Ground Water for Irrigation in the Brooten-Belgrade Area, West-Central Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1899-E

Prepared in cooperation with the West-Central Minnesota Resource Conservation and Development Committee and the Minnesota Department of Conservation, Division of Waters, Soils, and Minerals

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By WAYNE A. VAN VOAST

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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GROUND WATER FOR IRRIGATION IN THE BROOTEN-BELGRADE AREA, WEST-CENTRAL MINNESOTA

By Wayne A. Van Voast

ABSTRACT

Water for irrigation is needed to improve crop yields from sandy soils in the Brooten-Belgrade area. Ground-water supplies of sufficient quantity and suitable quality for irrigation are available in much of the area.

Quaternary glacial drift, as much as 300 feet thick, is underlain by Precambrian crystalline rocks and possibly by Cretaceous sedimentary rocks. Sand and gravel aquifers are buried at various depths in the drift and can be located by test drilling. One buried aquifer, possibly capable of high yields, is within 250 feet of the land surface in the vicinity of Belgrade.

Glacial outwash comprises the upper part of the drift in most of the project area and is locally more than 100 feet thick. The outwash is made up of cross-bedded sand and gravel that is interbedded in places with silt and clay deposits and has a saturated thickness of as much as 65 feet. Locally, the transmissivity of the surficial aquifer is as much as 60,000 gallons per day per foot, but elsewhere is generally less than 30,000 gallons per day per foot. The aquifer should yield more than 300 gallons per minute and locally more than 1,000 gallons per minute to individual wells in much of the northern and southwestern parts of the area.

Recharge to the surficial aquifer is almost entirely from precipitation. Significant ground-water losses occur as base flow and underflow, and through evaporation and transpiration.

Water in the buried and surficial aquifers is of the calcium magnesium bicarbonate type and is of suitable quality for irrigation.

An analog model, simulating yearly 30-day pumping periods and hypothetical volumes and distributions of withdrawals, showed the effects on the surficial aquifer of withdrawals of about 20,000 acre-feet per pumping season for 20 years. Predicted water-level declines caused by withdrawals of 20,000 acre-feet per pumping season were generally less than 5 feet in the surficial aquifer and years Predicted water-level declines caused by withdrawals of 20,000 acre-feet pumping season caused predicted water-table declines of more than 10 feet in large parts of the area and caused lake-level declines of as much as 8 feet. The model indicated that water removed from aquifer and lake storage accounted

for less than 50 percent of all withdrawals; the remainder was accounted for by water recovered from stream base flow and by water diverted from evaporation and transpiration.

INTRODUCTION

This investigation of the availability of ground water for irrigation in the Brooten-Belgrade area was made by the U.S. Geological Survey in cooperation with the West-Central Minnesota Resource Conservation and Development Committee and the Division of Waters, Soils, and Minerals, Minnesota Department of Conservation. This study is one of several made of the sandy-soil areas in Minnesota, where irrigation, using ground water from surficial aquifers, might feasibly supplement precipitation. Because of the low water-holding capacity of these sandy soils and the fact that rainfall usually is insufficient during the growing season, crop yields generally are poor. The purpose of the study was to investigate the adequacy of ground-water supplies, in both quantity and quality, for irrigation and to predict the effects of future development on the local ground-water system. The results of this study are intended to provide guidelines to local planners and irrigators for optimum development of the area's water resources.

The report area, in west-central Minnesota (fig. 1), is about 120 miles west of Minneapolis and St. Paul. The area occupies about 300 square miles in eastern Pope County, northern Kandiyohi County and southwestern Stearns County. Major towns in the report area are Glenwood, at the west end; Brooten, near the center; and Belgrade, in the east-central part.

The report area includes parts of three watershed units (fig. 1), as outlined by the Minnesota Division of Waters (1959). The northeast corner of the area is drained by Ashley Creek and is part of the Mississippi and Sauk Rivers watershed unit. The eastern half of the area is drained by the Middle and North Forks of the Crow River and lies in the Crow River watershed unit. The western third of the area is drained by the East Branch Chippewa River and is part of the Chippewa River watershed unit.

Farming is the principal occupation in the area; corn, soybeans, and hay are the principal crops. The soils are sandy and are subject to droughtiness and wind erosion. Mean annual precipitation is about 24 inches, about 18 inches of which falls during the growing season (May through Sept.). Average daily maximum temperatures during the growing season vary from about 30°C (86°F) in July to about 13.3°C (56°F) in April.

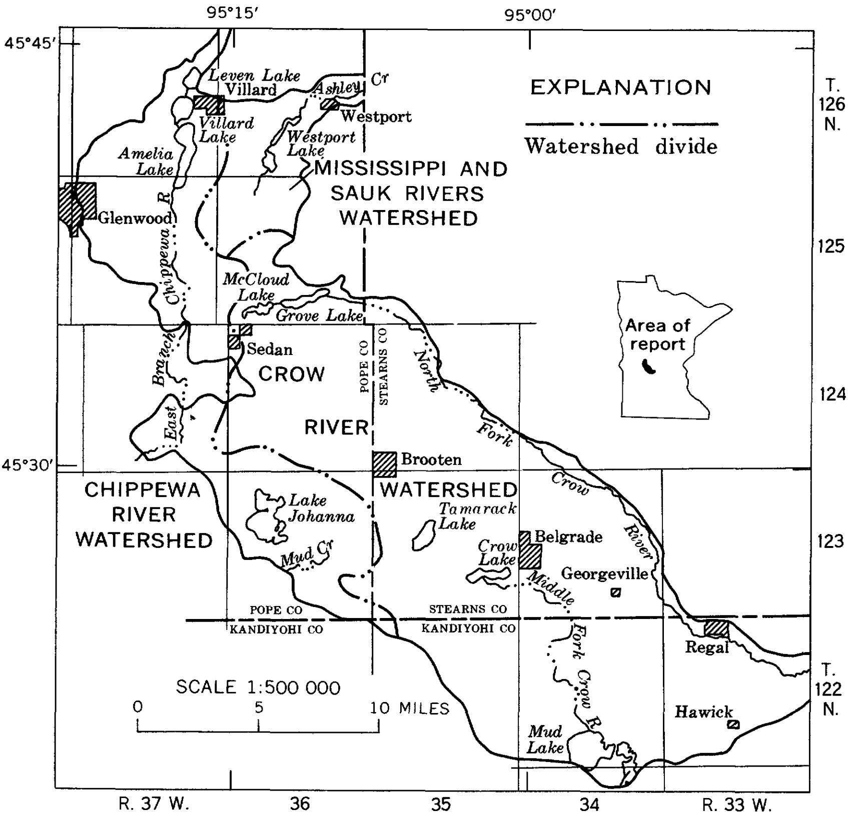

FIGURE 1.—Location of report area and major watershed divides.

PREVIOUS INVESTIGATIONS

The earliest investigation to include the Brooten area was a description of the general geology including some water-well data, by Upham (1888). Reports on the geology and underground waters of southern Minnesota by Hall, Meinzer, and Fuller (1911) and by Thiel (1944) described that part of Kandiyohi County included in the present study. In a report on the geology and water resources of northwestern Minnesota, Allison (1932) described the parts of Pope and Stearns Counties included in the project area. A description of the area is given in Leverett's (1932) report on the glacial geology of Minnesota and adjacent States, and a general description of the geology and water resources of the western third of the report area is included in a hydrologic atlas of the Chippewa River watershed, by Cotter, Bidwell, Van Voast, and Novitzki (1968).

METHODS OF INVESTIGATION

Fieldwork, begun in the summer of 1966, consisted of collecting and studying geologic and hydrologic data pertaining to the area. More than 300 selected irrigation and domestic wells were inventoried, and more than 250 power-auger test holes were drilled in the water-table aquifer. Three deep test holes to artesian aquifers were drilled by the hydraulic rotary method. Aquifer samples were collected, and their geologic characteristics were studied in detail. Altimeter surveys were conducted in areas where accurate topographic coverage was not available to obtain altitudes at test holes and wells. Pumping tests to determine the transmissivity and the storage coefficient of the water-table aquifer were conducted at four locations.

Continuous records of water-table fluctuations were collected at five observation wells during the period July 1966 to June 1968. Precipitation during the 1967 growing season was recorded at seven places for comparison with water levels in observation wells. Base flow in all streams in the area was determined by measurements in August 1967.

More than 60 partial chemical analyses of water from surficial and buried aquifers were performed by field personnel. Nine complete chemical analyses of water were made by the water quality laboratory of the U.S. Geological Survey at Lincoln, Nebr.

An electrical analog model of the surficial aquifer was constructed, using aquifer characteristics determined from field data. The model was subjected to hypothetical pumping situations in order to predict water-table responses to future withdrawals.

TEST-HOLE NUMBERING SYSTEM

The system of numbering test holes and wells is based on the U.S. Bureau of Land Management's system of subdivision of the public lands. The Brooten-Belgrade area is in the fifth-principal-meridian and base-line system. The first segment of a well or test-hole 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 test hole is situated. The lowercase letters a, b, c, and d, following the section number, indicate the well 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 2 illustrates the method of numbering a test hole. Thus, the number 125.35.8ddb1 identifies the first well or test hole located in the NW¼SE¼SE¼ sec. 8, T. 125 N., R. 35 W.

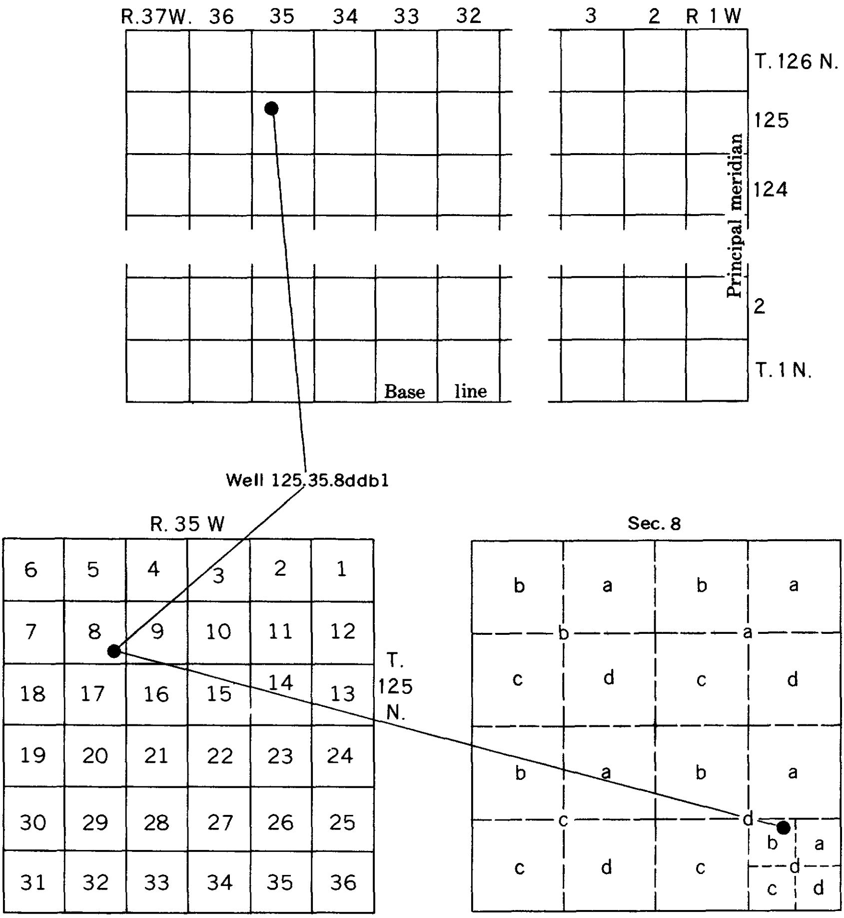

FIGURE 2.—Well and test-hole numbering system.

ACKNOWLEDGMENTS

The author thanks the many residents and well drillers who provided information and assistance. Special acknowledgment is given to irrigators who assisted with pumping tests and to residents who recorded precipitation data during the study.

GEOLOGY

BEDROCK

Crystalline rocks of Precambrian age form the basement complex in the study area. The rocks are granitic, and locally their upper surface is weathered to a soft kaolinitic clay. The basement rocks do not crop out in the report area, but there are numerous exposures 2 miles east of Westport. According to well data presented by Allison (1932, p. 172), granite lies 296 feet below the land surface at the east edge of Glenwood, and at least 225 feet below land surface 5 miles east of Sedan.

Sedimentary rocks of Cretaceous age may be present in the report area. Where identified in west-central Minnesota, the Cretaceous rocks are soft, blue and black shale interbedded with poorly consolidated siltstone and sandstone. The rocks originated as deposits of mud, silt, and sand deposited by a shallow sea transgressing from the west in Late Cretaceous time. From fossil evidence in southwestern and west-central Minnesota, these rocks have been correlated with the Upper Cretaceous Colorado Group (Sloan, 1964). Where present in other parts of Pope, Stearns, and Kandiyohi Counties, the Cretaceous rocks directly overlie the Precambrian basement complex, and are of various thicknesses, generally less than 100 feet. Thiel's (1944, p. 241) geologic map of subsurface rock formations shows Cretaceous rocks in all of northern Kandiyohi County, but no indication of their presence was found in data collected for this report. Test holes drilled in this study indicate that Cretaceous rocks, if present in the Brooten-Belgrade area, lie at depths greater than 200 feet below the land surface.

GLACIAL DRIFT

Quaternary drift representing the Wisconsin Glaciation forms the land surface in the project area (pl. 1, map *A*). Pre-Wisconsin drift may be present in the subsurface. The glacial deposits directly overlie Cretaceous sedimentary rocks, if and where present, and the Precambrian basement complex. Thickness of the glacial drift is unknown, but it is at least 200 feet in most of the area, and almost 300 feet at Glenwood. The drift is of three main types: till, an unstratified unsorted mixture of clay, silt, sand, and gravel deposited directly by glacial ice; outwash, beds of sand and gravel deposited by melt waters of glacial ice; and lake deposits, beds of clay and silt deposited by ponded waters along the ice margin.

Most of the report area is an outwash plain formed by glacial melt waters along the northeast margin of the Des Moines lobe of glacial ice (Leverett, 1932) which advanced southeastward across western Minnesota. As the lobe advanced, it modified a preexisting southward drainage formed on older glacial drift. The topography of the report area, prior to this final glaciation, resembled that shown in figure 3. Drainage was mainly to the south and southwest, and local relief was slight. The Des Moines lobe blocked the flow of the established streams along the southwest edge of the area, causing ponding and the deposi-

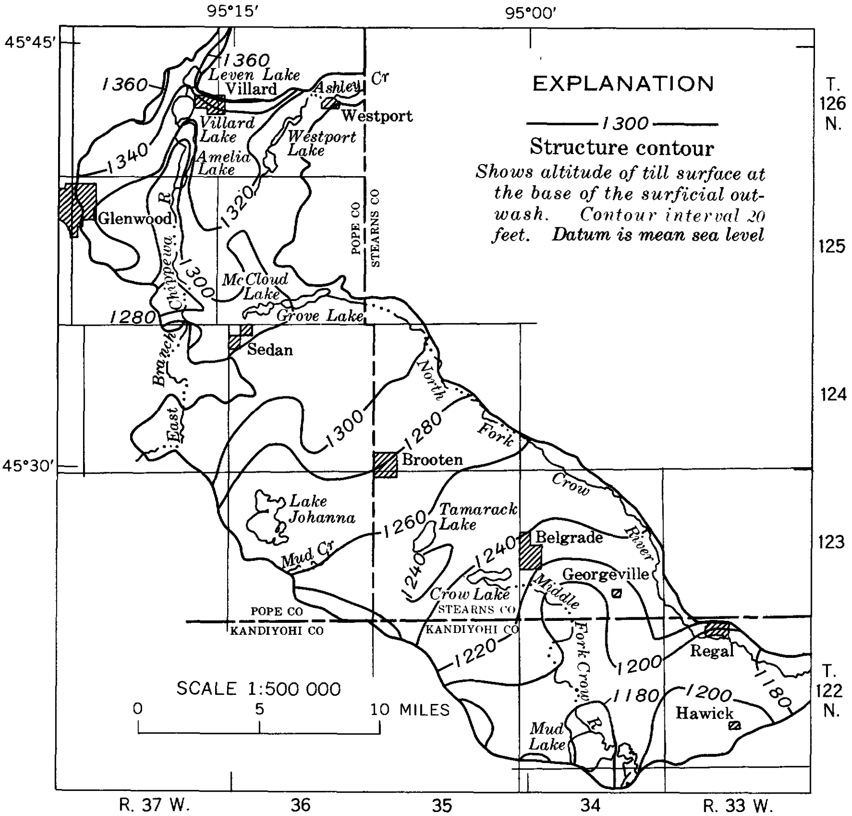

FIGURE 3.—Configuration of the drift surface at the base of the outwash.

tion of silt and clay interbedded with outwash sand and gravel. In the early stages of melting, most water flowed southeastward along the ice face. Subsequently, where sufficient outwash and lake deposits had accumulated, drainage in the northern part of the area was reversed such that melt water flowed northeastward by way of a channel at Westport. A small area near Villard and another near Sedan (pl. 1, map *A*) were above the level of the melt waters and now stand as islands of till completely surrounded by outwash. Along the West Branch Chippewa River, and in the southwestern part of the area, the outwash is interbedded with thin deposits of clay and silt and is as much as 100 feet thick. However, in most of the report area, its thickness is less than 30 feet.

The depositional history of the outwash suggests grain-size-distribution relationships that are verified by test-hole data: (1) sediments along the southwest edge of the outwash plain are mostly fine grained where they were deposited in areas of restricted drainage; (2)

sediments overlying the fine-grained deposits are coarse because of their nearness to the ice lobe and because drainage was established to the north and east; (3) sediments in the rest of the area are also coarse, particularly in channels where melt-water discharge was high, such as at Westport and near Regal.

GROUND-WATER OCCURRENCE

Ground water may be defined as all water that lies within the saturated zone—the zone in which geologic materials are saturated with water under hydrostatic pressure. The upper surface of the saturated zone is termed the "water table." The occurrence and movement of ground water is influenced by many things, including precipitation, streamflow, geologic conditions, and plant life. Under natural conditions, the ground-water system is in a state of dynamic equilibrium, continually recharging in some places and discharging in others, but always maintaining a balance between input and output. The source, or input, of almost all ground water is precipitation. The ground-water reservoir is recharged directly by infiltration of rainfall and snowmelt. Much water in the system is lost to the atmosphere through the processes of transpiration and evaporation. Seepage to streams and rivers, termed "base flow," can also account for significant losses from the ground-water system.

Water is stored within spaces between grains which make up geologic materials. The ratio of volume of spaces to the total volume of the material, expressed as a percentage, is known as porosity. All geologic materials are porous to some degree. The volume of water that geologic materials can release from, or take into, storage per unit of aquifer surface per unit of change in head is known as the storage coefficient. The capacity to transmit water is termed "hydraulic conductivity" and depends upon the size of the pore spaces and their degree of interconnection. Hydraulic conductivity, as used in this report, is defined as the flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 15.6° C (60° F).

In the project area geologic materials of significant permeability include sand and gravel and, where saturated with water, will be referred to herein as aquifers. Less permeable materials in the area are granitic rock, till, silt, and clay.

In aquifers that are confined at their upper surface by poorly permeable strata, water is under hydrostatic pressures that are generally greater than atmospheric pressure. In a well that is finished in a confined aquifer, the water level is higher than the top of the aquifer and can be higher than the land surface. When water is pumped from a confined aquifer, the aquifer remains saturated. Water is yielded because of its own expansion and because of compression of the aquifer due to the reduced pressure.

In aquifers not confined by overlying strata, the hydrostatic pressure is approximately equal to atmospheric pressure at the surface of the saturated zone or water table. In wells finished in unconfined aquifers, the water will stand at the same level as the water table. When water is pumped from an unconfined, or water-table, aquifer, ground water moves to the well mainly by gravity drainage toward an unsaturated cone of depression created on the water table.

In the project area, ground water occurs under both confined and unconfined conditions. The surficial outwash over most of the area is a water-table aquifer, although beds of silt and clay locally confine the system. The outwash deposits buried in glacial drift and the Cretaceous sandstone aquifers, if present in the area, hold water under confined conditions.

AQUIFERS IN THE BROOTEN-BELGRADE AREA

BURIED AQUIFERS

As a part of this study, three rotary test holes were drilled to provide information on aquifers buried in or beneath the glacial drift (fig. 4). Data from rotary test drilling (table 1) indicated that buried deposits of sand and gravel are common in the glacial drift. The water-yielding capacity of the buried aquifers varies locally, but in at least one of the test holes (123.34.22dbd), buried sand and gravel probably is sufficiently thick and permeable to yield the quantity of water considered necessary for irrigation (more than 300 gallons per minute). Test hole 124.37.27daa penetrated 32 feet of buried sand and gravel which may also be capable of high yield. Data from domestic and municipal wells may indicate the areal extent of the aquifers. For example, well-bottom altitudes in the vicinity of Brooten and Belgrade (fig. 4) correspond generally to the base of the sand and gravel in test holes 123.34.22dbd and 124.34.20bcd. Hydrologic data on the domestic wells are not available, but the municipal wells at Brooten and Belgrade reportedly are capable of prolonged yields in excess of 300 gpm (gallons per minute). Static water levels in deep wells are lower than the water table by 5 to 15 feet, indicating that the buried aquifers may be recharged at least partly by water from the surficial aquifer.

Confined aquifers are present beneath much of the project area. Although many of them may not yield water in sufficient quantity for irrigation, they can be considered as potential sources to at least augment water supplies from the surficial outwash.

SURFICIAL OUTWASH AQUIFER

The main objective of this study is to evaluate for irrigation purposes the water resources of the surficial-outwash aquifer which covers most of the project area (pl. 1, map *A*). The upper limit of the aquifer is the water table, and its base is glacial till. It is bounded by poorly permeable till on the north and northeast, and by ice-contact sand and gravel of generally high hydraulic conductivity on the south and southwest. The mapped geologic contact between the ice-contact deposits and the outwash aquifer is based upon soil types and surface topography; however, this contact is not a hydrologic boundary because water moves freely from one unit to the other.

The water table in most parts of the project area is within 20 feet of the land surface (pl. 1, map *B*). Along the west and southwest boundaries, the depth to water is generally greater because of local topographic relief. In this area the outwash plain was deeply dis-

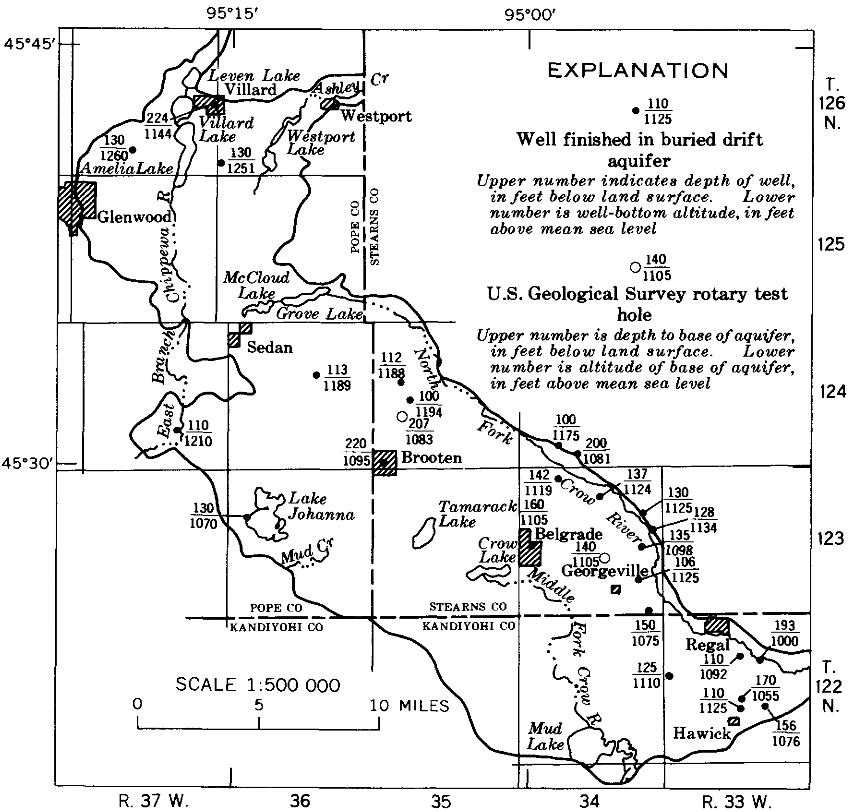

FIGURE 4.—Locations, depths, and bottom altitudes of deep test holes and wells.

TABLE 1.—*Logs of test holes penetrating buried sand and gravel deposits in the Brooten-Belgrade area*

Unit	Thickness (ft.)	Depth (ft.)
Test hole 123.34.22dbd		
[Altitude 1,245 feet above mean sea level]		
Sand, medium to very coarse, yellow	26	26
Till, very sandy, gray	22	48
Sand, very fine to very coarse, gravelly, gray	17	65
Till, very sandy, pebbly, medium-gray	27	92
Sand, coarse to very coarse, very clean, gravelly	48	140
Till, sandy, gray	31	171
Sand, coarse, clean, gray	5	176
Sand, fine to medium, gray	20	196
Till, sandy, yellow	6	202
Till, smooth, dark-gray-brown	7	209
Test hole 124.37.27daa		
[Altitude 1,320 feet above mean sea level]		
Sand, very fine to fine, yellow	24	24
Sand, very fine to medium, gray	26	50
Till, very sandy, silty, dark-gray	28	78
Sand, medium to very coarse, gravelly, yellow	32	110
Till, sandy, light-gray	72	182
Sand, medium to very coarse, gray	4	186
Sand, very fine to medium, gray	8	194
Till, sandy, medium-gray	10	204
Test hole 124.35.20bcd		
[Altitude 1,290 feet above mean sea level]		
Sand, fine to very coarse, yellow	18	18
Till, silty, sandy, gray	27	45
Sand, very fine to medium, gray	11	56
Till, sandy, pebbly, light-gray	79	135
Sand, fine to medium, yellow, clean	9	144
Till, sandy, gray-green	12	156
Sand, coarse; interbedded with green clay	14	170
Till, sandy, pebbly, yellow	23	193
Gravel, medium, clean	14	207
Till, yellow	2	209

sected by glacial melt waters, and remnants of the original surface lie as much as 50 feet above the water table. Between the topographic highs are low marshy areas in channels cut by ancient streams.

Ground water moves laterally through the surficial aquifer following the water-table gradients shown on plate 1, map *C*. Most flow is parallel to the gradient of the land surface, and the major ground-water divides correspond to surface drainage divides between the Chippewa, Crow, and Sauk River watersheds. Ground water flows to the streams from divides and from topographic highs along the north and northeast boundaries. Most of the ground water not lost to evapotranspiration leaves the area as streamflow (pl. 1, map *D*). The greatest groundwater contributions to streamflow occur along the West Branch Chippewa River and the Middle Fork Crow River. Lesser ground-water contributions to streamflow occur along Ashley Creek, Mud Creek, and the North Fork Crow River.

Saturated thickness of the outwash varies from less than 10 feet along the north and northeast boundaries of the area to approximately 60 feet along part of the southwest boundary and locally along the West Branch Chippewa River (pl. 2, map *A*). Clay and silt beds in the outwash in Glenwood Township (T. 125 N., R. 37 W.) locally are as much as 30 feet thick, but in most of the project area they are less than 10 feet thick. The clay and silt beds generally lie below the water table and are apparently fairly continuous within the areas outlined.

The aquifer is composed of stratified and crossbedded sand and gravel ranging in grain size from very fine sand to very coarse gravel (Wentworth scale). A map of the transmissivity of the aquifer, based on thickness and grain-size data from test holes is shown on plate 2, map *B*. Hydraulic conductivities of materials were estimated by correlating grain-size information and using the hydraulic conductivity values (table 2), in gallons per day per square foot, determined by Emery (1966).

The transmissivity was estimated by multiplying the saturated thickness by the hydraulic conductivity value at each data point. Transmissivities estimated by this method were compatible with computed transmissivities from controlled pumping tests and with transmissivities based on specific-capacity information. Plate 2, map *B*, shows that the highest transmissivity values are in the interglacial valley along the present course of the West Branch Chippewa River, and along the southwest border of the outwash plain. In these areas, materials are generally finer grained than elsewhere, but saturated thicknesses are greater (pl. 2, map *A*). Silt or clay lenses in these areas cause local artesian conditions. Because the confining beds of relatively low hydraulic conductivity are not extensive, recharge to the aquifer is not greatly retarded.

TABLE 2.—*Hydraulic conductivity values used in the estimation of transmissivity of the surficial aquifer*

[After Emery (1966)]

Material [1]	Hydraulic conductivity (gpd per sq ft) [2]
Clay and silt	0– 100
Sand, very fine, silty	100– 300
Sand, fine to medium	300– 400
Sand, medium	400– 600
Sand, medium to coarse	600– 800
Sand, coarse	800– 900
Sand, very coarse	900–1, 000
Sand and gravel	1, 000–2, 000

[1] Classifications based on the Wentworth scale of grain sizes.
[2] Gallons per day per square foot.

Storage coefficient for the water-table aquifer was not determined because sufficient aquifer-performance data was not available. However, the storage coefficient for the water-table aquifer probably is about 0.2, a reasonable value for unconfined aquifers. A storage coefficient for an artesian aquifer tested at well 125.37.23abb was computed to be 0.0003.

To relate transmissivity values to computed ground-water yields, a map of potential well yields was constructed (pl. 2, map *C*). The values were calculated using the nonequilibrium model of ground-water flow formulated by Theis (Wenzel, 1942), and they represent the theoretical maximum possible yields for 30 days of continuous pumping with drawdowns limited to about two-thirds of the aquifer thickness. When drawdown equals two-thirds of the aquifer thickness, about 90 percent of maximum yield is being obtained, and the well is being pumped at maximum efficiency Edward E. Johnson, Inc., 1966, p. 108). In calculation of values for use on plate 2, map *C*, interference between wells was assumed to be negligible, and drawdowns at the wells were corrected for decreasing transmissivity due to dewatering of the aquifer (Jacob, 1944). It should be noted that 30 days of continuous pumping is a stringent condition with present irrigation practices in the Brooten-Belgrade area and probably would be necessary only in abnormally dry years. Further, local exceptions to the yield values shown will be common because of local variations in transmissivity. The map is intended to show only the relative differences in water-yielding capacity for general areas.

The highest yields (pl. 2, map *C*) are likely to be obtained along the West Branch Chippewa River in Glenwood Township and along the southwest border of the project area in Lake Johanna and Colfax Townships. In the areas north of Sedan and southwest of Brooten and Belgrade, yields of at least 100 gpm should be available to properly constructed wells. In a large area between Sedan and Regal, mostly northeast of State Highway 55, the thin saturated thickness of the aquifer will limit well yields to less than 100 gpm.

In areas where maximum yields of less than 300 gpm are indicated on plate 2, map *C*, unless local exceptions are found, prospective irrigators will probably have to rely upon multiple-well systems or pits dug in the surficial aquifer or must try to get additional water from deeper aquifers buried in or beneath the glacial drift.

WATER QUALITY

Ground water in the Brooten-Belgrade area is of the calcium magnesium bicarbonate type (table 3). The quality of water in artesian aquifers (wells 122.36.14dcb and 124.37.6aad) is similar to that in the

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TABLE 3.—*Laboratory chemical analyses of ground water in the Brooten-Belgrade area*

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

Well location	Depth of well (ft)	Date of collection of sample	Temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (residue on evaporation at 180°C)	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Sodium-adsorption-ratio (me/l)[1]	Specific conductance (micromhos at 25°C)	pH
122.36.14dcb	83	Aug. 26, 1965	8	99	26	13	5.4	447	0	16	0.4	0.3	2.1	0.12	412	356	0	0.3	669	8.1
124.37.6aad	327	Aug. 28, 1965	------	44	29	31	1.8	339	9	1.2	2.0	.4	6.5	.15	317	229	0	.9	519	8.4
122.33.17ddd	25	Feb. 6, 1968	8	60	23	2.3	1.7	219	0	15	7.1	.0	52	.10	282	243	64	.1	477	7.3
122.35.13acc	20	Feb. 6, 1968	9	85	23	2.3	2.4	284	0	31	2.5	.0	49	.02	356	308	74	.1	570	7.4
123.34.21dbd	25	Feb. 6, 1968	7	85	33	6	19	370	0	101	13	.2	.6	.03	464	347	43	.1	782	7.2
123.35.19cdd	40	Feb. 6, 1968	8	90	28	2.9	4.1	424	0	2.7	2.1	.1	.3	.02	375	341	0	.1	628	7.1
124.35.33aaa	15	Feb. 6, 1968	9	98	28	5.7	35	405	0	33	7.2	.1	30	.03	460	357	25	.1	740	7.2
124.36.28ddd	22	Feb. 6, 1968	8	36	7.9	1.6	1.7	------	0	5.5	2.0	.0	2.8	.02	------	122	0	.1	------	7.8
125.36.19bba	35	Feb. 6, 1968	8	128	40	36	11	354	0	51	37	.1	221	.14	724	483	192	.7	1070	7.3
125.36.33dab	33	Aug. 28, 1965	------	72	22	2.8	1.4	245	0	26	7.0	.2	49	.0	327	269	68	.1	511	8.2
126.36.21dbb	26	Feb. 6, 1968	9	75	25	2.9	2.2	293	0	33	11	.0	12	.01	327	290	50	.1	545	7.5
126.37.34ccc	30	Feb. 6, 1968	6	71	22	1.9	4.8	252	0	48	2.8	.0	55	.01	351	269	62	.0	513	7.4

[1] Milliequivalents per liter. Milliequivalents per liter is the milligrams per liter of a dissolved ion divided by the gram-equivalent weight of the ion.

water-table aquifer. Some analyses of water from shallow wells show relatively high concentrations of sulfate, chloride, and nitrate—probably the result of pollution from barnyards or domestic sewage. The nitrate concentrations in five of the analyses are greater than 45 mg/l (milligrams per liter), the maximum limit recommended by the U.S. Public Health Service (1962). Such high concentrations of nitrate may be satisfactory in water for irrigation purposes but can be harmful to infants in the first few months of life. The high concentrations of sulfate, chloride, and nitrate emphasize the susceptibility of the surficial aquifer to pollution from the land surface.

A major concern resulting from irrigation in the area will be the possibility of increased or more widespread pollution in the water-table aquifer from the increased use of fertilizers. Because the water-table aquifer supplies water for domestic use to most farms in the area, irrigators should use care in applying only enough fertilizer for plant nutrition. Chemical analyses of water samples obtained periodically from irrigation and domestic wells would provide the necessary data to warn of any increased pollution.

The chemical suitability of ground water for irrigation purposes is dependent upon the concentrations of dissolved mineral constituents in the water. For ground water of western Minnesota, chemical factors which can be harmful to plant growth include sodium concentration, salinity, and boron concentration.

A danger from excessive concentrations of sodium in irrigation water is the possible reaction of the sodium in soil to reduce infiltration capacity. A parameter used to determine the possible interaction bteween soduim and soil is the sodium-adsorption-ratio (SAR) recommended by the U.S. Salinity Laboratory Staff (1954). The SAR is defined by:

$$SAR = \frac{Na^{+1}}{\sqrt{\frac{Ca^{+2}+Mg^{+2}}{2}}},$$

where the concentrations of the constituents are expressed in milliequivalents per liter.

SAR values calculated for water in the project area are all less than 1.0 (table 3). According to Salinity Laboratory criteria, these waters are suitable for irrigation on most soils, particularly in humid regions, with little danger of the development of harmful amounts of exchangeable sodium.

Salinity or dissolved-solids concentrations can be critical to the growth of certain plants. Of the crops grown presently in the project area, green beans have the least tolerance to salinity. Crops which have a moderate tolerance for salinity and which could be grown in the Brooten-Belgrade area include peas, sweet corn, potatoes, and alfalfa. The common test for salinity hazard in irrigation water is the measurement of specific conductivity of the water.

Waters in and near the project area have specific conductivities between about 300 and 1,100 micromhos per centimeter (fig. 5) and

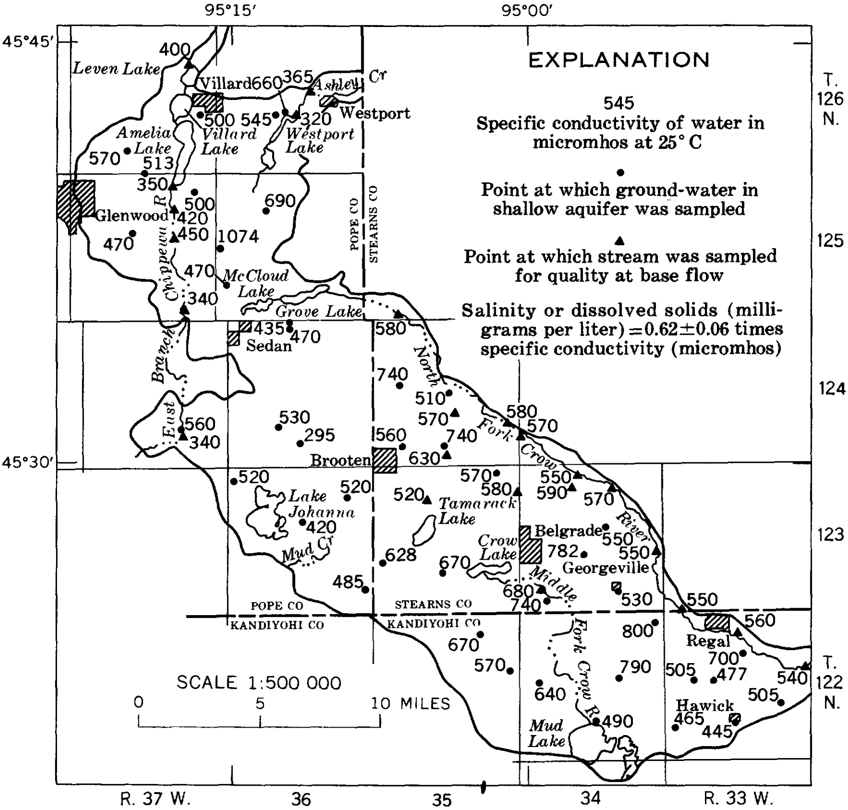

FIGURE 5.—Specific conductivity values of ground water and base flow.

are probably suitable for irrigation in humid areas with little danger to crops (Wilcox, 1955, p. 15, 16).

Relatively low concentrations of boron in irrigation waters can be toxic to certain crops. According to a classification of the tolerance of plants for boron by Wilcox (1955), crops grown in the project area may be sensitive to concentrations greater than about 1 milligram per liter. Table 3 shows the boron content found in water samples from both the buried and surficial aquifers. In none of the analyses was the boron content at a dangerous level, even for sensitive crops.

FUTURE DEVELOPMENT OF THE SURFICIAL AQUIFER

In order to estimate the effects of large withdrawals from the surficial aquifer over prolonged periods of time, an analog model was constructed to simulate the natural hydraulic system. The model was then subjected to possible situations of future ground-water withdrawal. The model, an electrical simulation of the aquifer, was constructed by the analog unit of the U.S. Geological Survey in Phoenix, Ariz., and will be maintained there permanently for future modification and use as more data are collected during actual development of the area's water resources.

CONSTRUCTION AND VERIFICATION OF THE ANALOG MODEL

Construction of the model was based on hydrologic data, including transmissivity and storage-coefficient estimates from test-hole information, streamflow data from base-flow measurements, and recharge values from observation wells. Verification to determine whether the hydrologic data built into the model were representative of actual field conditions was accomplished through the matching of the distribution of electrical potential on the model to the distribution of hydraulic potential (pl. 1, map *C*) in the aquifer. Hydraulic potentials used are those that represent steady-state conditions during which, on a long-term basis, no change in storage occurs. For the steady-state condition in the Brooten-Belgrade area, the distribution and volumes of particular items in the hydrologic budget are shown in figure 6.

Inflow to the system was modeled entirely as precipitation. Other possible types of inflow, such as streamflow and ground-water flow, were assumed to be negligible because no perennial streams enter the area and because no inflow across relatively permeable boundaries is indicated on the water-table map (pl. 1, map *C*). Recharge (inflow) to the aquifer was interpreted from observation-well hydrographs (fig. 7). Water level changes after the spring thaw were multiplied by porosity, estimated to be 0.2, to obtain recharge values, in inches of water. On the example hydrograph, recharge was found to be 0.2 of 2.2 feet, or 5.3 inches.

Outflow from the system occurs as streamflow, ground-water flow (underflow), and evapotranspiration losses. Streamflow leaving the area was modeled according to the base flow, shown on plate 1, map *D*. Ground-water outflow was simulated wherever water-table gradients indicated outflow in relatively permeable materials. Evapotranspiration losses from the water table were approximated by the subtraction of estimated average base flow and ground-water outflow from measured annual recharge. Because the effects of evapotranspiration in the many small lakes and marshy areas cannot be modeled directly, they

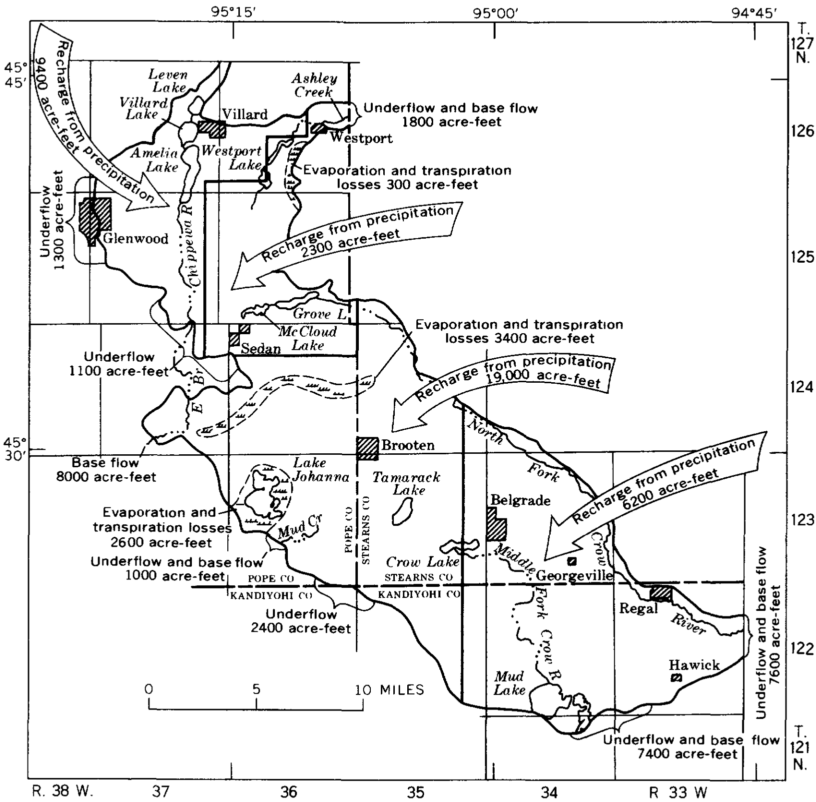

FIGURE 6.—Hypothetical average annual water budget for the surficial aquifer, as simulated by analog model.

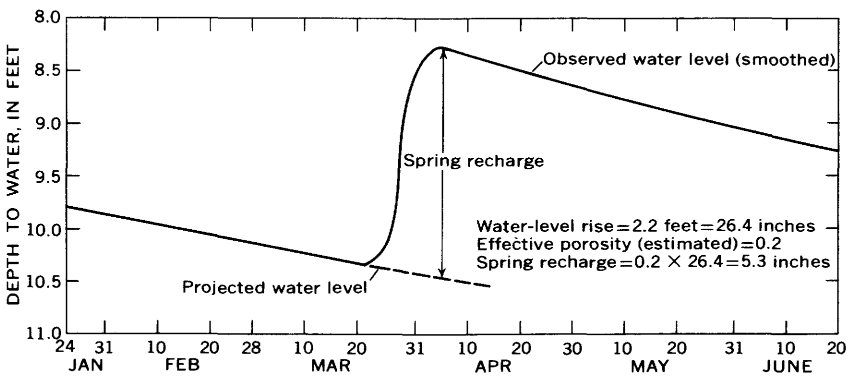

FIGURE 7.—Method of estimation of annual recharge to the surficial aquifer for a hypothetical observation well.

were accounted for in the steady-state model by a reduction in annual recharge. Large marshy areas, such as the one surrounding Lake Johanna (fig. 6), have strong control on the water-table configuration and were modeled directly as ground-water discharge areas.

ANALOG PROGRAM

To simulate possible future pumping conditions on the model, certain assumptions were made regarding the recovery of base flow, ground-water outflow, and evapotranspiration losses. Water now leaving the area as base flow and underflow and through the processes of evaporation and transpiration were assumed to be recoverable as the water table dropped in response to pumping. The model was programed such that base flow and underflow would be recovered and would be available to wells as water-table gradients decreased toward streams or across permeable boundaries. Recovery of water normally lost through evaporation and transpiration was programed in lake and marsh areas.

It was assumed that no water would return to the water table once it had been withdrawn. Actually, some water probably will reinfiltrate to the aquifier and will again be available for withdrawal.

Periods of continuous pumping for 30 days per year were programed. The 30-day period was used to simulate an extreme which may be needed by irrigators during abnormally dry growing seasons. However, during most growing seasons of normal precipitation, irrigation wells in the area are generally pumped for periods of less than 30 days.

Pumping centers simulated in the model represent locales of ground-water discharge, such as wells, groups of wells, infiltration pits, or ponds. The programed withdrawals, reported in acre-feet (acre-ft) per day per square mile (sq mi), correspond to the relative water-yielding capacity of the aquifer indicated on plate 2, may *C*. Three separate programs of withdrawal were modeled (pl. 2, map *D*, parts 1–4). In program 1, withdrawals of 1.3 acre-ft per day (about 300 gpm) per sq mi, 2.6 acre-ft per day (about 600 gpm) per sq mi, and 3.9 acre-ft per day (about 900 gpm) per sq mi, were simulated according to the distribution as shown on plate 2, map *D*, part 1. Increased development was simulated in programs 2 and 3 by increasing all withdrawals to two and four times, respectively, the rates of withdrawal used in program 1.

RESULTS

The analog program described above was designed to indicate water-level changes in response to withdrawals during a 20-year period. A hydrograph (fig. 8) plotted for an area affected by simulated withdrawals indicated that pumping and nonpumping water levels will decline over the 20-year period, and the net effect will be a decrease in the volume of water stored in the aquifer.

Potential errors in analog model results due to scale factors—particularly as related to well diameters—were outlined by Prickett (1967, p. 41). The effective diameter of each pumping center simulated in the model of the Brooten-Belgrade area is nearly 1,000 feet. To minimize possible errors due to the large simulated diameters, water-level declines at pumping centers were disregarded. Also, all measurements of water-level changes were made at the end of the period of water-table recovery in the 20th year (fig. 8). These declines most closely represent actual water-table response to withdrawals and are the least affected by differences in actual and simulated effective pumping-center diameters.

Water-table changes representing the differences between original water levels and water levels after 20 complete cycles of drawdown and recovery are shown on plate 2, map *D*, parts 2–4. The greatest water-level declines are predicted in areas where withdrawals are high and local recharge is not available from streams, marshy areas, or lakes. A large area of no water-table decline occurs along the North Fork Crow River because no withdrawals were programed in that area upstream from Regal. (See pl. 2, map *D*, part 1.) Another area of no water-table decline occurs along a reach of the East Branch Chippewa River in T. 125 N., R. 37 W., probably because of abundant recharge from Lake Amelia and from local marshy areas.

Water-table declines resulting from withdrawals simulated in program 1 are less than 4 feet after 20 years (pl. 2, map *D*, part 2). Withdrawals simulated in program 2 (pl. 2, map *D*, part 3) cause declines

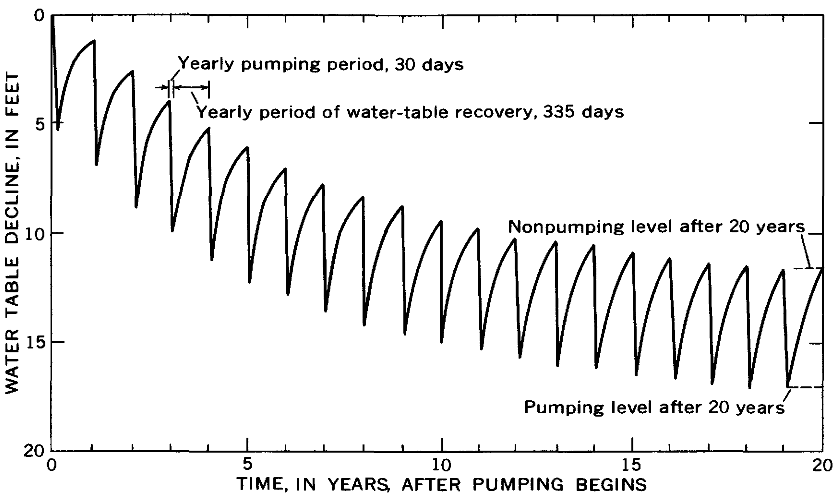

FIGURE 8.—Cycles of drawdown and recovery in an area affected by pumping.

greater than 5 feet locally, where discharge is high, and recharge is not available from lakes and marshes. Withdrawals simulated in program 3 (pl. 2, map *D*, part 4) cause water-table declines of more than 10 feet, which probably result in enough reduction in the saturated thickness to decrease well yields.

Less than one-half of all discharge comes from storage in the aquifer and lakes (table 4). Water diverted from evaporation and transpiration and water salvaged from the streams contribute high percentages of the total withdrawals.

TABLE 4.—*Source and volume of withdrawals from wells tapping the surficial aquifer in the Brooten-Belgrade area after 20 years' pumping, as simulated in analog programs 1, 2, and 3*

[Withdrawal data are given in thousands of acre-feet and in percent for each analog program]

Component of discharge	Withdrawals after 20 years					
	Program 1		Program 2		Program 3	
	Volume (10^3 acre-ft)	Percent of total	Volume (10^3 acre-ft)	Percent of total	Volume (10^3 acre-ft)	Percent of total
Aquifer and lake storage	65	32	160	40	390	49
Diverted from evaporation and transpiration	64	32	110	28	190	24
Salvaged from stream base flow	71	36	130	32	220	27
Total withdrawals	200	100	400	100	800	100

The model indicated that withdrawals in program 1 would include about 40 percent of the available base flow during the 20th pumping season. Withdrawals in programs 2 and 3 would include 100 percent of the available base flow by the 20th year. Streams would be dry during pumping seasons when 100 percent of base flow was recovered but would flow during nonpumping periods, particularly in springtime and early summer.

Water levels in all lakes drop in response to the simulated programs of development. Figure 9 shows the predicted water-level changes in lakes which are considered of local importance for resorts, summer homes, and general recreation. Factors which influence the degree of water-level change in a lake include the volume of water stored in the lake and the magnitude of withdrawals around it. The greatest declines were predicted to occur in Amelia, Westport, Grove, and McCloud Lakes. In these lakes, water-level declines of more than 5 feet are indicated for program 3 (fig. 9). The largest of these, Amelia Lake, stores the most water and is in an area of relatively high simulated withdrawals. The smaller lakes—Westport, Grove, and McCloud—are in areas of lesser simulated withdrawals but would have declines com-

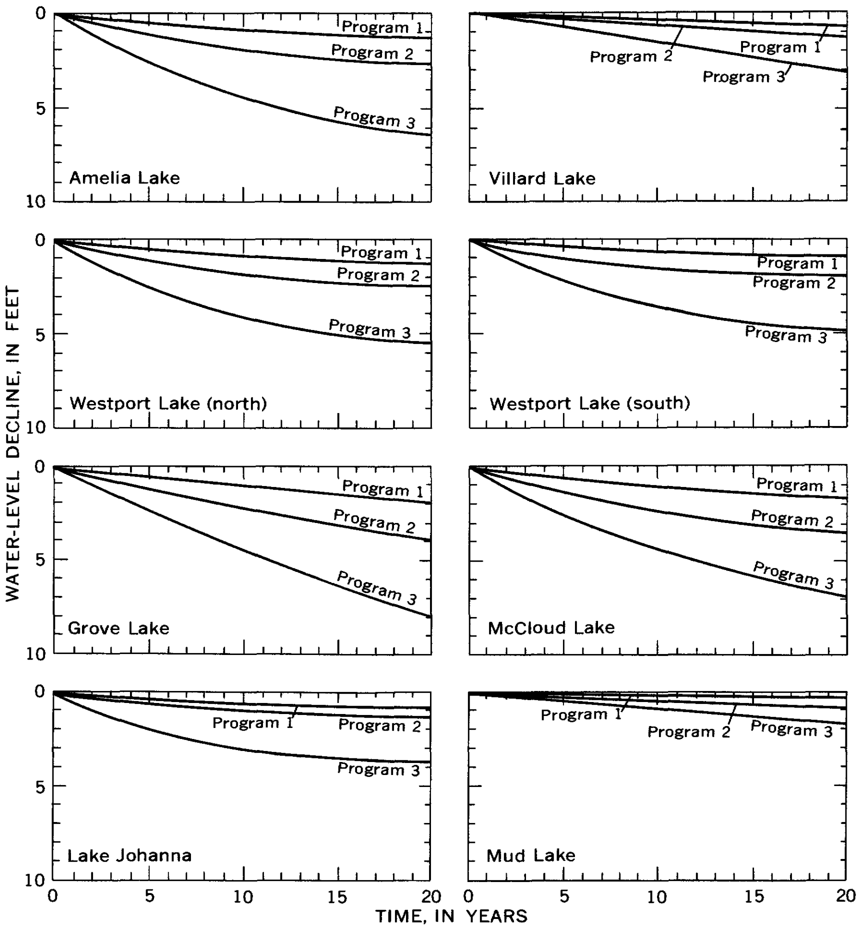

FIGURE 9.—Lake-level declines in response to ground-water withdrawals, predicted by analog model.

parable to that of Lake Amelia because they store less water. In some of the lakes affected by ground-water withdrawals, the rates of water-level decline decrease within the simulated 20-year period. For example, the water level in Lake Johanna appears to be approaching equilibrium almost 4 feet below the original level after 20 years of pumping in program 3.

Rates of decline predicted for Villard and Mud Lakes apparently do not decrease within the 20-year period. During actual development, rates of decline should decrease with time as equilibrium in the ground-water system is approached. Predictions by the model are likely in error for these lakes, probably because of incorrect programing of boundary conditions. Figure 9 probably infers correctly, however, that declines in Villard and Mud Lakes would be small relative to those in other lakes.

EVALUATION OF RESULTS

The water-table aquifer will support withdrawals of the volumes simulated in program 2 (pl. 2, map *D*, part 3) without serious decreases in saturated thickness or declines in lake levels. Withdrawals for program 2 total about 20,000 acre-feet per 30-day pumping season. In specific areas designated on plate 2, map *D*, part 1, withdrawals are about 80, 160, and 240 acre-ft per sq mi for each pumping season. These rates correspond, respectively, to discharges of 600, 1,200, and 1,800 gpm per sq mi. Note, however, that the analog model indicated only that the system would support those volumes of withdrawals and that local well hydraulics were not simulated in the analysis. In most places the aquifer will not yield the programed discharge rates to individual wells. For example, discharges of 1,800 gpm simulated in program 2 are greater than the maximum theoretical discharges for individual wells indicated for corresponding areas on plate 2, map *C*. In those areas, the 1,800 gpm per sq mi could be obtained, depending on local conditions, by a number of wells in each square mile whose combined total discharge equals 1,800 gpm. The map of theoretical maximum yields (pl. 2, map *C*) is intended to be used to determine probable discharges for individual wells and the analog-model results (pl. 2, map *D*) are intended to be used to determine water-table responses to selected volumes of withdrawals.

CONCLUSIONS

In parts of the Brooten-Belgrade area, adequate ground-water resources are available in a surficial aquifer for anticipated irrigation requirements. Additional potential sources are buried at places in the glacial drift and must be located by test drilling. Locations and depths of buried sand and gravel deposits are mostly unknown, but the presence of at least one buried aquifer that may be significant is inferred to be in the vicinity of Brooten and Belgrade.

The surficial aquifer, mainly under water-table conditions, covers most of the project area and is locally more than 50 feet thick. The aquifer is capable of yielding 300 gpm or more of water to wells in most of the northern and southwestern parts of the area.

The quality of ground water in the area is suitable for the irrigation of most crops. The buried and surficial aquifers contain water of the calcium magnesium bicarbonate type that has low sodium and salinity hazards. Boron concentrations are within acceptable limits even for sensitive crops.

Water-level changes predicted by analog model indicate that the surficial aquifer will support withdrawals of about 20,000 acre-ft per sq mi for at least 20 consecutive, abnormally dry growing seasons. Under the same conditions, withdrawals of about 40,000 acre-ft per sq mi per growing season cause serious declines in lake levels and, probably, excessive water-table declines which would result in decreased well yields.

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