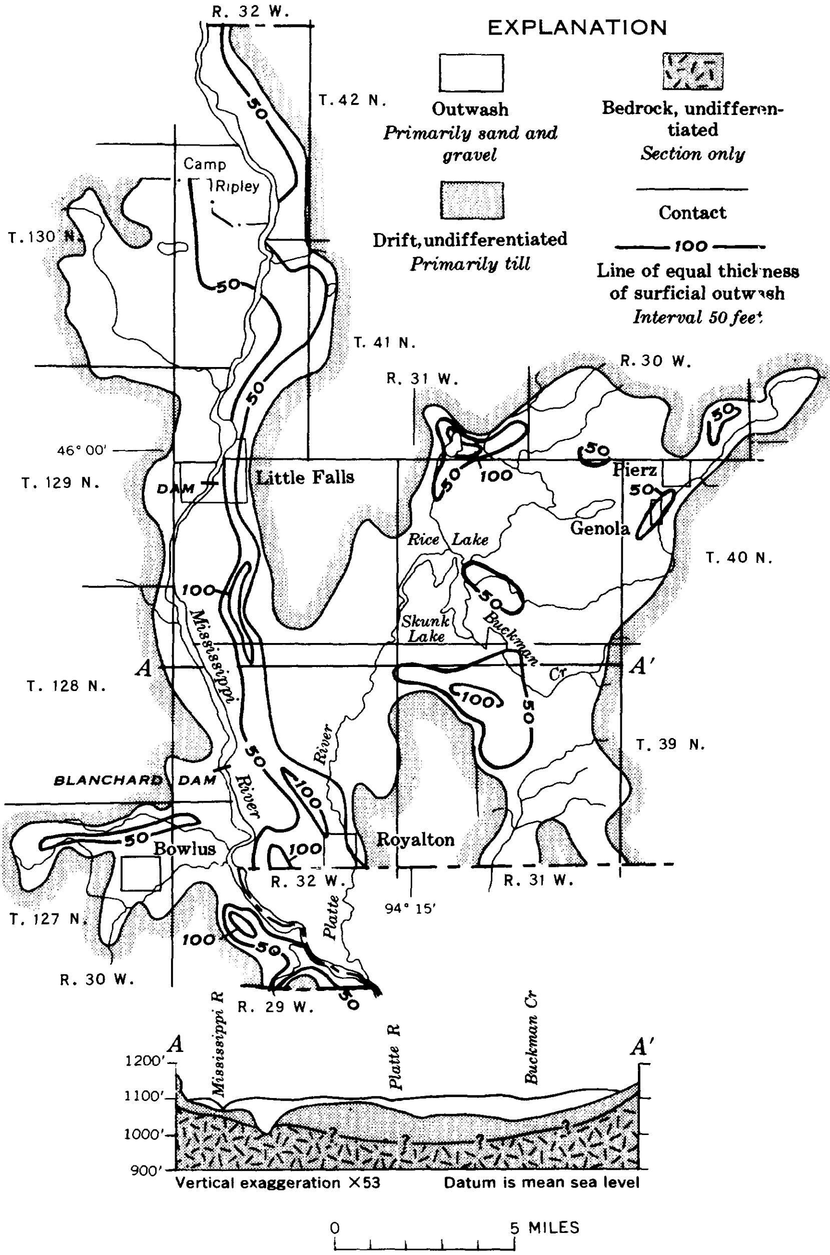

FIGURE 5.—Distribution of glacial geologic units and thickness of surficial outwash.

GROUND-WATER AVAILABILITY

BEDROCK

Relatively small amounts of water are available from Precambrian bedrock in the Little Falls area. Porosity and hydraulic conductivity of these rocks are very low. Ground water occurs only in openings resulting from jointing and fracturing. Interception by a drill hole of several of these openings, if they are sufficiently interconnected, may provide small quantities of water. Sustained yields of the magnitude generally considered necessary for irrigation, however, cannot be expected.

Cretaceous bedrock, because of its apparently small extent and clay-rich composition, is considered insignificant as a source of water.

UNDIFFERENTIATED DRIFT

The glacial drift which surrounds and underlies the surficial outwash is referred to in this study as undifferentiated drift. Because it consists partly of till and partly of outwash, it is widely variable in water-yielding capability. The till, being poorly sorted and containing much clay, is of low hydraulic conductivity and can yield very little water to wells. The outwash, which has been water sorted, has substantially higher hydraulic conductivity and therefore higher water-yielding capability. Maximum yields depend largely upon the thickness and extent of the outwash. Considerable test drilling would be necessary to delineate the buried outwash because of its unpredictable occurrence. Figure 6 shows locations and thicknesses of buried outwash as currently known in and near the study area. Some places, particularly in the southern part of the area, are underlain by buried aquifers probably of sufficient size to yield several hundred gallons per minute of water to a properly constructed well. Elsewhere, most of the buried sand and gravel is reportedly quite thin and of correspondingly lesser water-yielding potential.

Figure 6 also shows those areas where little or no undifferentiated drift is present, that is, those areas where bedrock is at or near land surface or where the surficial outwash is underlain directly by bedrock.

SURFICIAL OUTWASH

The single most extensive and readily available source of ground water is the surficial outwash. Its water-yielding capability is variable across the area, depending primarily upon thickness and texture.

SATURATED THICKNESS

That thickness of the aquifer which is significant to ground-water availability is the saturated thickness. It is the vertical distance

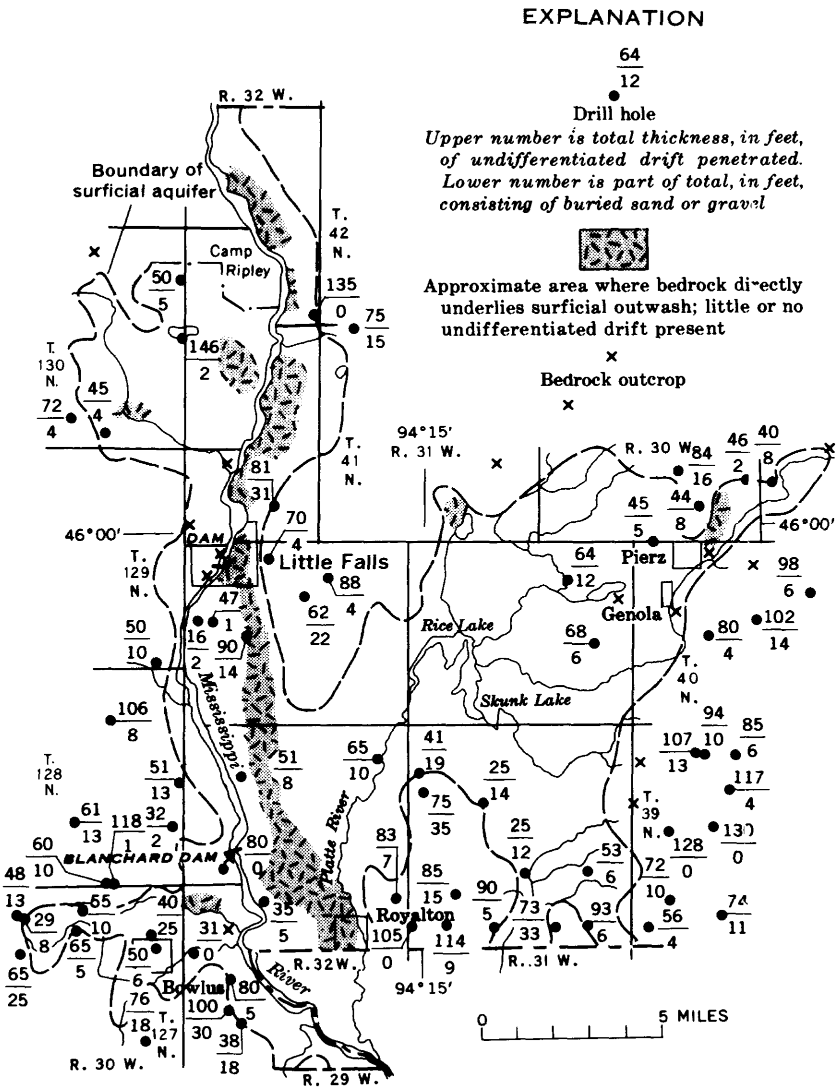

FIGURE 6.—Occurrence of buried drift aquifers in and near the Little Falls area.

between the water table and the bottom of the aquifer (contact between the surficial outwash and the underlying till or bedrock). In the study area, depth to the top of the saturated zone (water table) varies from less than 5 feet in some areas to as much as 40 feet in others (fig. 7). Despite the areal variations in depth to the water table, saturated thickness (pl. 1A) generally reflects total outwash thickness (fig. 5). Greatest saturated thicknesses (more than 60 feet) are found in

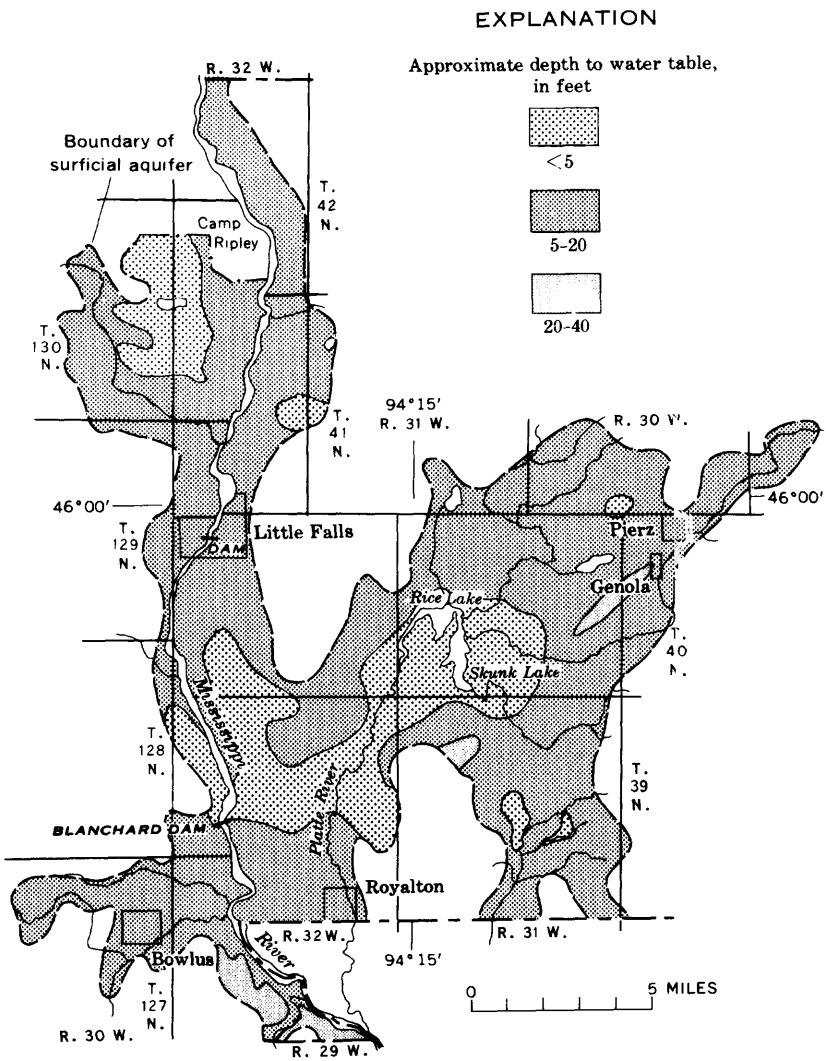

FIGURE 7.—Depth to the water table.

the previously mentioned bedrock channel and in scattered smaller areas. Most of the area is underlain by less than 40 feet of saturated surficial outwash.

HYDRAULIC PROPERTIES

Determinations of two hydraulic properties of the aquifer, transmissivity and storage coefficient, are needed to quantify water-yielding capability. These properties are strongly dependent upon texture, in that the size and interconnection of the pores govern how much water can be transmitted through and stored in the medium.

Transmissivity (saturated thickness times hydraulic conductivity) was approximated through analyses of six aquifer tests made in and near the study area (table 1; pl. 1*B*). Once determined, the value of transmissivity at each test site was related to the texture of the aquifer at that site. Vertical variations in grain size and sorting signify vertically varying hydraulic conductivity. Hence, values of hydraulic conductivity were assigned such that the sum of each multiplied by its corresponding saturated thickness would equal transmissivity of the aquifer at that test site. The values of hydraulic conductivity so determined were then used to estimate transmissivity at other test-hole sites where only texture and saturated thickness alone were known. Table 2 lists the values of hydraulic conductivity used. Lower values in each range were assigned to relatively poorly sorted materials and higher values to well-sorted materials.

The dependence of transmissivity (pl. 1*B*) on saturated thickness (pl. 1*A*) is illustrated by the close resemblance between their areal trends. In more than half the study area, transmissivity of the surficial aquifer is less than 50,000 gpd per ft (gallons per day per foot).

TABLE 1.—*Results of aquifer tests in the Little Falls area*

Location	Length of test (hr)	Yield of pumped well (gpm)	Aquifer characteristics: Transmissivity (gpd per ft)	Aquifer characteristics: Average hydraulic conductivity (gpd per sq ft)	Aquifer characteristics: Specific yield
38.31.20 bbd	48	1,100	100,000	1,300	0.2
39.32.1 bbd	4	45	15,000	1,100	-------
39.32.35 dbc	2	600	175,000	2,300	-------
41.30.28 ccd	4	55	10,000	600	-------
41.32.13 dca	3	140	125,000	2,800	-------
130.29.17 abb	11; [1] 53	640; [1] 850	175,000	2,500	.1

[1] Test conducted in 1949 (Jones and others, 1963)

TABLE 2.—*Values of hydraulic conductivity for surficial outwash in the Little Falls area*

Predominant material (Wentworth scale)	*Hydraulic conductivity (gpd per sq ft)*
Clay or silt	<100
Sand, very fine	100–500
Sand, fine	500–1,000
Sand, medium	1,000–3,000
Sand, coarse or very coarse	1,000–4,000
Gravel	1,000–5,000

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Over the bedrock channel, transmissivity may locally be several hundred thousand gallons per day per foot, such as immediately north of the study area where the channel underlies Camp Ripley Military Reservation (Jones and others, 1963, p. A18).

A storage coefficient that would be valid for long-term evaluation (specific yield) was indeterminable from most aquifer tests because of insufficient duration of pumping to allow for complete drainage of the dewatered zone. Laboratory analyses of samples collected during test drilling indicate specific yields mainly in the range of 0.2 to 0.3. It appears that 0.2 is most representative of the specific yield of the surficial aquifer. This value is typical of an unconfined aquifer, one whose upper limit is the water table. The aquifer as a unit is considered unconfined in the study area, though an overlying layer of silt or clay may confine it locally.

THEORETICAL WELL YIELDS

Definition of hydraulic properties enables calculation of theoretical optimum yield to a properly constructed well in the surficial aquifer. Certain assumptions necessary for these calculations are:

1. The aquifer is homogeneous and of infinite areal extent.
2. The well is open to the full saturated thickness of the aquifer, is 100 percent efficient, and is of large diameter (16 in. used in these calculations).
3. The well is pumped continuously for 30 days. Such a demand for irrigation is probably a maximum for the study area.
4. Drawdown, the lowering of water level in the well caused by pumping, is about two-thirds of the original saturated thickness. The well is being pumped at maximum efficiency under this condition (E. E. Johnson, Inc., 1966, p. 107–108).

Based on the preceding assumptions, calculations of theoretical optimum yield were made using the nonequilibrium equation of Theis (1935). Assumed drawdowns were decreased to account for decreasing transmissivity caused by dewatering the unconfined aquifer, by using the equation of Jacob (1944).

It is evident (pl. 1*C*) that water-supply potential of the surficial aquifer varies widely from place to place. In the area of the bedrock channel and in other smaller areas, yields to individual wells will probably exceed 1,000 gpm (gallons per minute). It is estimated that yields exceeding 2,000 gpm may be possible locally in these areas. However, less than one-third of the study area is underlain by surficial outwash likely to yield more than 300 gpm to a well. In the remaining area, ability of the aquifer to yield water to individual wells is generally inadequate for irrigation purposes. Other possible means of obtaining a satisfactory ground-water supply include pits or multiple well systems in the surficial aquifer, or deeper wells completed in buried aquifers.

Because the assumptions necessary for this evaluation involve idealized conditions, it is important to realize that plate 1*C* pertains to the surficial aquifer as a whole and cannot be used for an accurate prediction of well yield at a given site. There are variations in saturated thickness and texture between points of test-drilling control which will affect the yield. Proximity to streams, lakes, other wells, or to the boundary of the study area may also be significant factors. Furthermore, as ground-water development intensifies, the response of the system to pumping may be important in determining the rates of withdrawal which can be safely maintained.

THE GROUND-WATER SYSTEM

UNSTRESSED SURFICIAL AQUIFER SYSTEM

The surficial aquifer in the Little Falls area is a dynamic system in which water is continuously recharged and discharged. Before long-term effects which might result from pumping can be determined, the unstressed or natural state of the system must first be defined. To do so requires a description of water movement within the aquifer and an estimation of the average annual quantity of recharge and discharge and distribution of each component of recharge and discharge.

Water movement within the aquifer is roughly indicated by the configuration of the water table (fig. 8). The water table essentially parallels topography, indicating that ground-water moves from relatively high areas toward lower areas, where it is discharged from the aquifer system. The Mississippi River, the Platte River, and Rice and Skunk Lakes, are the main areas of discharge. Some ground water is discharged to other streams and lakes or is lost to evapotranspiration before reaching the main discharge areas.

The water table rises when recharge from precipitation occurs and falls when no precipitation occurs to replace ground water being discharged. These fluctuations ordinarily do not exceed a few feet annually, and tend to compensate on a long-term basis. Figure 8 is assumed to portray the water table in a system that is approximately in equilibrium.

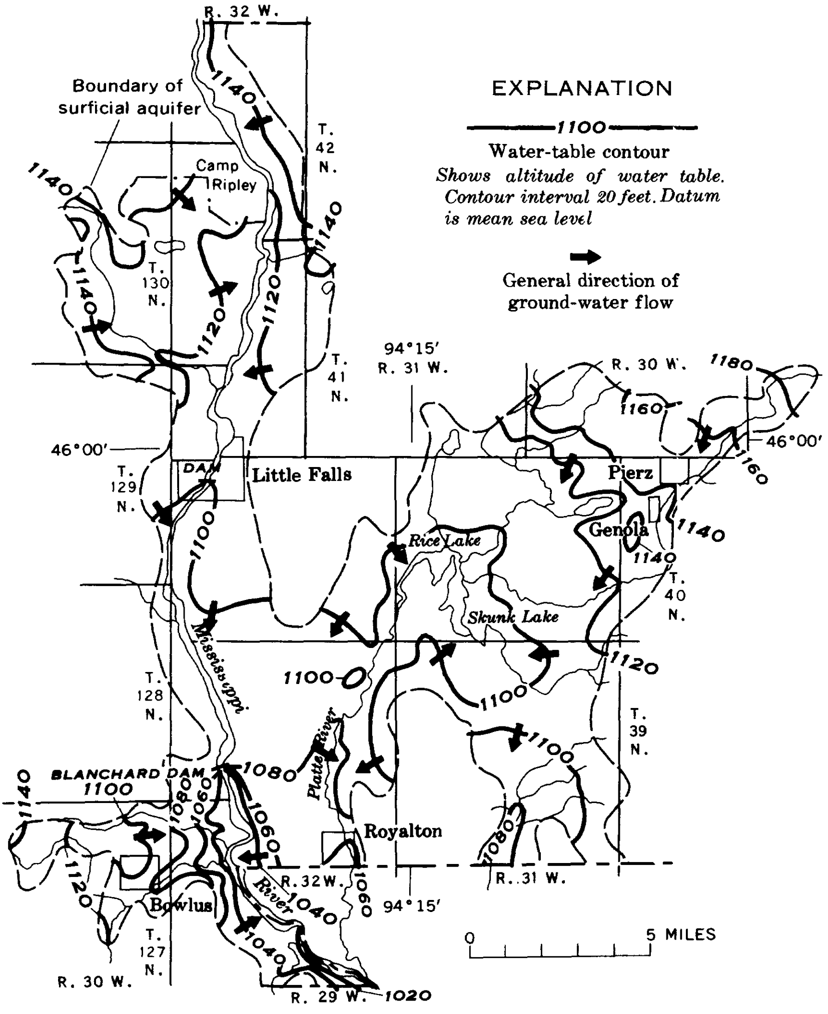

FIGURE 8.—Water-table configuration and general direction of ground-water movement.

RECHARGE AND DISCHARGE OF GROUND WATER

RECHARGE FROM PRECIPITATION

Most recharge to the surficial aquifer is that part of precipitation that percolates down to the saturated zone. Snowmelt and rainfall in the spring contribute most of this water. This amount is estimated from water-level measurements in observation wells, as shown in figure 9. Of the 2 years of available record, amounts calculated from

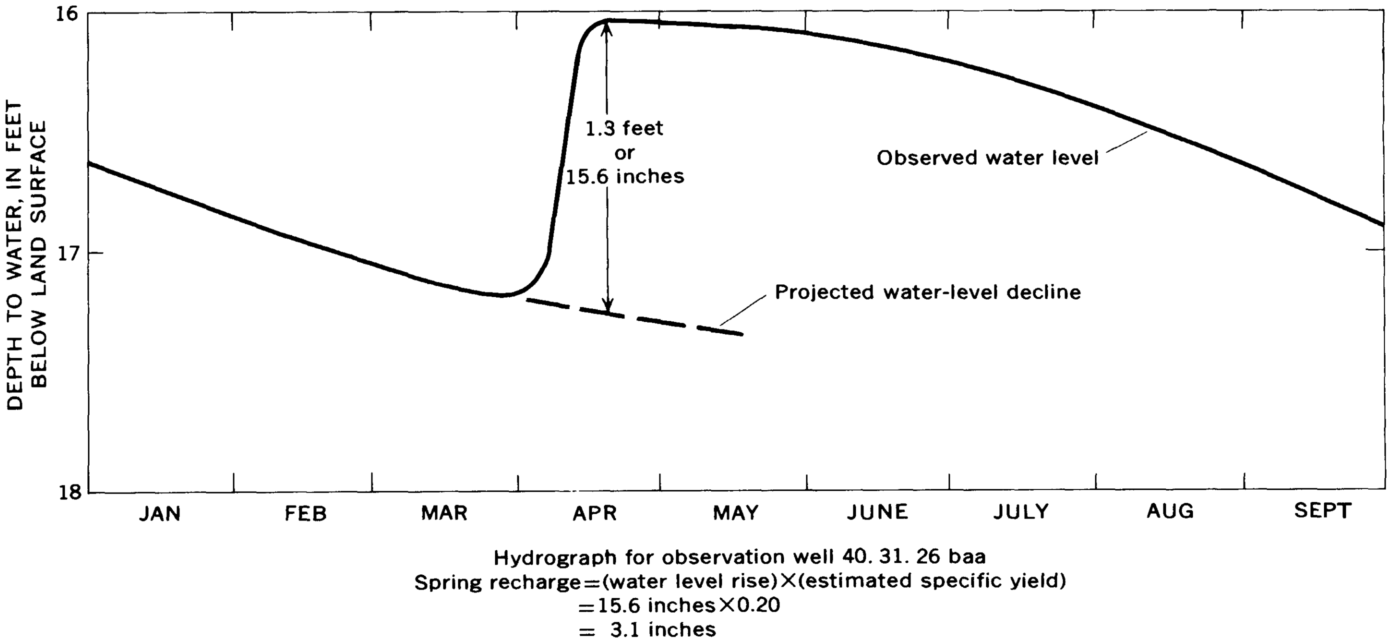

FIGURE 9.—Example of hydrograph showing method of estimating recharge to the surficial aquifer that occurs during the spring in the Little Falls area.

measurements made in the spring of 1970 are assumed to represent more closely the long-term values. This assumption is based upon the close similarity of 1969–70 winter snowfall and 1970 spring rainfall to long-term average precipitation for those seasons. Most of the aquifer receives about 4–7 inches of annual recharge in this manner, or about 57,000 acre-feet over the study area.

Recharge from rainfall during the summer and fall was estimated from continuously recorded water-level data from observation wells. The period June–November 1969 is considered representative of the long-term average precipitation for the same period of the year. Recharge to the aquifer from summer and fall precipitation, on this basis, totals about 2.5 inches, or about 25,000 acre-feet over the study area.

Total average annual recharge to the aquifer from precipitation is therefore considered to be distributed approximately as shown in figure 10.

GROUND-WATER–SURFACE-WATER RELATIONS

The surficial aquifer is in hydraulic connection with streams and lakes. Water normally moves into streams and lakes from the aquifer, so that volume of streamflow increases as the streams flow through the study area. During times of high flow, the gradient may be reversed, but this is short lived.

Discharge measurements were made during times of prolonged dry weather, when most flow comes from the aquifer. Series of measurements during August 20–22, 1969, and August 17–20, 1970, gave the best indications of the quantity and distribution of base flow during periods when irrigation would be likely to occur. Flow for the period August 20–22, 1969, is illustrated in figure 11 and is assumed to be representative of long-term ground-water–surface-water relations. All stream reaches measured receive water from the aquifer except a short reach of the Platte River just below Rice Lake, which recharges the aquifer. The net quantity of water gained by streams and lakes other than the Mississippi River is about 36 cfs (cubic feet per second), or about 26,000 acre-feet per year. Rates of gain generally range from about 100 to 500 acre-feet per year per mile of stream length within the study area.

Discharge of the Mississippi River at the gaging station near Royalton averaged 2,380 cfs during August 20–22, 1969 (the long-term average discharge is about 4,100 cfs). Ground-water contribution to the Mississippi River is not indicated in figure 11; its quantity and distribution are not directly determinable because of the river's large and regulated total discharge. However, on the basis of past

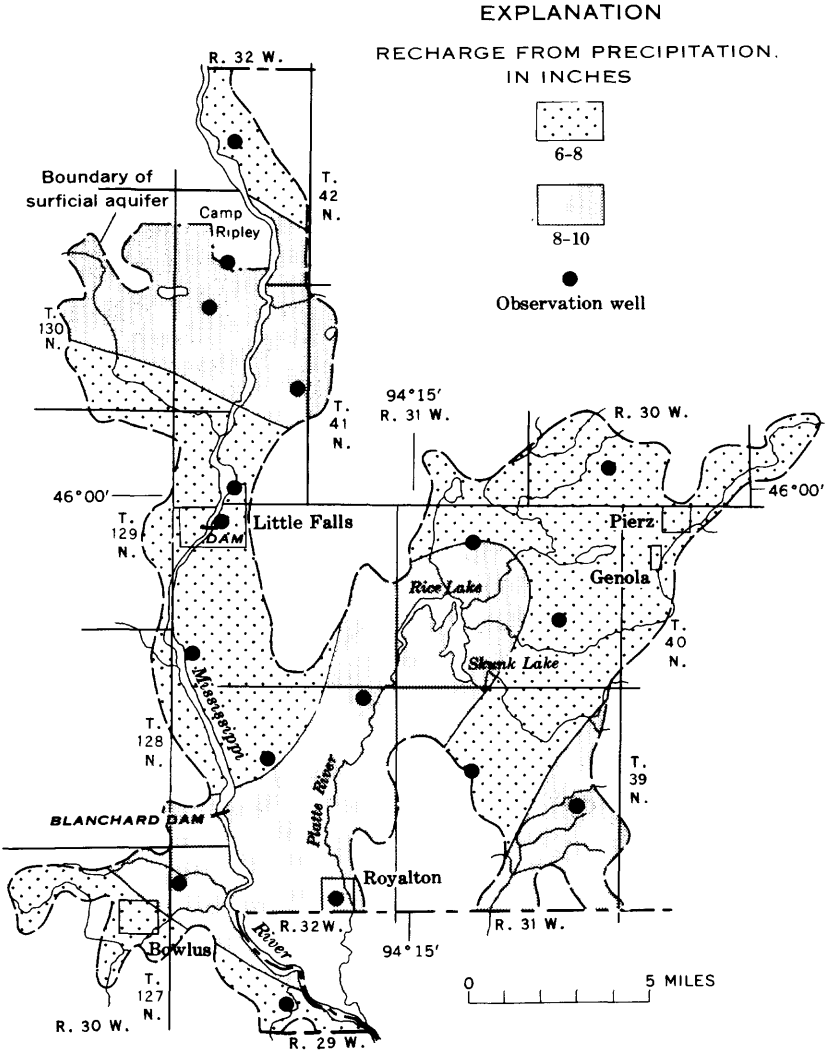

FIGURE 10.—Recharge to the surficial aquifer from precipitation during June 1969–June 1970.

records from stations in and upstream from the area, it is estimated that base flow directly to the Mississippi River may be about 60 cfs, or about 43,000 acre-feet per year in the study area.

EVAPOTRANSPIRATION

Where the water table is sufficiently shallow, water is discharged from the aquifer system by evapotranspiration. The depth below land

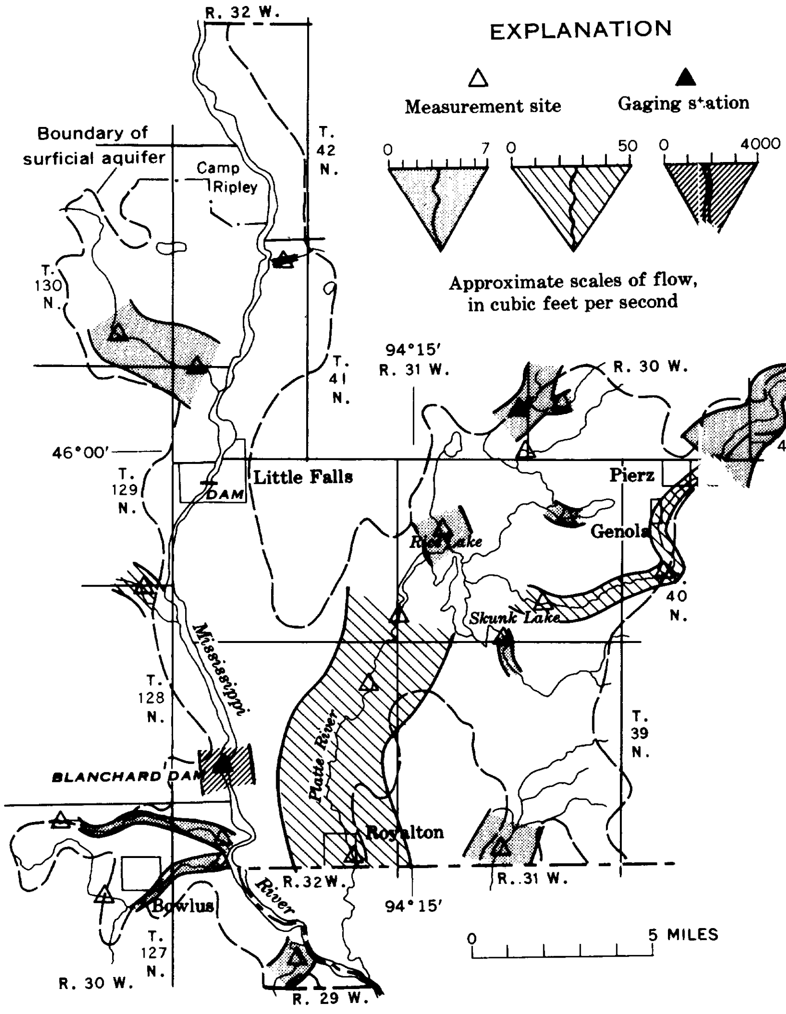

FIGURE 11.—Streamflow for August 20–22, 1969.

surface to which this process is effective is unknown; it is assumed to be about 5 feet for purposes of this study. Evapotranspiration from the saturated zone acts primarily, therefore, upon the approximately 40 square miles where depth to the water table is less than 5 feet (fig. 7).

Average total evapotranspiration in the Little Falls area is calculated to be about 22 inches per year, using the method of Thornthwaite and Mather (1957) and assuming a soil-moisture retention of 4 inches. The fraction contributed by the saturated zone is unknown, but an estimate was made by arbitrarily assuming that 18 inches per year is discharged where the depth to the water table is 0–3 feet, 12 inches per year where depth to water is 3–4 feet, and 6 inches per year where depth to water is 4–5 feet. Based upon this supposition, evapotranspiration removes about 29,000 acre-feet per year from the aquifer.

UNDERFLOW

Underflow, subsurface water that enters or leaves the system in the saturated zone, is relatively insignificant because of the low hydraulic conductivity of most of the material surrounding and underlying the aquifer. Largest quantities are involved where the water-table gradient indicates a significant component of flow through outwash that extends beyond the boundaries of the study area (figs. 5, 8). Subsurface inflow to the system is calculated to be about 2,500 acre-feet per year in the Camp Ripley area and about 1,300 acre-feet per year at the extreme southern boundary of the area, west of the Mississippi River. Subsurface outflow from the system is about 2,200 acre-feet per year across the southern boundary east of the Mississippi River. Other underflow is considered negligible.

STEADY-STATE ANALOG MODEL

An electric analog model of the surficial aquifer was employed to simulate the operation of the unstressed or steady-state system. The use of the analog model is based upon the analogy between groundwater flow and the flow of electricity (Robinove, 1962). Analogies exist between transmissivity and electrical resistance, storage and electrical capacitance, head (water-level elevation) and voltage, and water flow and electrical current.

The model is an idealized, two-dimensional representation of the study area constructed at a scale of 1 inch equals 1 mile. It consists basically of a network of resistors whose junctions, or nodes, occur at ½-inch intervals. The magnitudes of the resistors correspond to the magnitudes of transmissivity as described on plate 1*B* and thereby characterize the third dimension of the aquifer. Connected to appropriate nodes of the resistor network are other resistors, whose locations and values are such that current passed through them will represent the desired distribution and quantities of inflow and outflow to the system.

Current passed through the circuitry of the model represents steady-state recharge and discharge of water. The resulting voltage distribution in the network represents the water-table configuration which would be produced by the equivalent aquifer system. Deviations of this voltage distribution from the steady-state water- table configuration (fig. 8) indicate that the system is not correctly simulated. Reasonable modifications in amounts of recharge and discharge are then made until an approximate match between the voltage and water-table configurations is obtained. Most required changes were relatively small; the largest was a modification of the discharge to the Mississippi River. The correct voltage distribution in that area of the network requires a discharge from the aquifer to the river equivalent to about 29,000 acre-feet of water per year. This amount is believed to be more correct than the previous estimate of 43,000 acre-feet per year. Depending upon adjacent water-table gradients and transmissivities, base flow varies along the length of the river from about 200 to 2,000 acre-feet per year per mile.

When the water-table configuration is duplicated by the voltage distribution in the network of the model, the model is verified. That is, it is inferred to be an approximate simulation of the steady-state aquifer system. Consequently, this version of the model is considered to be a useful tool for estimating the future effects of stressing the system.

WATER BUDGET

The average annual water budget of the surficial aquifer system involves about 86,000 acre-feet of water. The quantities exchanged through various means of recharge and discharge are approximately those shown in table 3. Because climatic conditions vary, the water budget changes continuously, and for any given year will likely involve a change in storage rather than equal quantities of inflow and outflow. However, over a long period of time, recharge and discharge tend to compensate each other, and the long-term average annual

TABLE 3.—*Approximate average annual water budget for the surficial aquifer in the Little Falls area*

	Acre-feet per year
Inflow	
Recharge from precipitation	81,000
Underflow	3,000
Recharge from reach of Platte River below Rice Lake	2,000
Total	86,000
Outflow	
Discharge to Mississippi River	29,000
Discharge to other streams and lakes	26,000
Evapotranspiration	29,000
Underflow	2,000
Total	86,000

water budget of the unstressed aquifer system is probably correctly depicted to show little or no change in storage (table 3).

STRESSED SURFICIAL AQUIFER SYSTEM

If natural recharge or discharge of an aquifer system is changed as a result of man's activity, the system is stressed. Withdrawal of water for irrigation is the form of stress with which this study is concerned. To understand the expected response of the system, it is necessary to examine the effects of wells pumping from a surficial aquifer.

EFFECTS OF PUMPING WELLS

The static, or nonpumping, water level in a well completed in the surficial aquifer is at essentially the same depth as the adjacent water table. When pumping begins, the water level declines, establishing a gradient toward the well such that the dewatered part of the aquifer is in the shape of an inverted cone (cone of depression). Assuming an infinite, homogeneous aquifer, the cone of depression expands until the cross-sectional area through which water is flowing toward the well is sufficient to supply the rate being pumped. Depth to the level in the well under this condition is called the pumping water level.

The drawdown at any point within the cone of depression is the difference between the original water table at that point and the level caused by pumping. Theoretical relations between drawdown, unadjusted for dewatering, and distance from a well pumping for 30 days at 300 gpm are shown in figure 12 for various values of transmissivity. Though the curves are based on a well yield of 300 gpm, they are applicable to other yields because of the direct proportion which exists between yield and unadjusted drawdown. For example, if the pumping rate were 600 gpm, the unadjusted drawdown at a given distance would be twice as much as that indicated in figure 12.

Because the aquifer under study is unconfined, drawdowns must be adjusted for the decrease in saturated thickness caused by dewatering (fig. 13). This adjustment is particularly important near the pumped well, where dewatering is greatest. Examples of the use of these graphs are presented later in this section.

Variations from theoretical distance-drawdown relations may occur locally where hydrologic boundaries exist (fig. 14). Expansion of the cone of depression may be slowed or halted where it intercepts a stream or lake. Assuming sufficient hydraulic connection, induced infiltration from the stream or lake contributes some of the water which otherwise would have come from the saturated zone. An opposite effect results if development takes place near a relatively impermeable boundary such as the till which surrounds most of the study area.

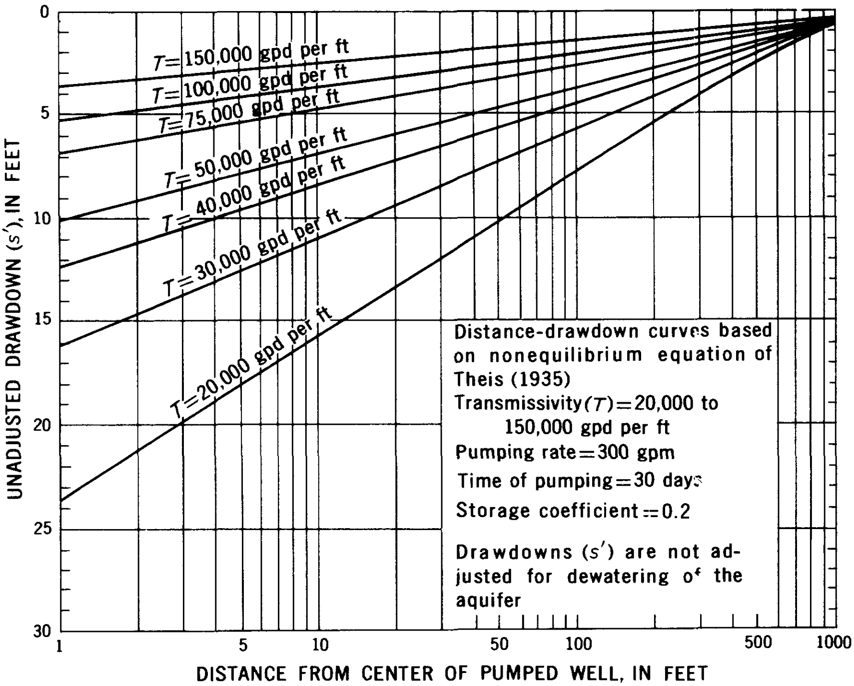

FIGURE 12.—Theoretical relation of drawdown to distance from a pumped well after 30 days of pumping at 300 gallons per minute.

The drawdown under this condition would be greater than if the aquifer had extended beyond the influence of the pumping well.

Increased drawdown also results from interference between wells placed so closely together that their cones of depression overlap (fig. 14). Some interference between wells may take place for optimum development of the aquifer, but significant interference may affect well yields or operating efficiency. Drawdown at a point affected by more than one pumping well is equal to the sum of the drawdowns at that point caused by each well. Predictions as to well interference can therefore be obtained through the use of figures 12 and 13, as illustrated by the following hypothetical problems:

Example 1. Two wells are 600 feet apart. Each pumps 900 gpm from an unconfined aquifer where the saturated thickness is 50 feet, the transmissivity is 75,000 gpd per ft, and the storage coefficient is 0.2. The wells are open to the full saturated thickness and are 100 percent efficient.

a. Find the drawdown midway between the wells after 30 days of pumping.

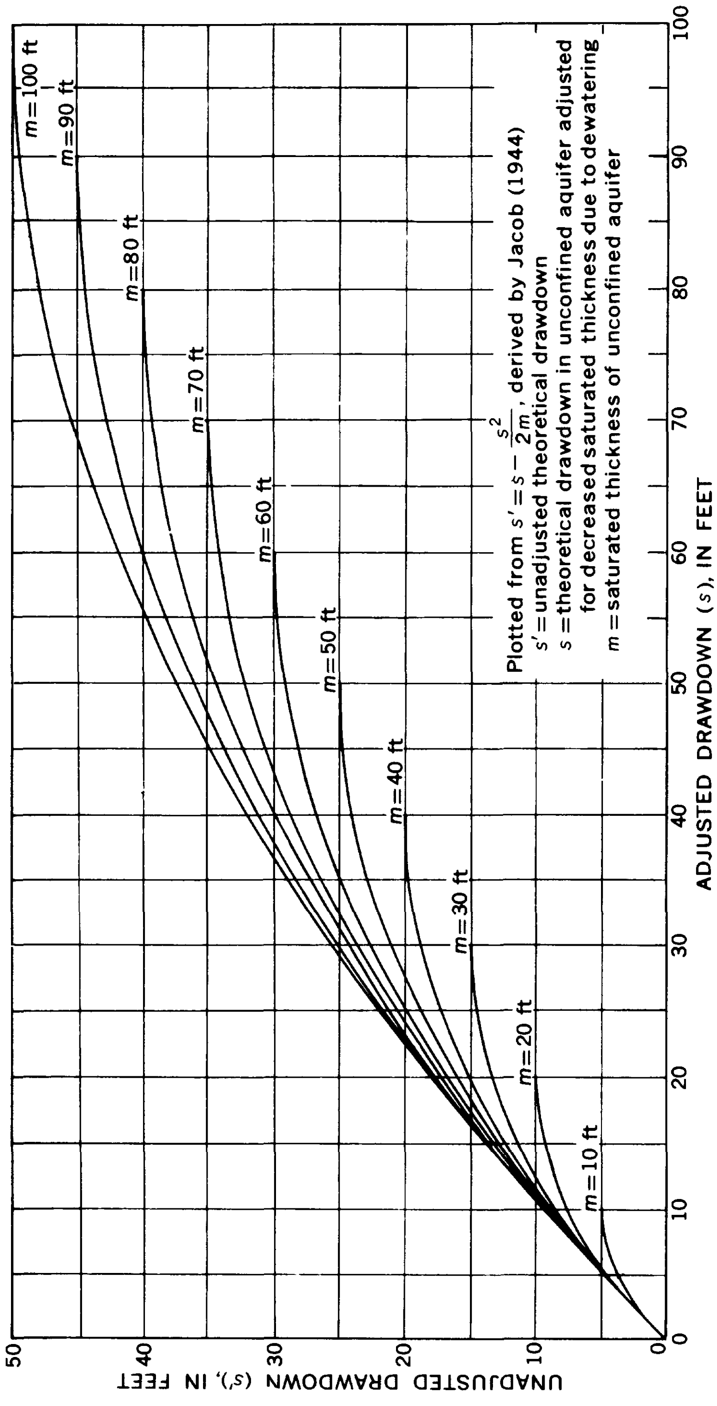

FIGURE 13.—Theoretical curves for adjustment of drawdown to compensate for dewatering of the unconfined aquifer.

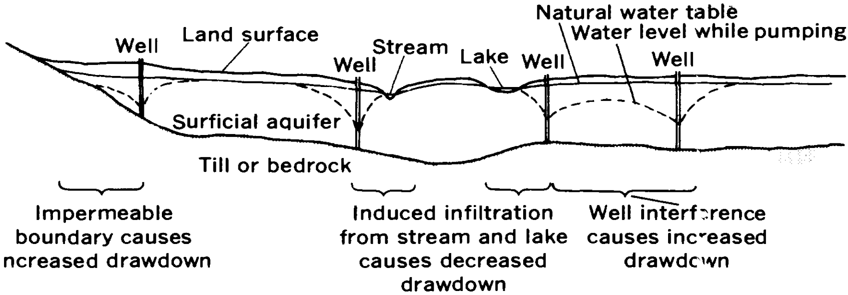

FIGURE 14.—Schematic cross section illustrating effects of nearby wells and natural boundaries on cones of depression.

1. From figure 12, the unadjusted drawdown 300 feet from a well pumping at 300 gpm is about 1.6 feet. Because the wells in question are pumping 900 gpm, the unadjusted drawdown caused by each is about $1.6 \times 3 = 4.8$ feet.
2. From figure 13, the adjusted drawdown caused by each is about 5.0 feet.
3. The drawdown midway between the wells after 30 days of pumping is therefore about $5.0 + 5.0 = 10.0$ feet (the sum of the drawdowns caused by each well).

b. Find the drawdown 1 foot from the center of each well after 30 days of pumping.
1. From figure 12, the unadjusted drawdown 1 foot from each well is about $6.9 \times 3 = 20.7$ feet. From figure 13, the adjusted drawdown is about 29.0 feet.
2. From figure 12, the unadjusted drawdown 599 feet from each well is about $1.1 \times 3 = 3.3$ feet. From figure 13, the adjusted drawdown is about 3.4 feet.
3. The drawdown 1 foot from the center of each well after 30 days of pumping is therefore about $29.0 + 3.4 = 32.4$ feet (the sum of the drawdowns caused by each well).

Example 2. Two wells with anticipated yields of 300 gpm are planned in an area of an unconfined aquifer where the saturated thickness is 30 feet, transmissivity is 50,000 gpd per ft, and the storage coefficient is 0.2. The wells will be open to the full saturated thickness and be 100 percent efficient.

How far apart should the wells be placed if not more than 1 foot of drawdown is desired midway between them after 30 days of pumping?

1. The adjusted drawdown caused by *each* well midway between them is intended to not exceed $\frac{1}{2} \times 1 = 0.5$ feet.

2. From figure 13, the unadjusted drawdown caused by *each* well will also be about 0.5 feet.
3. From figure 12, the distance at which the unadjusted drawdown is 0.5 feet in an aquifer of $T=50{,}000$ gpd per ft is about 1,100 feet (slightly beyond the edge of the graph). The distance between the wells should therefore be at least $1{,}100 \times 2 = 2{,}200$ feet, if the drawdown midway between them is not to exceed 1 foot.

Depending on its pattern and intensity, ground-water pumpage will affect inflow to the aquifer system, outflow from the system, and storage within the system. In areas where water is lost from the aquifer through evapotranspiration, the lowering of the water table caused by pumping may decrease this rate of loss. Consequently, water which would have been discharged from the system by evapotranspiration is available for man's use. Pumpage may similarly intercept water which, in the unstressed system, would have been discharged to streams or lakes. A sufficiently effective influence may directly induce infiltration of surface water, as discussed previously in this section. Development near a permeable boundary of the study area may either increase the natural subsurface inflow or decrease the natural outflow.

Based on the steady-state analysis, 86,000 acre-feet of ground water per year is potentially available for pumpage without a long-term loss in storage. This figure pertains to the aquifer as a whole and does not preclude possible water-table declines resulting from excessive withdrawals in any given part of the study area.

NONSTEADY-STATE ANALOG MODEL

The nonsteady-state analog model of the aquifer system consists of superimposing on the steady-state model an outflow to represent man's withdrawal of water. Resistors installed at 81 nodes form hypothetical pumping centers. Capacitors at each node of the network, corresponding to a storage coefficient of 0.2, simulate changes in storage which result from pumping. Larger capacitors, corresponding to lake volumes, were installed to represent Rice, Skunk, Pierz, Green Prairie Fish, Pelkey, and Mud Lakes.

The model was programed to allow components of the system other than storage also to respond to the imposed stress. It is assumed that of the water being lost from the aquifer through evapotranspiration, an increasing amount can be recovered during pumping until the water table declines to 5 feet below land surface, at which point the rate recovered is a maximum. Current-limiting diodes in the model simulate recoverable quantities, which vary over the study area, depending upon the depth to the nonpumping water table. (See discussion of "Evapotranspiration" under "Recharge and Discharge of Ground Water).'' No water lost to evaportanspiration is considered recoverable where the nonpumping level is deeper than 5 feet.

Current-limiting diodes were also used to represent recoverable discharge to streams, other than the Mississippi River. Quantities of base flow which occur in the steady-state system were assigned as the maximum recoverable. Because of its relatively large flow, the Mississippi River was modeled as a constant-head source, and its contribution to the pumpage was monitored but not limited.

Provisions were made in the model whereby aquifer-storage changes, lake-storage changes, and quantities moving across permeable boundaries to pumping centers were also monitored.

The rates of pumpage applied to the model are commensurate with the approximate well yields expected to be obtained (pl. 1*C*). Different areas of the model were therefore stressed differently, according to the aquifer's theoretical water-yielding capability. No pumpage was applied where the expected well yield is less than 100 gpm. The response indicated by the model is regional in nature and cannot reveal, for example, drawdowns near individual wells. It is assumed that varying the total withdrawal at pumping centers will result in approximately the same regional changes in the system as varying the intensity of development. Thus, a total withdrawal of about 18,000 acre-foot per irrigation season (program 1) is considered to produce effects approximately equivalent to two pumping centers per square mile; a withdrawal of 36,000 acre-feet per season (program 2) approximately equivalent to four pumping centers per square mile; and a withdrawal of 72,000 acre-feet per season (program 3) approximately equivalent to eight pumping centers per square mile.

The irrigation season consists of about 90 days each year. To simulate this cyclical pumping, current pulses are applied to the model at appropriate time intervals (measured in microseconds), and the periods between pulses represent recovery periods of the system. Because actual pumping would not be continuous throughout the irrigation season, withdrawals equivalent to 30 days of pumping were distributed over a period representing 90 days in the model. Simulated response of the system is thereby assumed to be more comparable with that which might be caused by actual pumping practices.

HYPOTHETICAL RESPONSE TO DEVELOPMENT

Analog model programs 1, 2, and 3, were each run for a period simulating 10 years of cyclical pumping. When pumping begins, most water is withdrawn from ground-water storage. As pumping continues

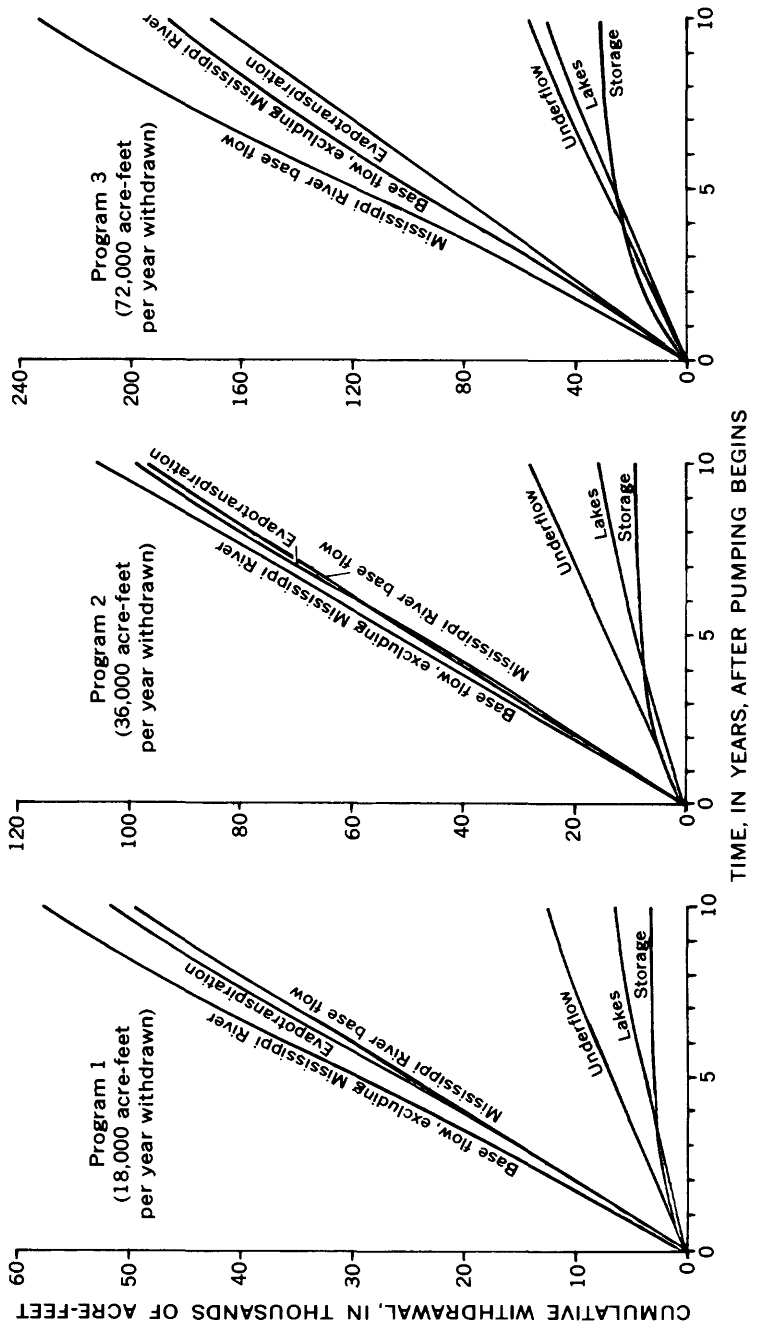

FIGURE 15.—Time-cumulative withdrawal relations for each component of the system simulated in analog-model programs 1, 2, and 3.

(fig. 15), increasing quantities are intercepted from base flow, evapotranspiration, and underflow. Eventually, all water is supplied by sources other than storage, at which time the simulated system has reached a new equilibrium in response to pumping. This equilibrium occurred after about 10 years of pumping for all three programs, as indicated by the flattening of the "storage" curves in figure 15. The total cumulative withdrawal at any time within the 10-year period can be obtained from the graphs by summing the quantities indicated for each individual source. Water which would have been discharged as base flow or evapotranspiration becomes most of the water pumped for all three programs.

In program 1, intercepted base flow (excluding that to the Mississippi River) totals about 29 percent of the steady-state base flow after the 10 -year period. This increases to 52 percent in program 2 and 94 percent in program 3. In program 1, Buckman Creek is the only stream which the model indicates to be losing its entire steady-state base-flow quantity. This suggests the possibility of no flow in that stream during dry periods of the irrigation season. No other stream is indicated as having its entire base flow diverted until program 3, where this situation develops for Two Rivers and Little Rock Creek.

Intercepted base flow from the Mississippi River amounts to about 17 percent of the steady-state value in program 1, 36 percent in program 2, and 83 percent in program 3. Only in program 3 does the model indicate that some reaches of the river contribute more than their respective steady-state base-flow quantities.

Water diverted from discharge as evapotranspiration is 18 percent of the steady-state quantity in program 1, 34 percent in program 2, and 61 percent in program 3.

The model indicates that underflow quantities in the steady-state system are not changed significantly by the programed pumping. Inflow quantities are increased slightly beyond their steady-state values, and natural outflow gradients are not reversed except in program 3.

Lake levels in the study area will decline in response to pumping as modeled. When ground-water flow to lakes is diverted to pumpage, the inflow-outflow balance of the lake is changed. The consequences will be least serious at Rice and Skunk Lakes where stream inflow is important in maintaining lake levels. Because the other lakes are smaller and depend largely on ground water for maintaining levels, they will be more easily depleted.

Rick and Skunk Lakes showed a decline of 0.3 foot in program 1 and 1.0 foot in program 2 over the 10-year period. Pierz and Green Prairie Fish Lakes each showed declines of about 5 feet and 10 feet in programs 1 and 2, respectively. The indication was that the smaller lakes, Pelkey and Mud, would become dry within about the first 5 years of all programs. In program 3, the results indicate total depletion of all lakes within 10 years.

The water table will decline in those parts of the aquifer where recharge is less than withdrawals. This response is illustrated by a hydrograph showing simulated water-table changes at a selected node in the network during program 1 (fig. 16). Decline of the nonpumping level is most rapid during the first few years, then approaches a new level of equilibrium. Figure 16 indicates a nonpumping level decline of about 0.8 foot at the end of the first recovery period, and about 1.3 feet after 5 years when a new equilibrium for that program of pumping has been reached. The model indicates that equilibrium is attained in all three programs within 5 years in most areas.

Figures 17, 18, and 19, show simulated regional static water-table declines after 10 years of pumping as modeled. Because all areas of the network are at or near equilibrium by this time, later changes are relatively small. These maps identify areas where regional water-level declines might become of concern as a result of withdrawals as programed. Where lowering of the water table becomes significant (greater than, perhaps, 10 percent of the original saturated thickness), well yields may be affected. According to the model, water-table declines may not be a problem anywhere as a result of the hypothetical withdrawals in program 1 (fig. 17). In program 2 (fig. 18), excessive lowering is indicated just south of Little Falls, southeast of Skunk Lake, and in a few smaller areas. Effects of pumping are most pronounced in program 3 (fig. 19), and the most serious water-table de-

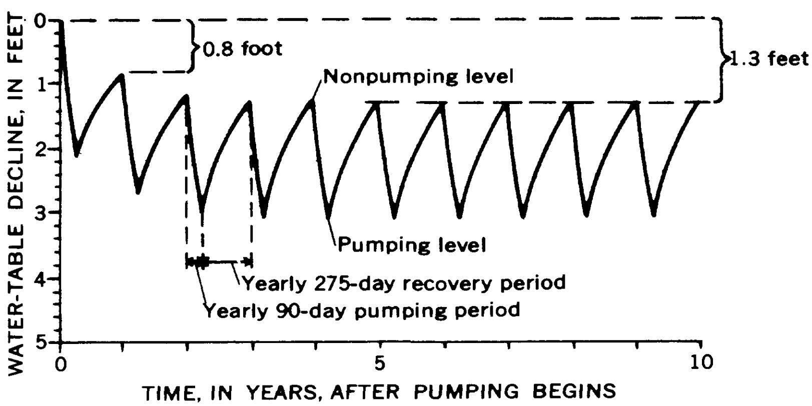

FIGURE 16.—Example hydrograph showing response of water table to cyclical pumping simulated in analog-model program 1.

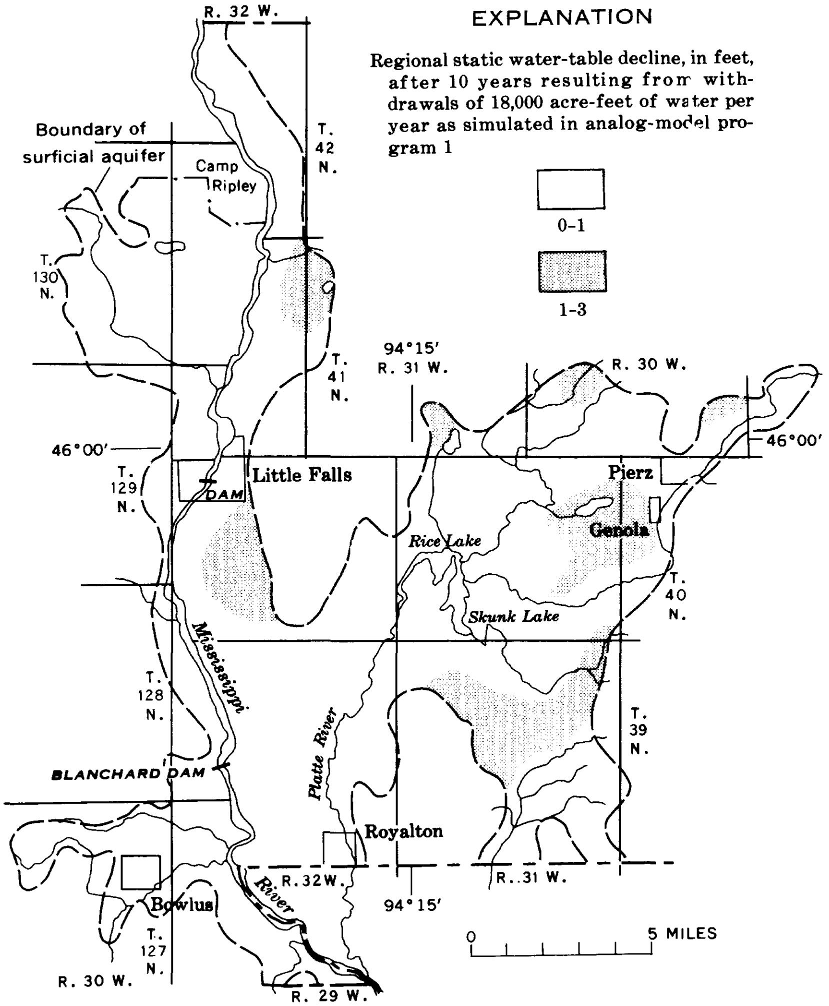

FIGURE 17.—Regional static water-table declines resulting from withdrawals simulated in analog-model program 1.

clines are indicated just south of Little Falls, near Bowlus and Elmdale, northeast of Little Falls, and in most of the eastern half of the study area.

DISCUSSION OF RESULTS

The analog model results are intended to be used as a guide in estimating future effects of ground-water development in the study area. Discussed here are several qualifications which must be recognized in interpreting the analyses.

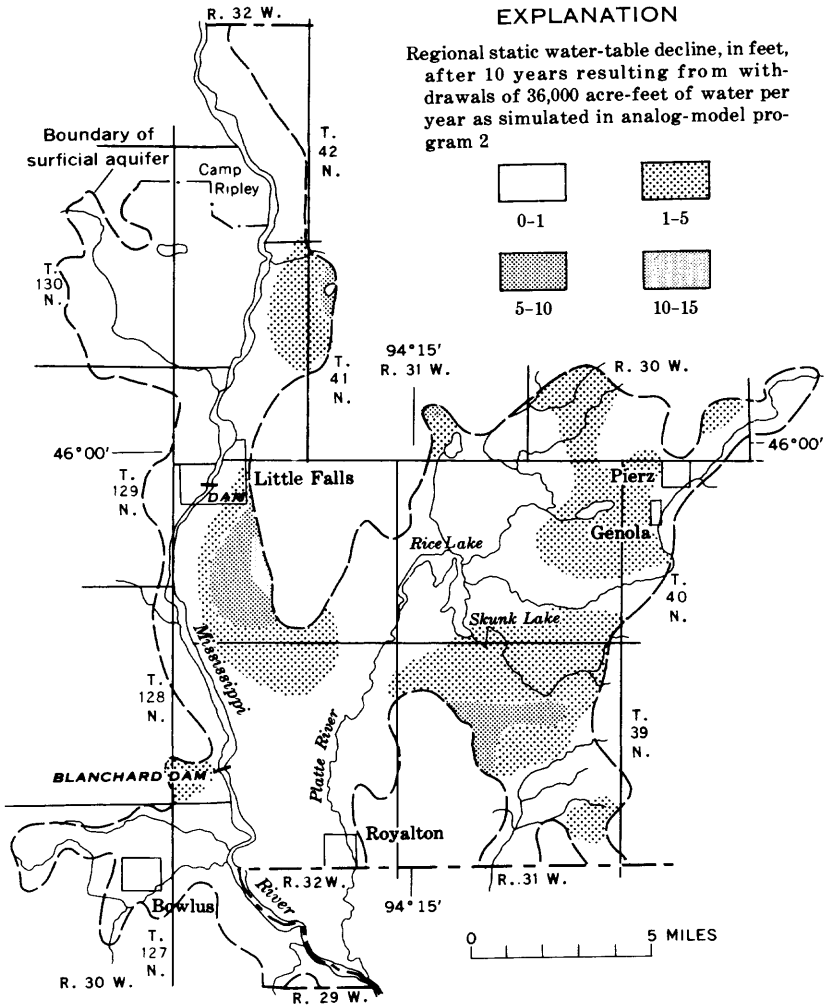

FIGURE 18.—Regional static water-table declines resulting from withdrawals simulated in analog-model program 2.

Simulated pumping has been imposed on a model of a steady-state system, the magnitude and distribution of whose components are considered long-term averages. The real aquifer system is subject to continually varying climate and therefore varying recharge and discharge quantities. The application of analog model results must always include considerations of current hydrologic conditions. Several consecutive years of below normal or above normal precipitation, for example, may cause significant water-table changes which need be superimposed on declines caused by pumping.

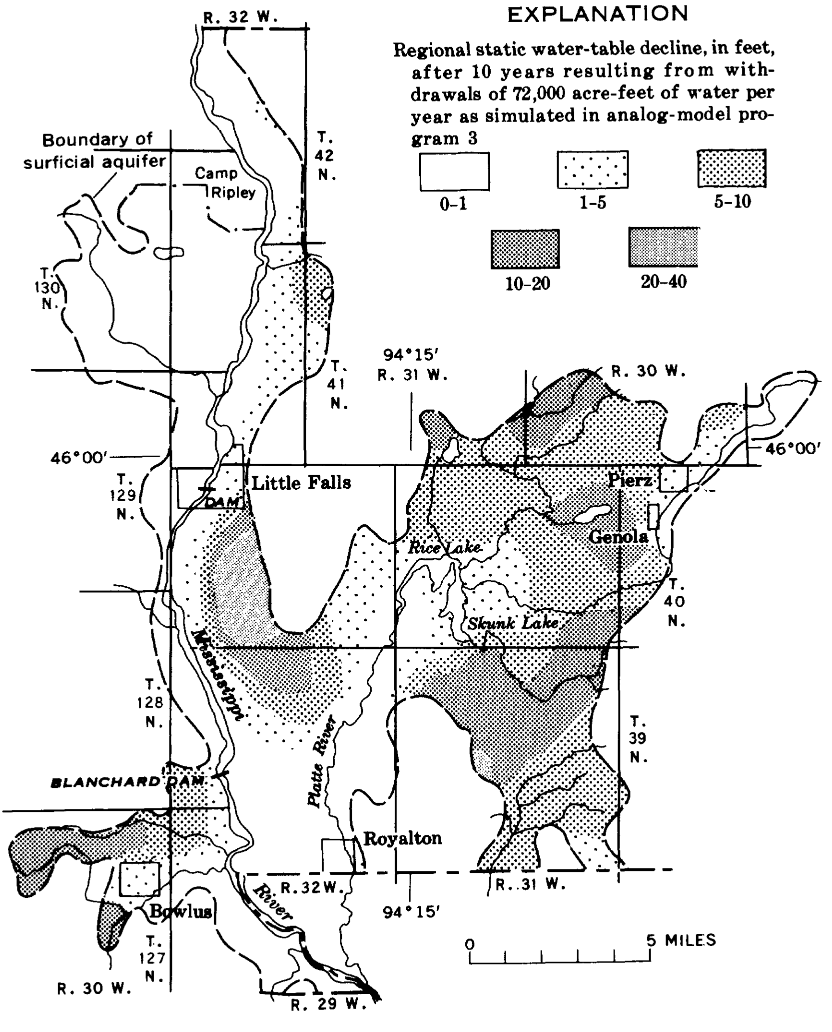

FIGURE 19.—Regional static water-table declines resulting from withdrawals simulated in analog-model program 3.

Also important is the realization that the results presented here apply to selected, hypothetical intensities of ground-water development. Actual irrigation practice will probably develop gradually and at varying densities within the area. Program 3 is assumed to approximately simulate expected withdrawals at eight wells per square mile, a density which is not likely to be exceeded anywhere in the area.

Proximity of individual wells to lakes and streams will be an important factor in determining the response of those features. All simulated lake-volume changes are probably extreme, as pumping centers occur in the model very close to each lake.

The maps of simulated water-table declines (figs. 17, 18, and 19) identify probable areas which will or will not safely support pumpage under the hypothetical development schemes selected. Where potential problem areas exist, excessive water-table declines may be prevented by withdrawing less water than that programed in the model.

It must also be remembered that these analyses apply to the surficial aquifer system as a whole, as the model does not simulate local well hydraulics. The model indicates responses to selected volumes of withdrawal, but the success in obtaining these volumes depends also on local aquifer conditions, proper placement of wells, and proper well construction.

WATER QUALITY

The suitability of the water supply for irrigation depends not only on the quantity of water available but on its chemical quality as well. Dissolved minerals are acquired by water from the soil and rocks through which it moves. Water from the surficial aquifer in the Little Falls area is of the calcium bicarbonate type and is moderately hard to very hard. Important constituents and properties of water samples are given in table 4.

Certain chemical characteristics are of particular interest if the water is to be used for irrigation. Conductivity and sodium-adsorption-ratio are two which may be critical if they are high enough to result in accumulation of salts in the soil (U.S. Salinity Laboratory Staff, 1954, p. 75–79). All samples analyzed showed salinity and sodium concentrations to be within satisfactory limits. Furthermore, precipitation provides sufficient leaching to greatly reduce the danger of detrimental effects in the study area.

Boron, though needed in small amounts for plant growth may be toxic in slightly higher concentrations (U.S. Salinity Laboratory Staff, 1954, p. 75). All samples analyzed in this study contained boron in amounts well below the critical concentrations, even for sensitive crops.

Nitrate, which is a pollutant if present in great amounts, is already present in abnormally high concentrations locally in the study area. Increased use of fertilizers that would probably accompany irrigation might introduce more nitrate into the ground water. The surficial aquifer is unconfined and its susceptibility to pollution from nitrates should be realized.

On the basis of the analyzed samples, water in the surficial aquifer

TABLE 4.—*Chemical analyses of ground water*

[Analyses by U.S. Geological Survey. Constituents

Well	Depth of well (ft)	Date of collection	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)
39.31.23 add	12	4-29-70	13	0.92	0.93	64	16	26	5.1	156	0
39.32.26 abc	61	4-28-70	16	.01	0	42	11	2.8	1.3	154	0
40.31.26 dca	24	4-29-70	24	.07	.02	20	6.0	9.1	4.9	83	0
40.31.32 ccc	12	4-29-70	17	.03	.03	42	8.5	17	0.8	153	0
40.32.29 cbb	14	4-28-70	16	.01	.08	55	14	5.7	5.9	162	0
41.30.35 ddd	18	4-29-70	16	.08	.41	52	16	5.8	4.4	232	0
41.31.36 aaa	45	4-29-70	17	1.6	.18	26	11	4.3	1.0	88	0
41.32.34 ddc 4	100	4-28-70	21	7.4	1.9	48	14	8.0	12	224	0
42.32.14 bbc	30	4-27-70	18	.56	.01	39	9.1	2.5	1.4	139	0
127.29.27 bad	68	4-28-70	16	.82	.36	39	22	6.9	3.8	219	0
127.30.13 bbb	16	4-28-70	22	2.6	.29	66	14	4.8	8.5	274	0
130.29.18 ddd	21	4-27-70	9	2.3	.27	26	7.1	3.3	2.3	128	0

is considered suitable for irrigation. Because of the changes in water chemistry and soil conditions that could develop from irrigation, monitoring of the water quality is advisable.

SUMMARY

Bedrock in the Little Falls area is composed almost entirely of metamorphic and igneous rock types and contains relatively small amounts of ground water. The bedrock surface slopes generally southward and lies at depths of 0–150 feet below the land surface.

Glacial drift contains the more productive sources of ground water in the area. It consists partly of gray till, deposited by the Wadena Lobe, overlain by brown till, deposited by the Pierz Sublobe. Buried within the till are outwash bodies which, though presently undelineated, may yield water supplies adequate for irrigation in some areas.

The most readily available source of ground water in the study area is surficial outwash. This unit consists mostly of moderately well to well-sorted sand and gravel. Water in the aquifer is primarily unconfined. Some of the thickest outwash (about 100 ft) occupies a channel cut into bedrock, probably by glacial meltwaters as they drained southward roughly parallel to the present Mississippi River. Here, and in a *from the surficial aquifer in the Little Falls area*

in milligrams per liter (mg/l), except as indicated]

Alkalinity as $CaCO_3$, total	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Phosphorus as P, total	Boron (B)	Dissolved solids, residue	Hardness as $CaCO_3$		Sodium-adsorption-ratio	Specific conductance (micromhos at 25°C)	pH	Temperature (°Celsius)	Color
								Total	Noncarbonate					
128	31	35	0.2	96	0.03	0.05	438	228	100	0.75	577	8.0	10.0	5
126	22	3.0	.3	8.5	.03	.01	198	150	24	.10	298	7.9	8.5	0
27	14	6.8	.2	65	0	.02	194	75	48	.46	218	7.7	6.5	0
125	14	7.2	.2	33	.02	.02	228	140	14	.63	334	8.1	------	0
133	22	9.4	.2	68	.01	.03	311	197	64	.18	437	7.9	9.0	5
190	18	3.4	.3	1.1	.02	0	241	196	6	.18	386	8.2	6.0	5
72	16	3.2	.3	45	.01	0	167	108	35	.18	226	8.0	9.0	0
184	3.0	20	.3	1.9	.03	.01	244	179	0	.26	397	8.3	11.5	5
114	8.3	2.8	.2	21	.01	.08	172	135	21	.09	267	7.9	9.0	5
180	22	4.0	.2	.1	0	.01	226	190	10	.22	370	8.3	10.5	5
225	16	1.4	.2	.1	.11	0	278	223	0	.14	441	8.1	6.0	5
105	1.7	1.4	.2	.1	.02	.01	132	94	0	.15	199	7.9	6.5	2

few smaller areas, well yields exceeding 1,000 gpm are possible. In more than two-thirds of the study area, expected well yields from the surficial aquifer are generally less than 300 gpm, probably not sufficient for irrigation from individual wells.

It is estimated that an average of 86,000 acre-feet of water moves through the surficial aquifer system annually. Most recharge to the system is provided by precipitation. Discharge occurs mostly as evapotranspiration, base flow to the Mississippi River, and base flow to other streams and lakes.

Analog-model analyses in which each area is stressed in accordance with expected well yields indicate that most pumpage would be derived from intercepted base flow and evapotranspiration. The aquifer system will safely support a sustained withdrawal of 18,000 acre-feet of water per year as simulated in program 1. Withdrawals of 36,000 and 72,000 acre-feet per year (programs 2 and 3, respectively) are indicated to cause excessive water-table declines in some parts of the study area. The analyses also showed that significant lake-level declines are possible from extensive ground-water development near lakes. Most streamflow is not expected to be seriously depleted except in a few smaller streams in response to the largest programed withdrawals.

Application of analog results to actual ground-water development must always include considerations of current climatic conditions, local aquifer conditions and well hydraulics, and differences between actual patterns of development and the hypothetical situations upon which these analyses were based.

Chemical quality of water in the surficial aquifer is considered satisfactory for irrigation use.

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Contributions to the Hydrology of the United States, 1971

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2009

This volume was published as separate chapters A–D

UNITED STATES DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

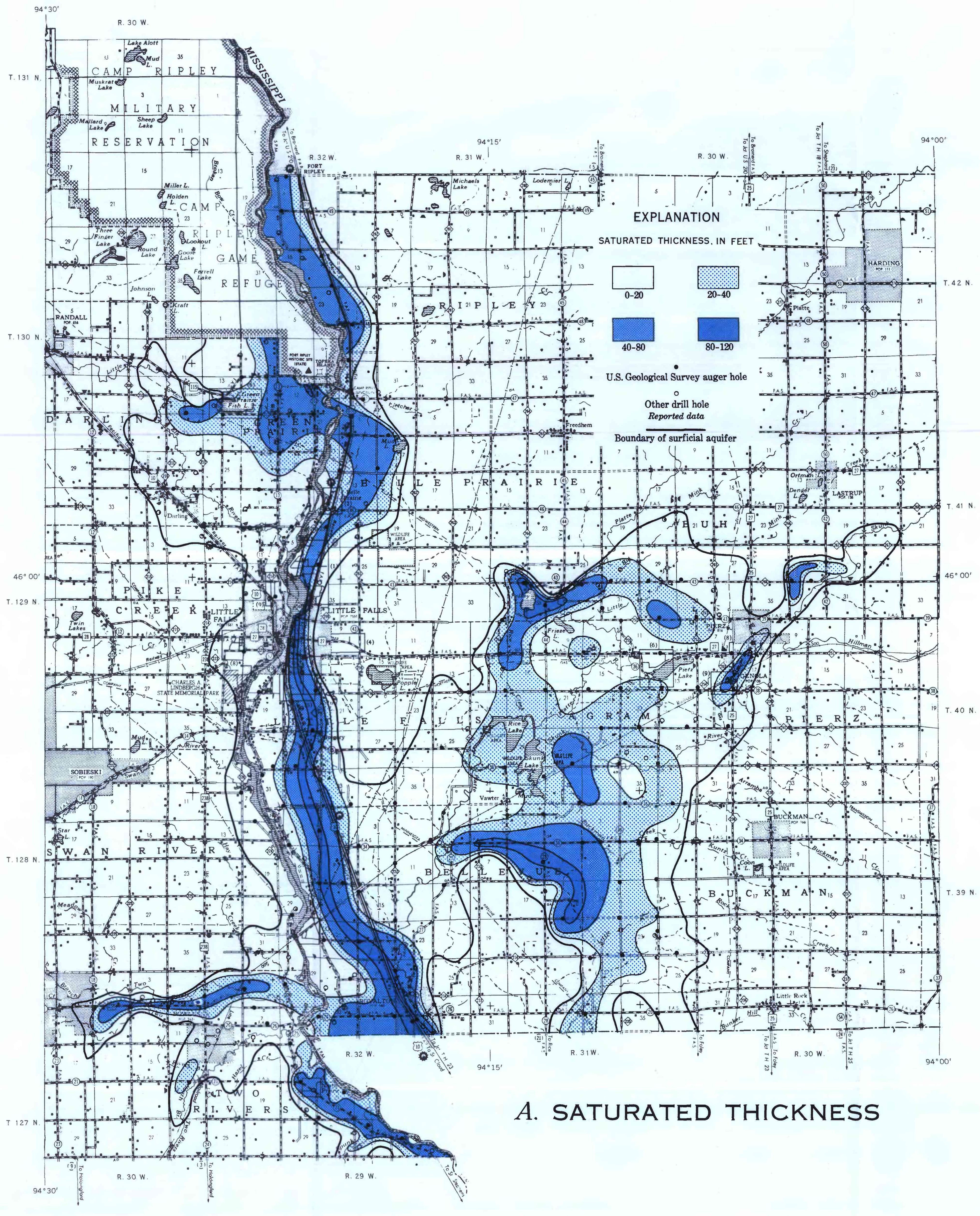
CONTENTS

[Letters designate the chapters]

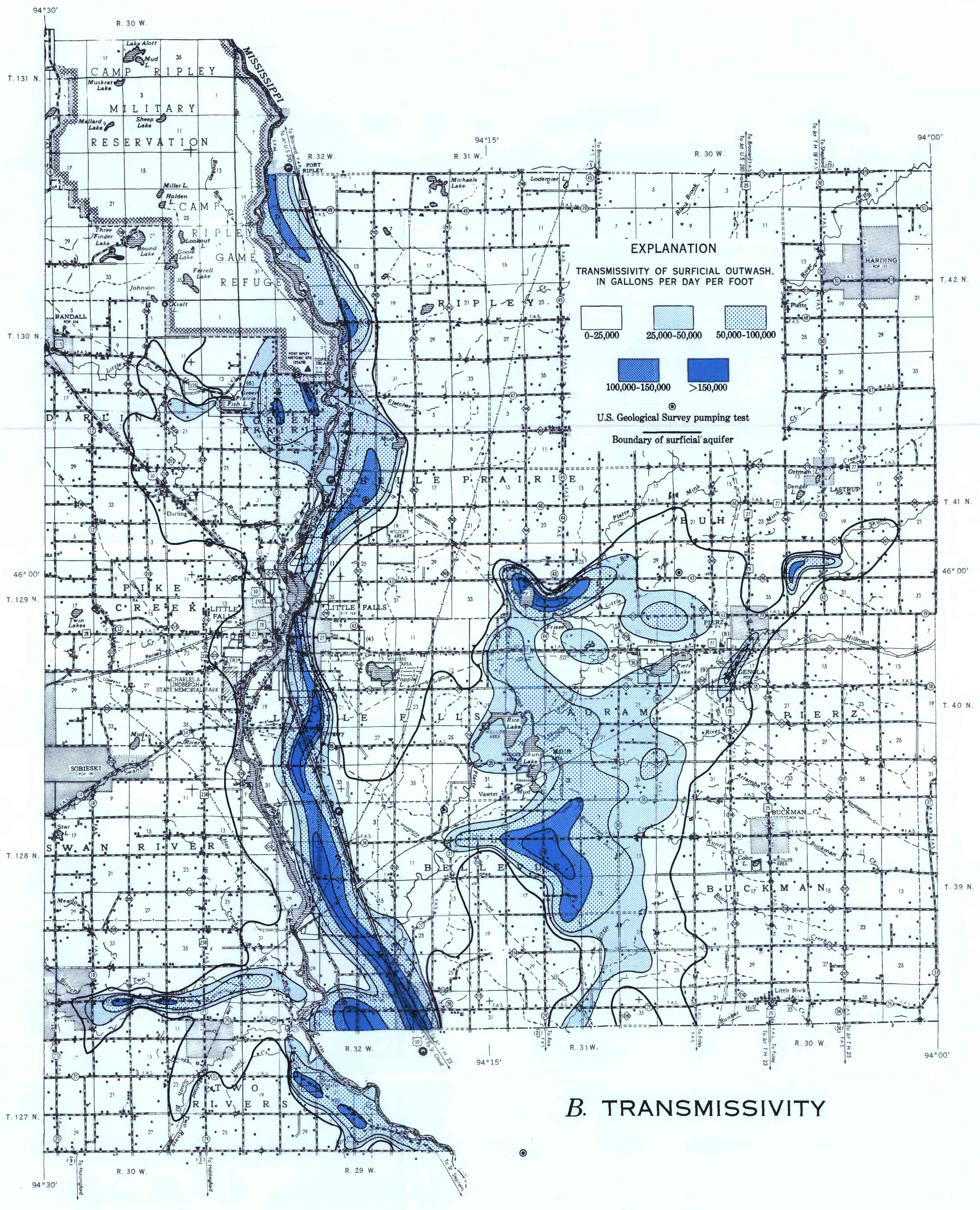
U.S. GOVERNMENT PRINTING OFFICE: 1973 O—490-09?

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

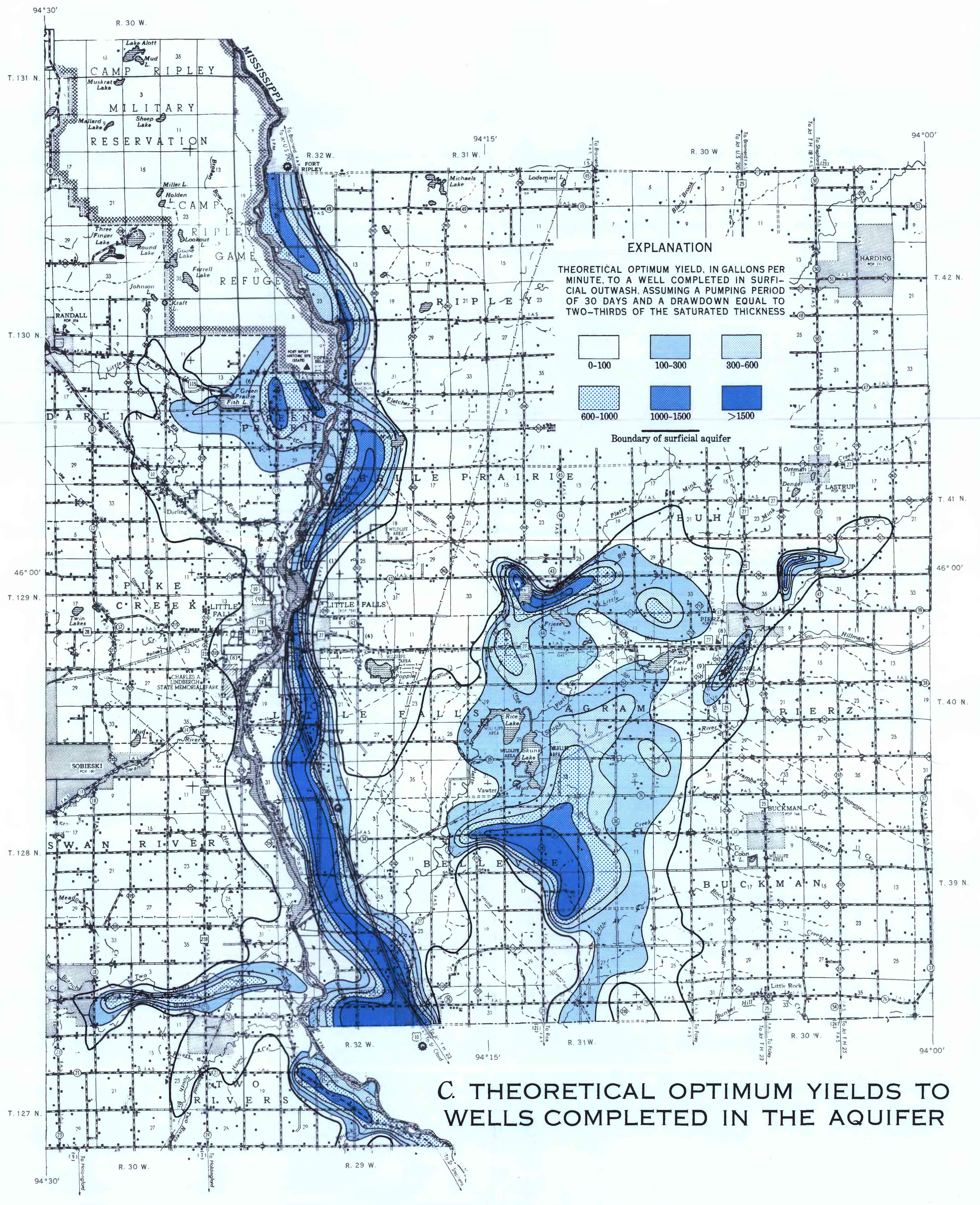
PREPARED IN COOPERATION WITH THE
MORRISON COUNTY SOIL AND WATER CONSERVATION DISTRICT
AND THE
MINNESOTA DEPARTMENT OF NATURAL RESOURCES,
DIVISION OF WATERS, SOILS, AND MINERALS



A. SATURATED THICKNESS



B. TRANSMISSIVITY



C. THEORETICAL OPTIMUM YIELDS TO WELLS COMPLETED IN THE AQUIFER

Base from Minnesota Department of Highways
General Highway Map of Morrison County,
1963, 1:63,360

2 1 0 2 4 6 8 10 MILES
2 1 0 2 4 6 8 10 12 14 KILOMETERS

HYDROLOGIC MAPS OF THE SURFICIAL AQUIFER, LITTLE FALLS AREA, MORRISON COUNTY, MINNESOTA