GROUND-WATER APPRAISAL OF THE PINELAND SANDS AREA, CENTRAL MINNESOTA

U. S. GEOLOGICAL SURVEY

Water—Resources Investigations 77—102

Prepared in cooperation with

WesMin Resource Conservation and Development Association

Headwaters Resource Conservation and Development Association

Pineland Sands Steering Committee

Minnesota Department of Natural Resources

UNITED STATES DEPARTMENT OF THE INTERIOR

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By John O. Helgesen

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(Plates are in pocket)

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CONVERSION FACTORS

For the convenience of those readers who prefer to use International System (metric) units rather than English units, the conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
inches (in)	25.40	millimeters (mm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
acres	.4047	hectares (ha)
square miles (mi^2)	2.590	square kilometers (km^2)
gallons per minute (gal/min)	.06309	liters per second (L/s)
feet per day (ft/day)	.3048	meters per day (m/d)
feet squared per day (ft^2/day)	.0929	meters squared per day (m^2/d)
cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)

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.

Drawdown. The vertical distance between the static (nonpumping) water level and the level caused by pumping.

Drift. All deposits resulting from glacial activity.

Drumlin. A streamlined ridge of glacial drift with long axis paralleling the direction of flow of the former glacier.

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 Water withdrawn by evaporation from water surfaces and moist soil and by plant transpiration.

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

Hydraulic conductivity. The rate of flow of water transmitted through a porous medium of unit cross-sectional area under a unit hydraulic gradient 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 the volume of water which a saturated rock or soil will yield by gravity to 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.

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ABSTRACT

The Pineland Sands area consists of 770 square miles of surficial glacial outwash, which is undergoing increasing ground-water development for irrigation. The aquifer material is commonly very fine sand to fine gravel, and grain size generally increases from south to north. Thickness, transmissivity, and theoretical well yields are highest in the northern part. In places, saturated thickness exceeds 100 feet, transmissivity exceeds 20,000 feet squared per day, and expected well yields exceed 2,000 gallons per minute.

Water in the aquifer is chemically suitable for irrigation. It is calcium bicarbonate water generally containing dissolved-solids concentrations of 100-300 milligrams per liter.

An estimated long-term water budget for the aquifer involves inflow and outflow of 295 cubic feet per second. Over 80 percent of recharge to the aquifer is directly from snowmelt and spring rain; the remainder is from underflow across the northern boundary of the aquifer and locally from streams and lakes. Over 90 percent of discharge from the aquifer is flow to streams and lakes; the remainder is through evapotranspiration.

A mathematical model of the surficial aquifer was made to facilitate analysis of the hydrologic system. The model was calibrated through simulation of the natural ground-water flow system. Subsequent applications of the model to estimate effects of future ground-water development indicate that much of the system can safely support long-term, large-scale withdrawals.

Results of model analysis show that present development (withdrawals totaling 3.3 cubic feet per second) has no significant effect on the aquifer system. Simulations of hypothetical withdrawals of 60 to 120 cubic feet per second resulted in computed water-table declines as great as 12 feet in places.

Most pumpage is derived from intercepted base flow to streams, thus reducing streamflow. Similarly, some lake levels can be expected to decline in response to nearby intensive development.

INTRODUCTION

The Pineland Sands area is undergoing a substantial increase in irrigation. Without irrigation, the sandy well-drained soils are especially susceptible to crop failure during dry years. Average annual precipitation is 26 inches. Although the average May-September precipitation is 17 inches, its distribution throughout the growing season is commonly unfavorable for crop growth.

Essentially, irrigation has developed since 1965, most of it since 1970. In 1976, 60 irrigation systems were in operation, 45 of which obtained water from wells. The others were supplied from surface-water sources. Twenty-three irrigation wells and three municipal wells (in Park Rapids) withdrew water from an extensive surficial sand and gravel aquifer. This aquifer is also a common source of water for domestic and stock use. Other irrigation wells are completed in buried (deeper) sand and gravel aquifers.

Purpose and Scope

The major purpose of this study is to evaluate the ground-water resources in the Pineland Sands area and their potential for development. The study focuses mainly on the surficial aquifer, the single most readily available source of ground water. Primary objectives of the study are to (1) map the areal extent and thickness of the surficial aquifer, (2) determine its ability to transmit water to wells and define the availability of the water, (3) describe the chemical quality of the water, and (4) model the aquifer and simulate probable effects of future development.

By evaluating the adequacy of the surficial aquifer, this study should aid in the proper development and management of water resources in the Pineland Sands area.

Location and Description of Study Area

The area studied is underlain by 770 square miles of a surficial glacial outwash deposit in Becker, Cass, Hubbard, and Wadena Counties (fig. 1). Its boundary is determined

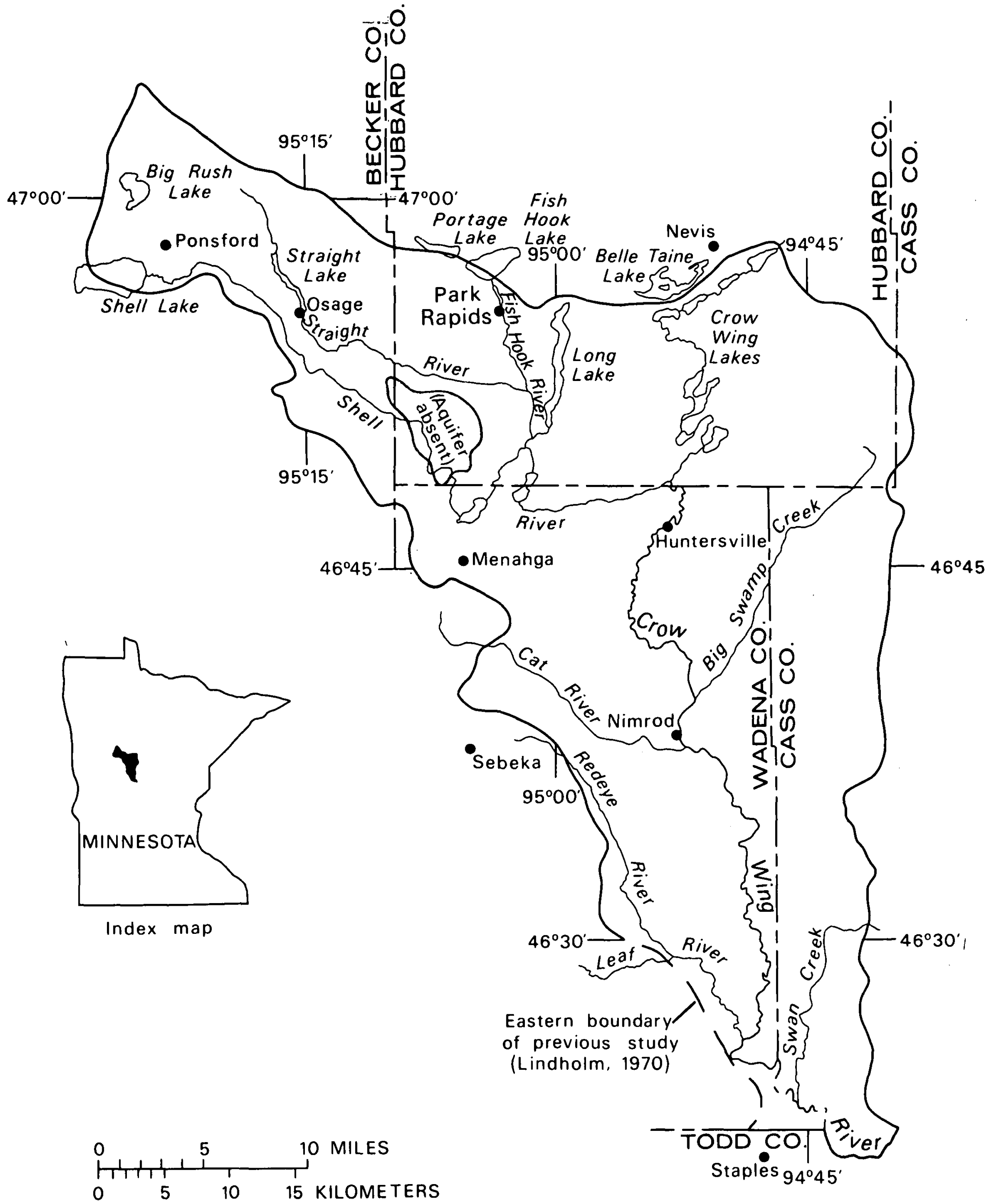


Figure 1.--Location and extent.

mainly by the extent of the outwash. Part of the southwestern boundary, however, coincides with the eastern limit of an area previously investigated (Lindholm, 1970). The Todd County line forms the extreme southern boundary.

The area is drained entirely by the Crow Wing River and tributaries (fig. 1). Lakes constitute 4 percent of the area, mostly in the northern half. Wetlands constitute 12 percent, mostly in the southern half. Most of the remainder is farm land or forest. Principal crops include corn and hay; crops most commonly irrigated are corn, potatoes, and dry edible beans. Water-based recreation is popular, particularly in the north where lake homes are common.

Flat to gently undulating topography characterizes much of the area, though local relief may reach 50 feet near some streams and lakes in the northern half.

Previous Investigations

Early descriptions of geology are presented by Winchell and Upham (1888) and Winchell and others (1899). A general discussion of geology and ground water is included in the work of Allison (1932). Further detail on glacial geology is provided by Leverett (1932), Wright (1962), and Wright and Ruhe (1965). Lindholm (1970) appraised the availability of water from glacial outwash immediately southwest of the present study area. Lindholm and others (1972) reconnoitered the water resources of the Crow Wing River watershed, which includes the entire Pineland Sands area.

Methods of Investigation

Most data were collected and analyzed during a 3-year period beginning in July 1974.

Extent of the aquifer was mapped by field examination of surficial deposits and interpretation of topographic maps (1:24,000 scale) and aerial photographs (1:90,000 scale). Thickness and texture of the aquifer were determined primarily from 330 test holes drilled by power auger. Information describing about 400 other drill holes in the area was collected and analyzed.

Casings were installed in 34 of the test holes to permit observation of water-table fluctuations. Five of the wells were equipped with continuous recorders. Depth to water in one well was measured weekly, and water levels in the remainder were measured monthly. The levels of five lakes were read monthly.

To aid in determining hydraulic properties of the surficial aquifer, 83 sand and gravel samples were collected during test augering and analyzed in the laboratory for particle-size distribution. Also, aquifer tests to determine hydraulic properties were run at four locations. Five series of low-flow stream-discharge measurements were made to define ground-water - surface-water relationships. (Dates of the measurements were Oct. 2-5, 1974; July 28-30, 1975; Oct. 15-16, 1975; June 1-3, 1976; and Sept. 7-9, 1976.) Chemical analyses were made of 29 ground-water samples and 29 stream-water samples (under low-flow conditions).

Simulation of the ground-water-flow system and analysis of probable future effects of pumping was done by digital computer model.

Test-Hole Numbering System

The method of numbering test holes and wells is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The Pineland Sands 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 well is situated. The lowercase letters a, b, c, and d, following the section number, indicate 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 with the northeast quarter. Consecutive numbers beginning with 1 are added as suffixes to distinguish wells within a given 10-acre tract. Figure 2 illustrates the method of numbering. Thus, the number 136.34.10 bcd1 identifies the first test hole or well in the SE¼SW¼NW¼, sec.10, T.136 N., R.34 W.

Acknowledgments

The author is grateful for much useful information furnished by well drillers, well owners, and State agencies. Special thanks are extended to those who gave permission for test drilling on their land, who allowed their wells to be

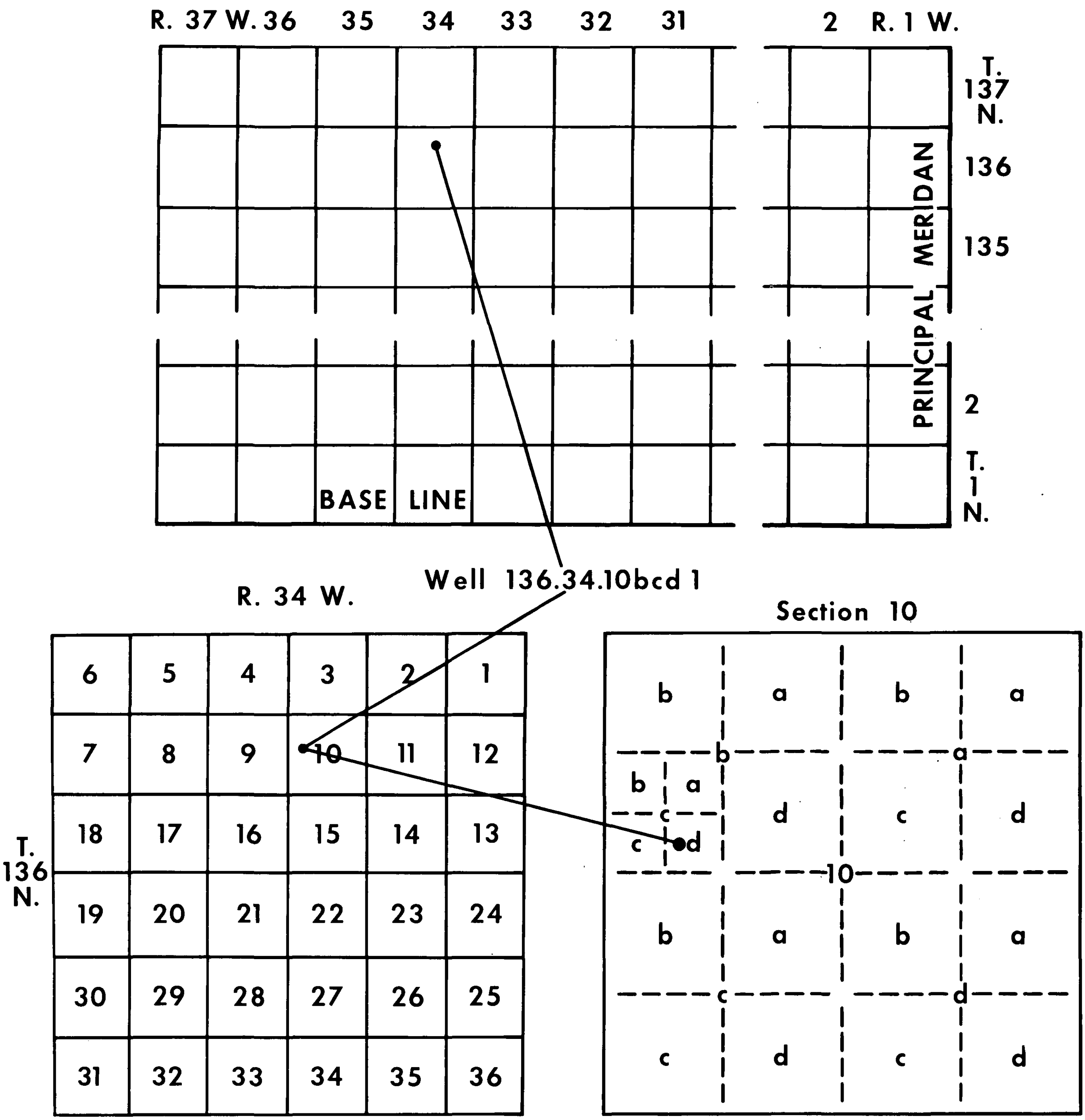


Figure 2.--Test-hole and well-numbering system.

tested, and who permitted water samples to be collected from their wells. The U.S. Soil Conservation Service was helpful in providing information on soils and land irrigability.

HYDROGEOLOGY

Bedrock

Basement rock consists of Precambrian igneous and metamorphic rocks (Sims, 1970). These rocks are hard, dense, and of very low porosity and hydraulic conductivity. Water occurrence is limited to fractures in the rock, and possibly weathered zones at its top. Although few drill holes have penetrated the basement rock, expectable well yields would seldom be more than 10 gal/min (gallons per minute).

Cretaceous sedimentary rocks, overlying the basement rock, have been reported in a few drillers' logs near the study area (Lindholm and others, 1972), but are not known within the study area. The occurrence of Cretaceous rocks in central Minnesota is discontinuous, and their water-yielding potential is typically low.

Undifferentiated Drift

Glacial deposits cover essentially the entire study area (fig. 3). The only known bedrock outcrop is a few miles northeast of Staples in the NW¼ sec.27, T.134 N., R.32 W. Most of the drift cover is 200 to 600 feet thick, generally increasing from south to north (Lindholm and others, 1972). Physiographic features are chiefly a product of the Wadena Lobe of Wisconsin Glaciation, which advanced from the northeast (Wright, 1962; Wright and Ruhe, 1965). The drift consists of till, lake sediments, and outwash.

Surficial outwash is treated separately in the remainder of this report, whereas other drift is discussed briefly below.

Till directly underlies most of the surficial outwash (fig. 4). Surface deposits of till surround most of the study area and occur at places within it (fig. 3). Till forms the "Wadena Drumlin Field", which transects the southern half of the study area. Till also forms the land surface in part of southwestern Hubbard County. Till is poorly sorted and contains much clay; therefore, it transmits only small quantities of water to wells.

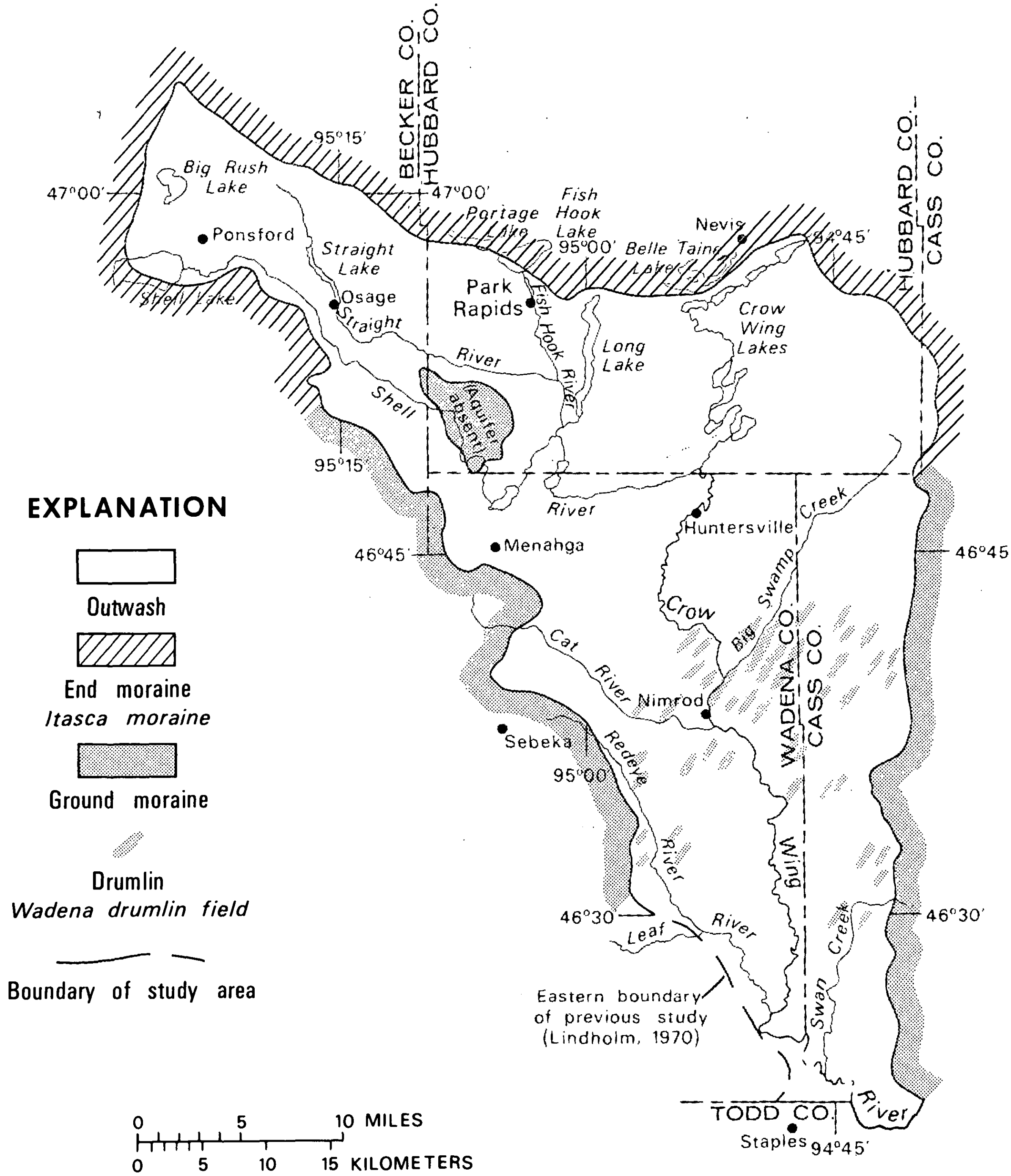


Figure 3.--Surficial geology.

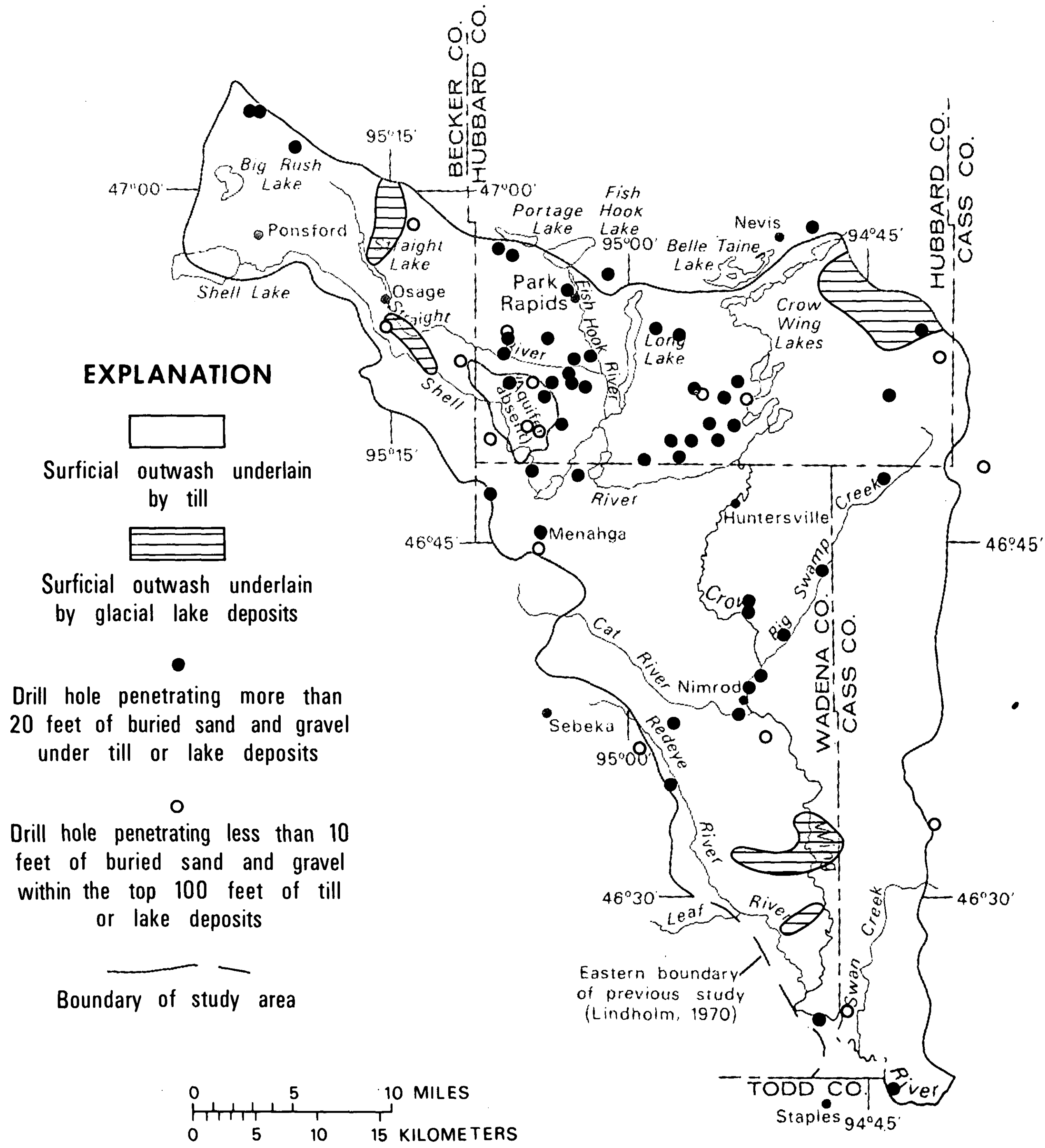


Figure 4.--Distribution of materials underlying the surficial aquifer and location of drill holes penetrating buried outwash.

Clay or silt beds remain where lakes formed during glacial recession. Some extensive lake deposits, underlying the surficial outwash (fig. 4), were defined by test drilling. Their fine texture makes them of little practical value for water supply.

Buried outwash consists of sand and gravel deposits overlain by till or lake sediments. To map and evaluate individual buried aquifers would require extensive deep test drilling. Data (fig. 4) indicate that significant thicknesses of buried outwash are commonly penetrated during drilling. Many wells currently pumping from buried outwash aquifers yield more than 1,000 gal/min. Considering that most of the deeper drift is unexplored, buried outwash seems to be a potential source of large ground-water supplies in much of the area.

Surficial Outwash

Extensive surficial outwash (sand and gravel) was deposited by meltwaters from three sources during glacial recession. Most outwash was derived from the north, where the Itasca Moraine (fig. 3) was formed during a pause in the recession of the Wadena Lobe ice front. Some of the outwash in the eastern and southern parts of the area was derived from the Brainerd Sublobe of the Lake Superior Lobe, which approached from the east, and from the Des Moines Lobe, which contributed meltwaters from the southwest (Wright, 1962). Wright (1962) describes some of the sand in the southern part of the study area as being lake deposited; this is considered to be a part of the surficial outwash aquifer.

Grain sizes in the surficial aquifer commonly range from very fine sand to fine gravel. The range of particle-size distribution curves for 83 samples is shown in figure 5. Grain sizes generally increase from south to north. Cobbles and boulders (beyond the scale of the graph) are common near the Itasca Moraine, particularly in the northwestern part of the study area. Degree of sorting tends to be slightly higher in the southern part of the area than near the moraine.

The surficial outwash ranges in thickness from 0 to about 135 feet. The outwash is absent where a till "high" forms the land surface in extreme southwestern Hubbard County and where drumlins are present in Wadena and Cass Counties.

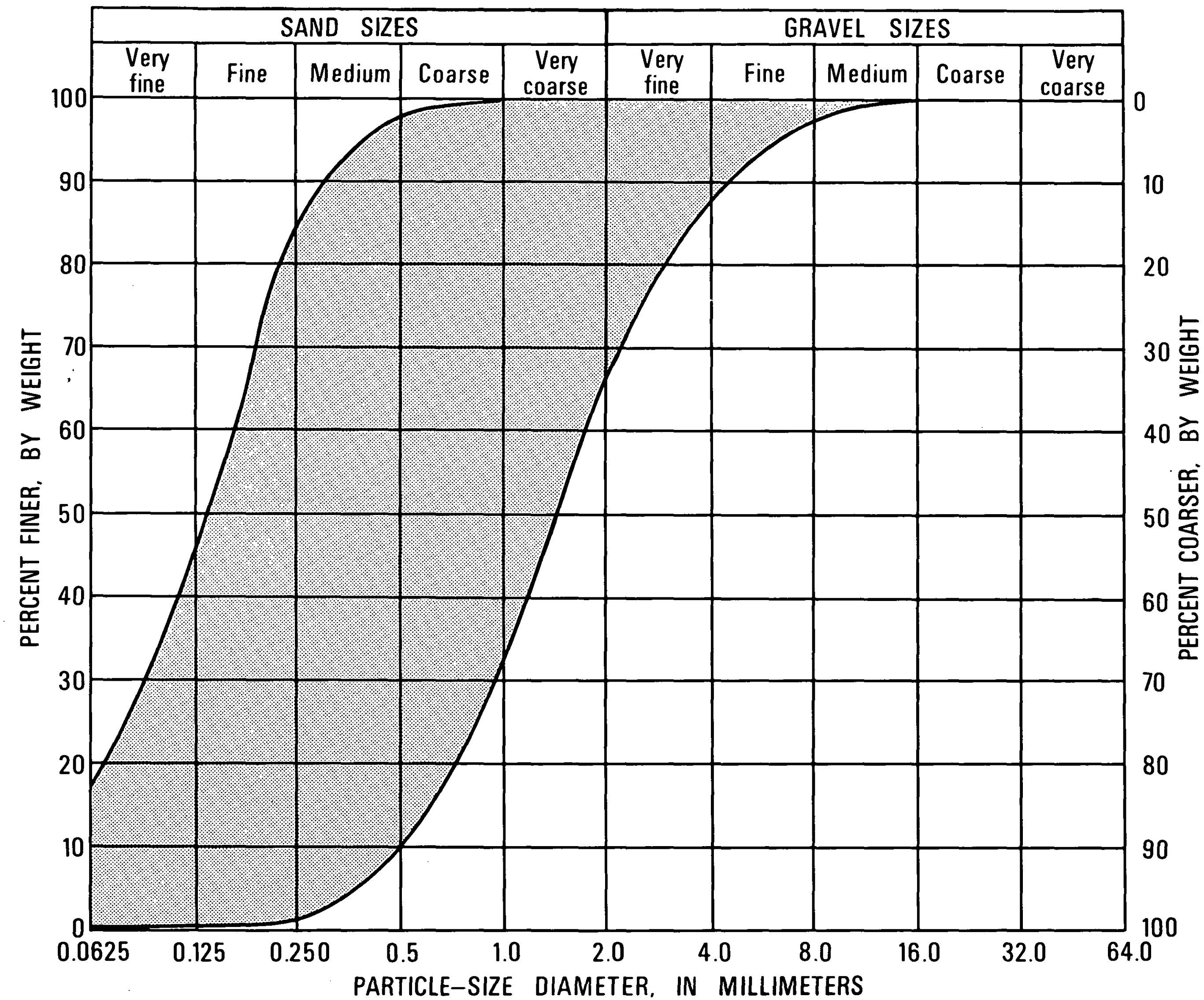


Figure 5.--Range of particle-size distribution curves of test-hole samples.

Saturated Thickness

Saturated thickness, the vertical distance between the water table and the bottom of the aquifer, ranges from 0 to about 130 feet (pl. 1). The bottom of the aquifer is considered to be at the top of the first till or clay layer that is thicker than 5 feet.

The aquifer is generally thickest in the northern half of the study area. Although thicknesses may vary considerably within short distances, some of the thickest parts of the aquifer are traceable over large areas (pl. 1). For example, a linear outwash-filled channel seems to be continuous along much of the north half of the western boundary of the aquifer. This channel, cut into till before being filled, was probably a major southeasterly trending drainageway for meltwaters.

The aquifer thins out toward most boundaries of the study area, but continues beyond the northern boundary in places where the Itasca Moraine is composed mainly of sand and gravel.

Hydraulic Properties

Properties pertinent to evaluating water-supply potential of the aquifer include hydraulic conductivity, transmissivity, and storage coefficient (or specific yield).

Hydraulic conductivity depends largely on texture of the aquifer materials, descriptions of which were obtained by test augering. Values of horizontal hydraulic conductivity are assigned for different particle sizes, as shown in table 1. (The main component of flow in this aquifer is horizontal.) Higher values in each range were assigned to the better-sorted materials.

Transmissivity equals saturated thickness multiplied by the appropriate hydraulic conductivity and is indicative of total water-yielding potential of the aquifer at any given location. Values of transmissivity were calculated for every test-augering site.

Field determinations of transmissivity were obtained at four different sites (pl. 2) by using aquifer-test data. Transmissivity was also estimated by using (1) specific-capacity data from production wells (Theis and others, 1963), (2) measured streamflow gain along given reaches under base-flow conditions, and (3) water-level data from wedge-shaped

Table 1.--Range of values of hydraulic conductivity for surficial outwash in the Pineland Sands area.

Predominant material (Wentworth scale)	Hydraulic conductivity (ft/day)
Clay or silt (< 1/16 mm)	Less Than 10
Sand, very fine (1/16-1/8 mm)	10-50
Sand, fine (1/8-1/4 mm)	50-100
Sand, medium (1/4-1/2 mm)	100-400
Sand, coarse to very coarse; gravel (> 1/2 mm)	400-600

parts of the aquifer (Stallman and Papadopulos, 1966). Although these three methods provided relative values of transmissivity, most confidence was placed in those values derived from aquifer-test data. The pertinent data concerning the tests are presented in table 2. Analyses of the test data were made according to the method of Boulton (1963). Results indicated that the hydraulic conductivities originally assigned were underestimated for the coarser grain sizes. Consequently, values for materials of medium-sand and coarser sizes were revised upward toward the higher ends of the ranges listed in table 1.

Areal variation in transmissivity is shown on plate 2. The resemblance between trends on plates 1 and 2 emphasizes the strong influence of saturated thickness on transmissivity.

Storage coefficients calculated from aquifer-test data (table 2) are typical of an unconfined (water table) aquifer. Unconfined conditions prevail except where thin clay or silt beds of small areal extent may impart confined (artesian) conditions locally. A value of 0.20 was selected to represent specific yield of the aquifer as a whole (storage coefficient approaches this value as gravity drainage progresses during pumping).

Theoretical Well Yields

Saturated thickness and transmissivity, along with certain necessary assumptions, are used to calculate expectable short-term well yields from the surficial aquifer. Assumptions are:

(1) The well is open to the full saturated thickness of the aquifer, is 100 percent efficient, and has a diameter of 16 inches.

(2) Drawdown after 30 days of pumping is equal to two-thirds of original saturated thickness. (The well is being pumped at maximum efficiency under this condition. See E. E. Johnson, Inc., 1966.)

(3) Effects of other wells and hydrologic boundaries are negligible.

(4) Storage coefficient of the aquifer is 0.20.

Table 2.--Results of aquifer tests in the Pineland Sands area.

Location	Length of test (hours)	Pumping rate (gal/min)	Aquifer properties		
			Transmissivity (ft^2/day)	Average hydraulic conductivity (ft/day)	Storage coefficient
134.32.7bcb2	48	300	10,700	320	0.18
140.34.27acc	48	75	12,000	440	.25
140.35.23dca2	72	145	8,700	360	.23
140.37.12ddb	53	960	36,800	630	.18

The equation of Theis (1935) was used to compute theoretical yields to wells. The effect of dewatering on drawdowns was taken into consideration (Jacob, 1944).

About 15 percent of the study area consists of surficial outwash capable of yielding more than 1,000 gal/min to individual wells (pl. 3). Locally, in areas of highest transmissivity, well yields exceeding 4,000 gal/min may be obtainable. Expected yields are less than 100 gal/min in about 30 percent of the area underlain by the surficial aquifer. Plate 3 defines regional trends in water-yielding capability, but it cannot be used for an accurate prediction of well yield at any given location.

Water Quality

Ground water acquires natural chemical characteristics from the materials through which it moves. Water in the surficial aquifer is of the calcium bicarbonate type, is moderately hard to very hard, and contains dissolved solids generally in the range of 100-300 mg/L (milligrams per liter). Results of chemical analyses made of water samples collected from different parts of this aquifer are given in table 3.

Mineralization of water in the northwestern half of the surficial aquifer is typically greater than in the southeastern half (fig. 6). Similarly, very hard water (greater than 180 mg/L hardness as $CaCO_3$) prevails in the northwestern half, whereas nearly all water in the southeastern half is moderatly hard (61-120 mg/L) or hard (121-180 mg/L). The difference in hardness is probably related to: (1) the presence, in the southeastern half, of outwash from the Brainerd Sublobe, which contains less soluble minerals than the carbonate-rich outwash of the Wadena Lobe, and (2) thicker outwash and fewer streams in the northwestern half, resulting in longer ground-water-flow paths and therefore longer time of contact with soluble minerals.

The chemical quality of water in the surficial aquifer is satisfactory for irrigation. Concentrations of boron are safe, even for boron-sensitive crops. According to a classification developed by the U.S. Salinity Laboratory Staff (1954), all samples show low sodium hazard and low-to-medium salinity hazard. Those having medium salinity hazard include all samples collected from the northwestern half of the aquifer. Apparently, precipitation has provided sufficient leaching to prevent salt accumulation in these well-drained soils. However, if irrigation increased substantially, chemical analyses of periodically collected water samples could provide data indicating possible increased salt accumulations.

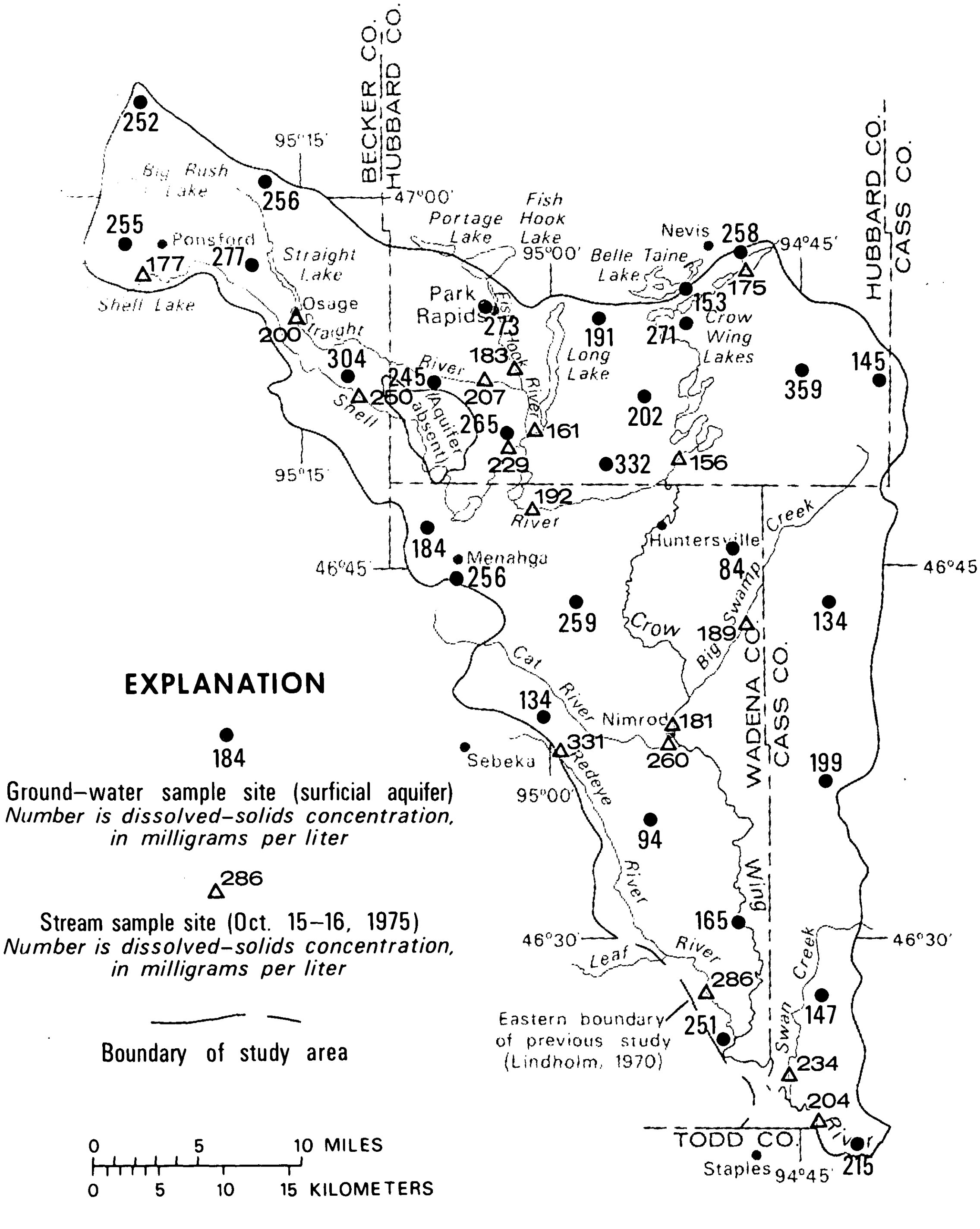


Figure 6.--Dissolved-solids concentration of ground water.

Table 3.--Chemical analyses of
Sands area. [Analyses by
except temperature, sodium

Well location	Depth of well (ft)	Date of collection	Temperature (°C)	Silica (SiO_2)	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)
133.32.2cdc	41	7-31-75	8.5	16	0.03	0.07	50	12	2.9
134.33.15aca	32	7-31-75	8.0	19	.39	0	51	16	2.8
135.32.33cdd	14	7-31-75	8.5	9.2	8.2	.34	27	6.9	2.2
135.33.14acc	18	9- 1-76	9.5	15	.97	.17	50	11	2.2
136.32.9cdd	40	9- 1-76	8.0	16	.28	.10	50	10	6.4
136.33.19bcb	14	7-30-75	7.0	12	3.3	.16	23	4.1	2.2
137.32.29bbc	10	7-31-75	10.5	15	11.0	.11	17	6.2	3.6
137.34.32bbd	58	8-31-76	9.5	14	.20	.08	36	9.3	3.1
138.32.34baa	24	8-30-76	10.0	15	2.0	.16	33	8.8	4.1
138.33.14cca	9	7-30-75	12.5	7.5	13.0	2.6	20	3.9	1.2
138.34.34cbb	35	9- 1-76	12.0	13	6.8	.45	80	15	6.9
138.35.17aaa	33	8-31-76	9.5	13	0	0	57	13	1.4
138.35.27cbc	11	7-30-75	11.5	19	.10	.02	49	14	12
139.32.1dcd	34	8-30-76	11.0	13	.09	0	46	8.1	1.7
139.32.4bcc	45	8-30-76	9.5	15	.03	0	110	19	4.2
139.33.18ccc	63	8-31-76	9.0	14	.02	0	62	15	1.5
139.34.27ddb	40	7-29-75	10.5	14	.04	.02	80	18	3.3
139.35.9bbc2	49	9- 1-76	8.0	15	1.6	.21	71	19	2.9
139.35.24dab	86	7-29-75	7.5	21	.70	.15	62	17	11
139.36.2ccc	16	7-29-75	7.5	14	7.5	--	71	16	4.5
140.33.2dda	116	7-29-75	8.5	17	.01	0	63	17	2.9
140.33.16cad2	76	8-31-76	10.0	5.2	.75	.12	35	18	4.2
140.33.28cbb	48	7-29-75	7.0	14	1.4	--	62	15	2.9
140.34.27acc2	57	8-31-76	8.5	13	1.9	.16	62	16	2.4
140.35.23dca2	52	7-30-75	8.5	22	.66	.06	67	19	4.1
140.37.12ddb	98	7-30-75	8.0	14	1.3	.17	70	19	2.3
140.38.1dba	14	7-30-75	8.0	13	5.8	.09	65	19	1.6
141.36.30ddb2	42	8-31-76	13.0	9.1	1.2	.08	70	21	2.6
142.37.31daa	65	8-31-76	9.0	13	.02	0	71	21	1.2
Recommended limits for domestic consumption (Minnesota Pollution Control Agency, 1972).					.30	.05			

ground water from the surficial aquifer in the Pineland
U.S. Geological Survey. Results in milligrams per liter
-adsorption ratio, specific conductance, pH, and color.]

Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate + nitrite (NO_3 + NO_2 as N)	Boron (B)	Dissolved solids (residue on evaporation at 180°C)	Hardness		Sodium-adsorption ratio	Specific conductance (micromhos per cm at 25°C)	pH	Color (platinum-cobalt units)
								Total	Noncarbonate				
1.9	180	11	8.3	0.2	3.6	0	215	170	27	0.1	395	7.8	5
3.0	224	12	2.8	.1	3.6	.002	251	190	10	.1	450	7.9	6
1.2	77	2.7	7.1	.1	6.1	.008	147	96	33	.1	210	7.9	10
0.6	187	5.4	.6	.1	.10	.02	165	170	17	.1	340	7.1	3
1.2	127	35	22	.1	.25	.02	199	170	62	.2	380	8.2	3
0.6	95	6.0	.8	.1	1.8	0	94	74	0	.1	165	7.5	15
1.6	82	5.9	6.5	.1	.43	.01	106	68	1	.2	190	7.2	40
2.5	136	8.3	3.8	.1	1.4	.01	134	130	17	.1	268	7.9	3
0.9	122	7.1	3.9	.1	2.2	.01	134	120	19	.2	255	6.9	3
1.4	85	.7	.7	.2	.05	0	84	66	0	.1	130	7.1	40
8.0	341	4.8	15	.2	.07	.06	259	260	0	.2	620	7.6	180
0.4	212	6.4	.5	.1	1.5	.01	184	200	22	0	400	7.8	2
1.2	173	14	13	.1	7.2	.05	256	180	38	.4	450	7.7	4
.5	165	5.0	.2	.1	.95	.01	145	150	13	.1	340	7.9	3
1.5	309	7.9	17	.1	20	.02	359	350	99	.1	661	7.5	3
.7	245	7.5	1.6	.2	1.0	.009	202	220	16	0	420	7.9	2
.9	267	--	11	.1	3.5	.02	332	270	55	.1	555	7.9	3
1.6	307	4.3	1.1	.1	.27	.01	245	260	4	.1	500	7.8	2
1.9	309	.2	3.0	.2	0	.06	265	220	0	.3	460	7.6	4
2.3	258	8.5	10	.1	6.7	.03	304	240	32	.1	540	7.7	7
1.2	264	5.3	1.3	.1	.26	.006	258	230	11	.1	490	7.7	2
1.6	194	1.8	1.7	.2	.09	.02	153	160	2	.1	335	7.7	3
1.3	274	3.9	3.1	.1	.49	.01	271	220	0	.1	400	7.6	15
1.1	252	5.8	2.4	.1	1.3	.02	191	220	14	.1	390	7.9	2
1.6	309	--	.7	.2	0	.01	273	250	0	.1	500	7.6	4
1.5	292	--	1.6	.1	.41	.008	277	250	14	.1	485	7.6	5
1.7	291	--	2.5	.1	.05	.01	255	240	2	0	505	7.4	7
1.4	313	5.6	1.8	.1	.09	.02	256	260	5	.1	520	7.7	2
1.9	303	6.5	.8	.2	2.4	.009	252	260	15	0	515	7.6	2
		250	250	1.5	10		500						15

The concentrations of some constituents, though not critical to plant growth, exceed recommended limits for domestic consumption (Minnesota Pollution Control Agency, 1972) in some places. The surficial aquifer, being unconfined, is highly susceptible to pollution. Nitrate concentrations higher than a few milligrams per liter may be derived from barnyards, septic tanks, or agricultural fertilizers and could endanger the health of infants. Natural concentrations of iron and manganese, which pose no health hazard but may cause a staining problem, each exceed recommended limits in about two-thirds of the samples analyzed.

Chemical quality of stream water under base-flow conditions is somewhat similar to quality of water in the surficial aquifer (fig. 6), but it reflects other controls as well. Drainage from lakes tends to decrease dissolved-solids concentration of stream waters in the northern part of the study area. Streams such as the Cat and Redeye Rivers, which originate in till areas, have the relatively high dissolved-solids concentrations typical of waters draining those areas.

SURFICIAL AQUIFER SYSTEM

An understanding of natural inflow, outflow, and movement of ground water is basic to an evaluation of the response of the system to pumping. The direction of water movement through the aquifer is approximately perpendicular to water-table contour lines (fig. 7). Contouring is based on water-table altitudes in test holes and observation wells and on altitudes of streams and lakes shown on topographic maps. Flow is from topographically high areas toward low areas. Surface drainage is generally southward, and a regional southward water-table gradient is also evident. Most ground water, however, moves relatively short distances laterally before it discharges into the nearest stream, lake or low wetland.

Inflow and Outflow

Recharge from precipitation

The major source of recharge to the aquifer is snowmelt and rain during the spring. Most rain entering the soil during May through October is evaporated and transpired. Although above-normal precipitation during the fall can contribute ground-water recharge, it is not considered of long-term

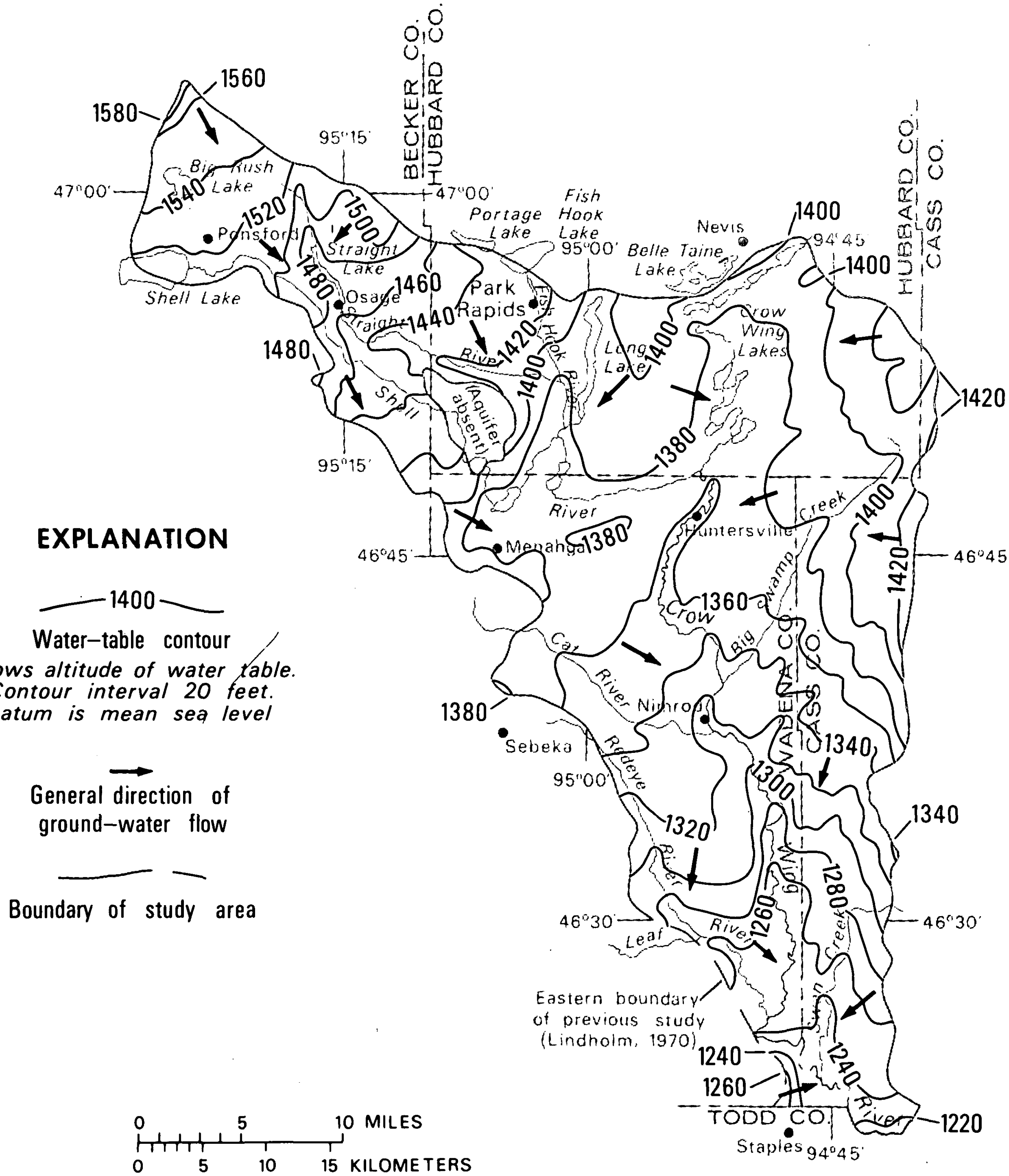


Figure 7.--Water-table configuration and general direction of ground-water movement.

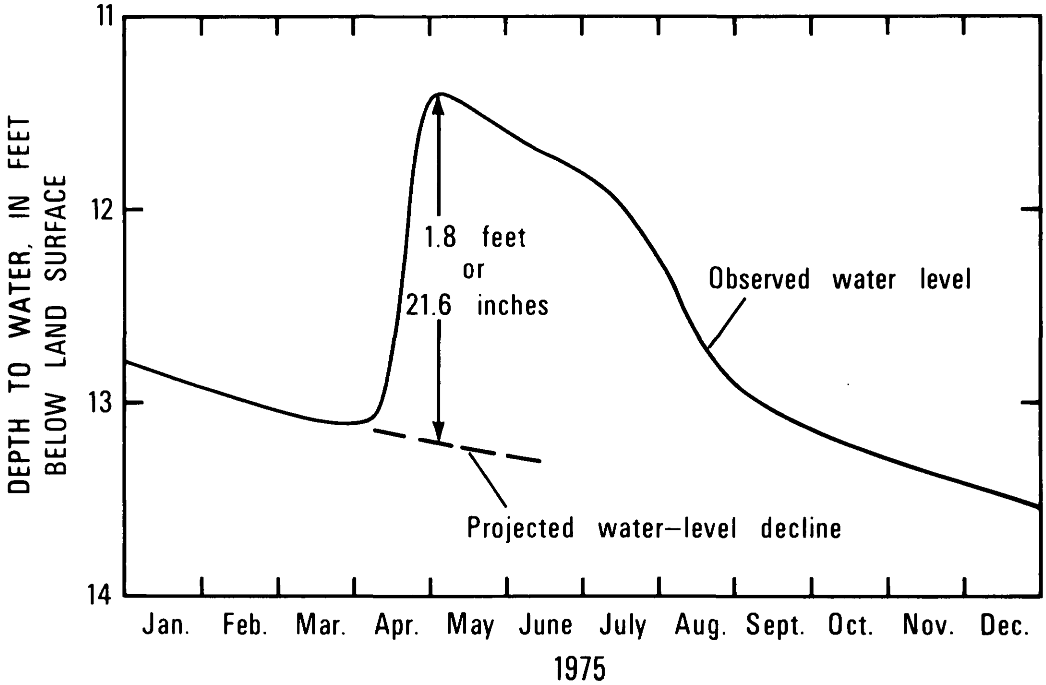
significance. Determinations of annual recharge were made using 1975-76 water-level records from 33 wells and 1971-76 records from 1 well. (Locations of observation wells are shown on pl. 1.) An example hydrograph and computation of recharge is shown in figure 8. Examination of climatic records suggests that the 1975 quantity of recharge from precipitation may be considered representative of long-term conditions. This quantity averaged 5.1 inches at the observation sites.

Ground-Water - Surface-Water Relationships

Discharge from the ground-water system is mainly to streams and lakes. Amount and distribution of this discharge was determined by streamflow measurements made during five periods of base flow. Discharge at the gaging station on the Crow Wing River at Nimrod at these times is indicated in figure 9. Assuming that streamflow characteristics at the gaging station are representative of the study area, a wide range in base-flow conditions is described by the measurements obtained. Yet streamflow gains along particular reaches were generally similar for the five periods. Many of the measured gains were in the range of 0.3 to 2 ft^3/s per mile of stream, higher gains tending to be associated with areas of relatively high aquifer transmissivity. Some stream reaches commonly lose water, particularly in areas where the aquifer is thin and somewhat discontinuous (Wadena Drumlin Field). Slight losses were determined along various reaches of Crow Wing and Redeye Rivers.

Evapotranspiration

Discharge from the ground-water system by evapotranspiration occurs mostly during May through October and where the water table is within the root zone of vegetation. Based on values of root-zone depth given by Thornthwaite and Mather (1957), a depth of 5 feet is considered applicable for the study area. Therefore, evapotranspiration from the aquifer is considered to occur where the water table is less than 5 feet below land surface (fig. 10), and to be greatest where the water table is at land surface (wetland areas). The net rate of loss from the aquifer in wetland areas is the difference between evapotranspiration, determined by the method of Thornthwaite and Mather (1957), and that part of evapotranspiration that is satisfied by May-through-October precipitation. During May through October, long-term average



Hydrograph for observation well 136.33.36bcb

Spring recharge = (water–level rise) × (estimated specific yield)
= 21.6 inches × 0.20
= 4.3 inches

Figure 8.--Method of estimating spring recharge to the surficial aquifer.

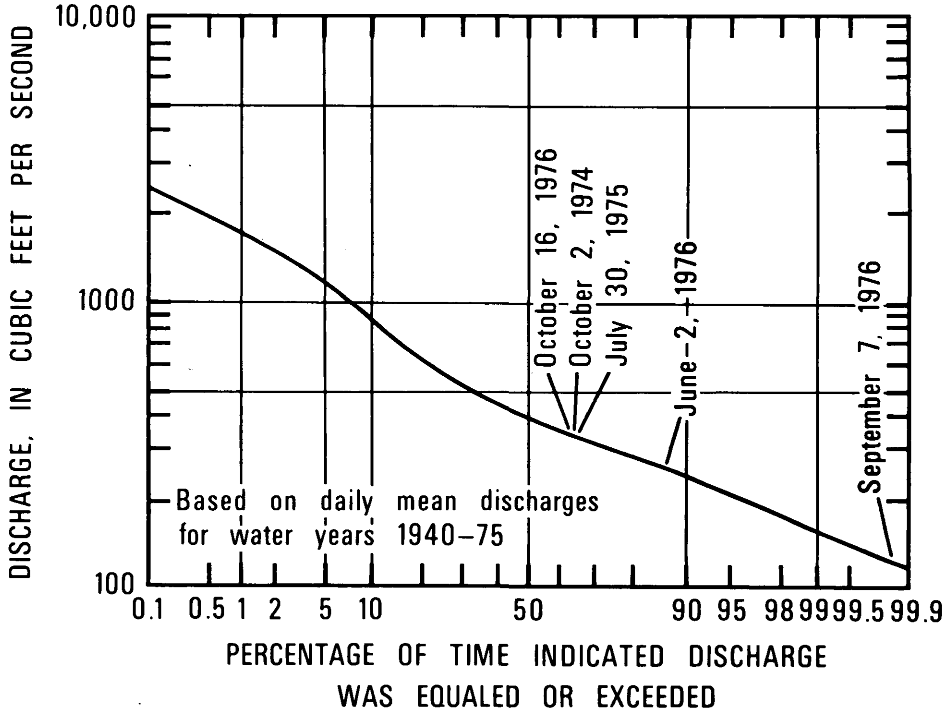


Figure 9.--Flow-duration curve for Crow Wing River at I

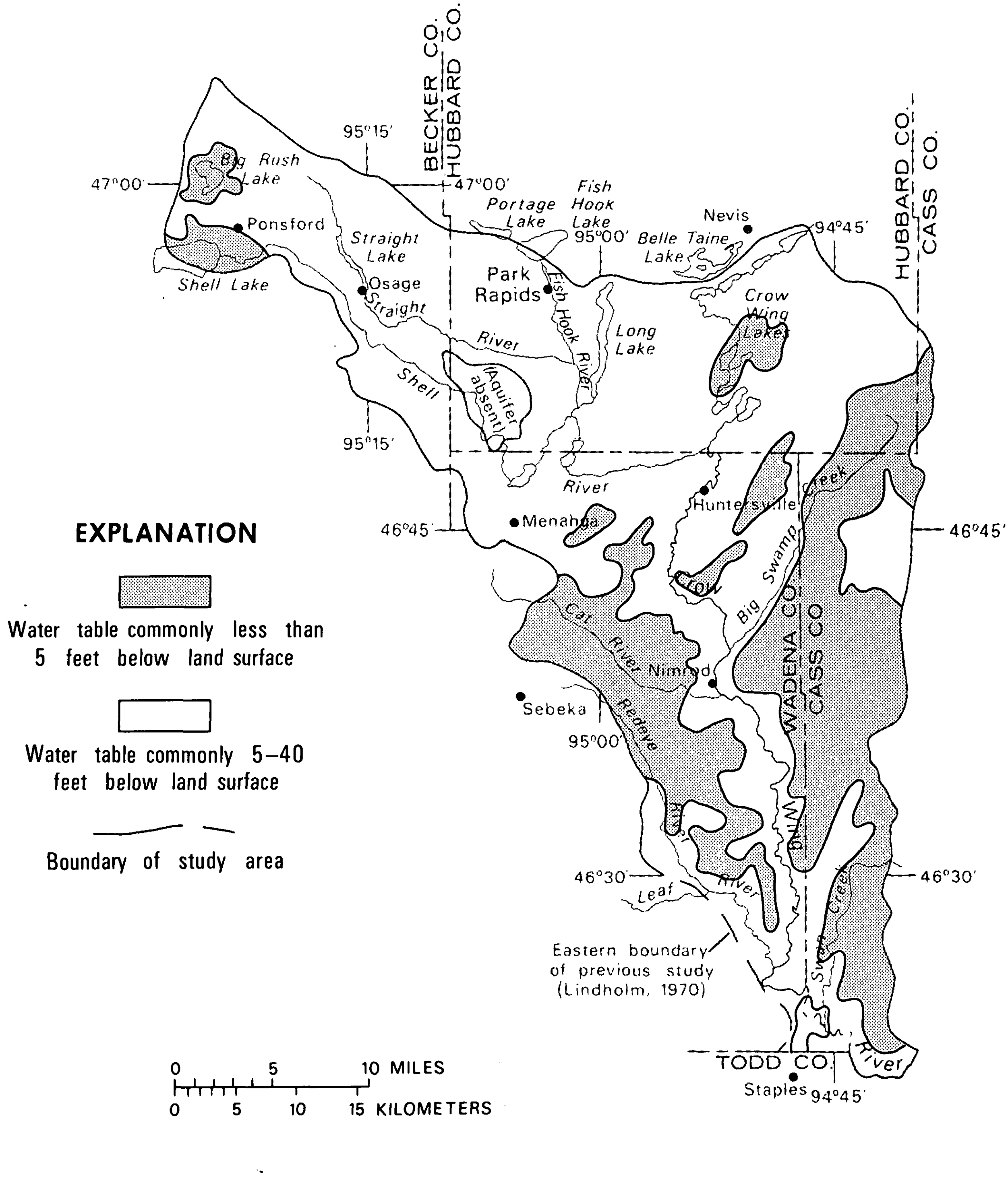


Figure 10.--Depth to water table.

evapotranspiration is 22 inches and average precipitation is 19 inches. Therefore, the maximum evapotranspiration from the aquifer is 22 minus 19 = 3 inches per year.

Underflow

Some recharge to the aquifer occurs as underflow across the northern boundary of the study area. Most underflow enters in the Belle Taine Lake area and across the extreme northwestern part of the boundary. Calculated rates total 40 to 50 ft^3/s, based on water-table gradients and estimated values of transmissivity. However, part of the underflow moves directly from Belle Taine Lake to adjacent Crow Wing Lakes and is of little concern because of its short distance of travel before discharging from the aquifer. As discussed previously, the aquifer also extends beyond part of the southwestern and southern boundaries; however, flow directions and generally low transmissivity indicate underflow to be negligible there.

Mathematical-Simulation Model

A two-dimensional (horizontal flow) mathematical model of the ground-water system was made to simulate flow conditions in the surficial aquifer. Ground-water flow is considered to be essentially horizontal, as vertical-head changes are small in relation to horizontal-head changes in this aquifer. The model used was first developed by Pinder and Bredehoeft (1968) and later improved by Trescott and others (1976). It is designed to solve the partial-differential equation describing ground-water flow, which can be written as:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t),$$

where T is transmissivity (L^2/T),
h is hydraulic head (L),
S is storage coefficient (dimensionless),
t is time (T),
and W is a function describing volumetric flux (recharge or discharge) per unit area (L/T).

Input to the model includes hydraulic properties, boundary conditions, and other data that determine the character of inflow (recharge) and outflow (discharge). Model output consists of the head distribution and water budget (inflow and outflow rates) for the aquifer. A network of grid cells, or nodes, represents the horizontal extent of the aquifer. Nodal-data values are averages for each node. A computer is used to solve the flow equation for each node by finite-difference techniques.

Model Development

The Pineland Sands model consists of a network of 30x63 nodes, each node representing an area of the aquifer 1 mile long and 1 mile wide (fig. 11). The rows of the grid are oriented approximately northwest-southeast to minimize the number of nodes outside the aquifer boundaries.

Hydraulic conductivity was varied within the modeled area, based on test augering, as discussed previously. Specific yield was assumed to be uniform at 0.20. The modeled area, like the aquifer, extends slightly beyond parts of the northern limit of the study area and beyond part of the southwestern and southern limits, although the Crow Wing and Leaf Rivers form somewhat of a hydrologic boundary there.

Lakes larger than 0.5 square mile, except Straight Lake, are modeled as nodes having constant head. At each node representing Straight Lake, smaller lakes, and perennial streams, a streambed leakage term was assigned a relatively low value (0.25 ft/day per foot of streambed thickness). A streambed thickness of 1-foot was assumed. Recharge or discharge occurs across this bed, depending on the relative head values of the aquifer and the stream or lake. Normally, aquifer head is higher, which causes discharge to the stream or lake.

Recharge from precipitation was initially modeled as being uniform over the area but was revised as described below under "Model Calibration".

Evapotranspiration from ground-water bodies occurs in the simulation when and where the simulated water table is sufficiently shallow. The rate decreases linearly from 3 inches per year at land surface to 0 at 5 feet below land surface. This value is a net loss computed as described previously under "Evapotranspiration".

Underflow was first simulated by introducing constant flux into appropriate nodes along the northern model boundary. These nodes were later treated as constant head to permit the amount of underflow to change during simulations involving pumping. The revision had little effect on simulation of the natural system.

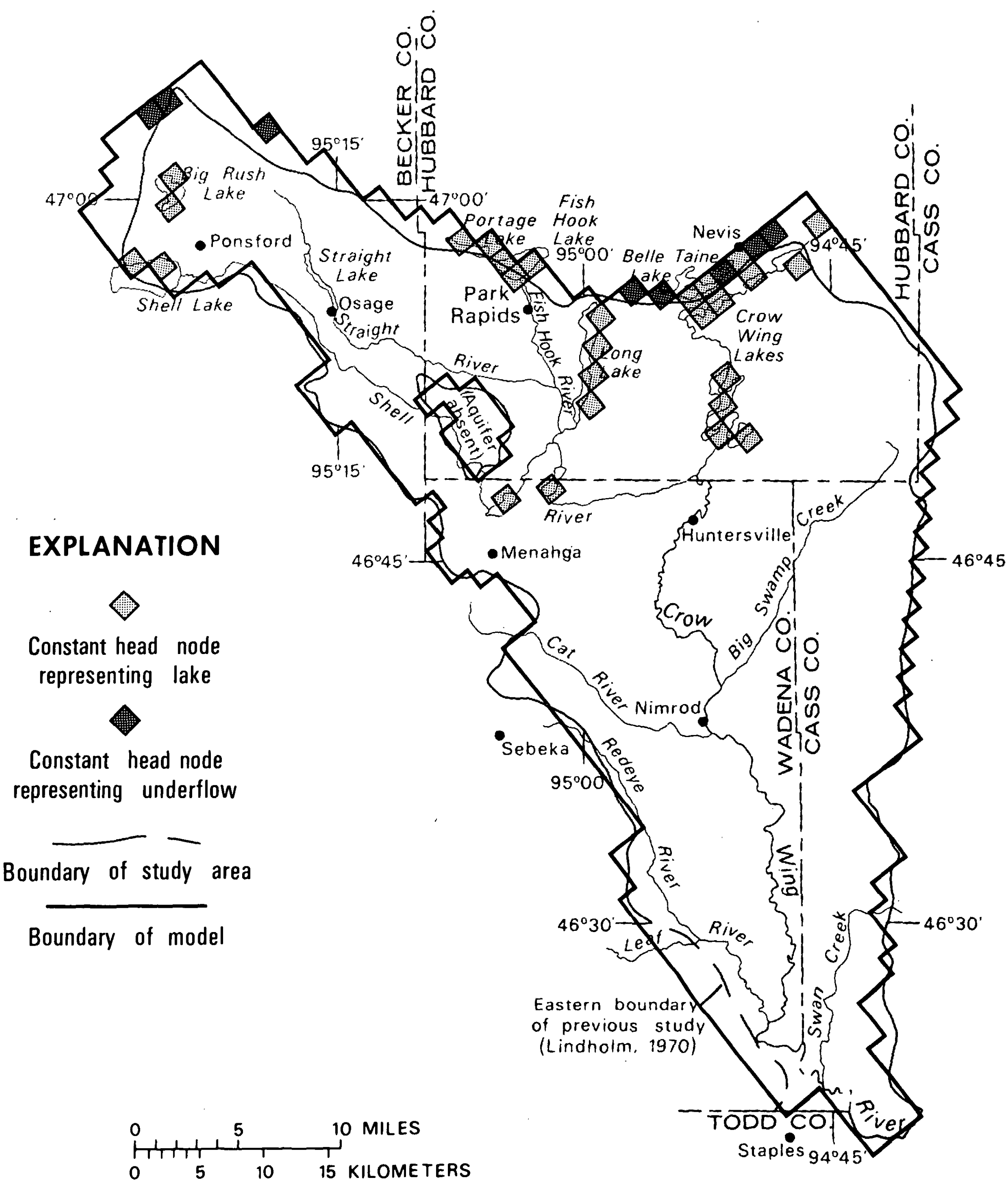


Figure 11.--Extent of modeled area and modeled boundary conditions.

Model Calibration

The model was calibrated by obtaining a satisfactory simulation of steady-state conditions in the aquifer. The steady-state system is composed essentially of natural inflow and outflow; no evidence shows that present pumping has significantly affected the natural system. The water-table configuration on figure 7, drawn from field data, is assumed to represent natural steady-state conditions, that is, the head distribution (water table) is in equilibrium with inflow and outflow which are approximately equal. Calibration was achieved when reasonable agreement between the modeled and natural systems was reached regarding (1) water-table configuration and (2) inflow and outflow magnitudes and distributions.

An important step toward close simulation was made by changing from uniform to areally variable recharge from precipitation. Reexamination of data showed that areas in which the topsoil and subsoil are both sandy tend to receive greater recharge than those where either the topsoil or subsoil is loamy. A description of soil-type distribution is given in the Minnesota Soil Atlas (University of Minnesota, 1969). Furthermore, wetland areas receive the lowest net recharge because most precipitation runs off or is evaporated and transpired where the aquifer is fully saturated. Improved simulation of the water-table configuration was obtained by distributing recharge as follows: 6 inches per year in areas of sandy soil, 4 inches per year in areas of loamy soil, and 2 inches per year in wetland areas.

Other modifications toward calibration were minor. The final values used for hydraulic properties and for all components of inflow and outflow are reasonable approximations for the study area. Furthermore, nodal values of base flow to streams agree generally with the distribution of measured streamflow gains; and nodal values of evapotranspiration agree with expected rates based on the known areas of shallow water table.

Water Budget

The water budget for the natural steady-state system is shown in table 4. During 1 or even several years, inflow normally does not equal outflow because of climatic variations. The steady-state model, however, represents average long-term conditions and therefore provides an appropriate basis for

Table 4.--Approximate average water budget of the surficial aquifer in the Pineland Sands area.

INFLOW	ft^3/s
Recharge from precipitation	246
Underflow	25
Flow from streams and lakes	24
Total	295

OUTFLOW	ft^3/s
Flow to streams	238
Flow to lakes	37
Evapotranspiration	20
Total	295

analyzing future changes in the system. Present (1976) pumpage from the aquifer is only about 1 percent of the total average water budget.

RESPONSE OF AQUIFER TO DEVELOPMENT

Effects of Pumping Wells

The natural ground-water system changes in response to pumping. Drawdown in a well causes a water-table gradient toward the well, establishing a cone of depression. As pumping continues, the cone expands until sources of water other than storage can completely supply the amount being pumped.

Magnitude of drawdown decreases with increasing distance from a pumping well (fig. 12). The drawdowns shown on figure 12 are not adjusted for decrease in saturated thickness caused by dewatering. Figure 13 provides a means for applying this adjustment, which is necessary under unconfined conditions. Although figure 12 pertains to a pumping rate of 300 gal/min, it can be used for other pumping rates because yield is theoretically proportional to unadjusted drawdown. If the pumping rate were 600 gal/min, for example, unadjusted drawdown at a given distance would be twice that shown on the graphs in figure 12. These graphs may be useful in estimating local effects of pumping, as shown by the following hypothetical examples:

Example 1. A well is pumping 600 gal/min from an unconfined aquifer where saturated thickness is 40 feet, transmissivity is 10,000 ft^2/day, and storage coefficient is 0.20. The well is 100 percent efficient and open to the full saturated thickness of the aquifer. Find the drawdowns 1 foot and 200 feet from the center of the well after 30 days of pumping.

1. From figure 12, when T is 10,000 ft^2/day, unadjusted drawdown 1 foot from a well pumping 300 gal/min is 6.8 feet. Because the pumping rate of the example well is 600 gal/min, unadjusted drawdown is 6.8 x (600 ÷ 300) = 13.6 feet.

2. From figure 13, when saturated thickness is 40 feet, adjusted drawdown is about 18 feet.

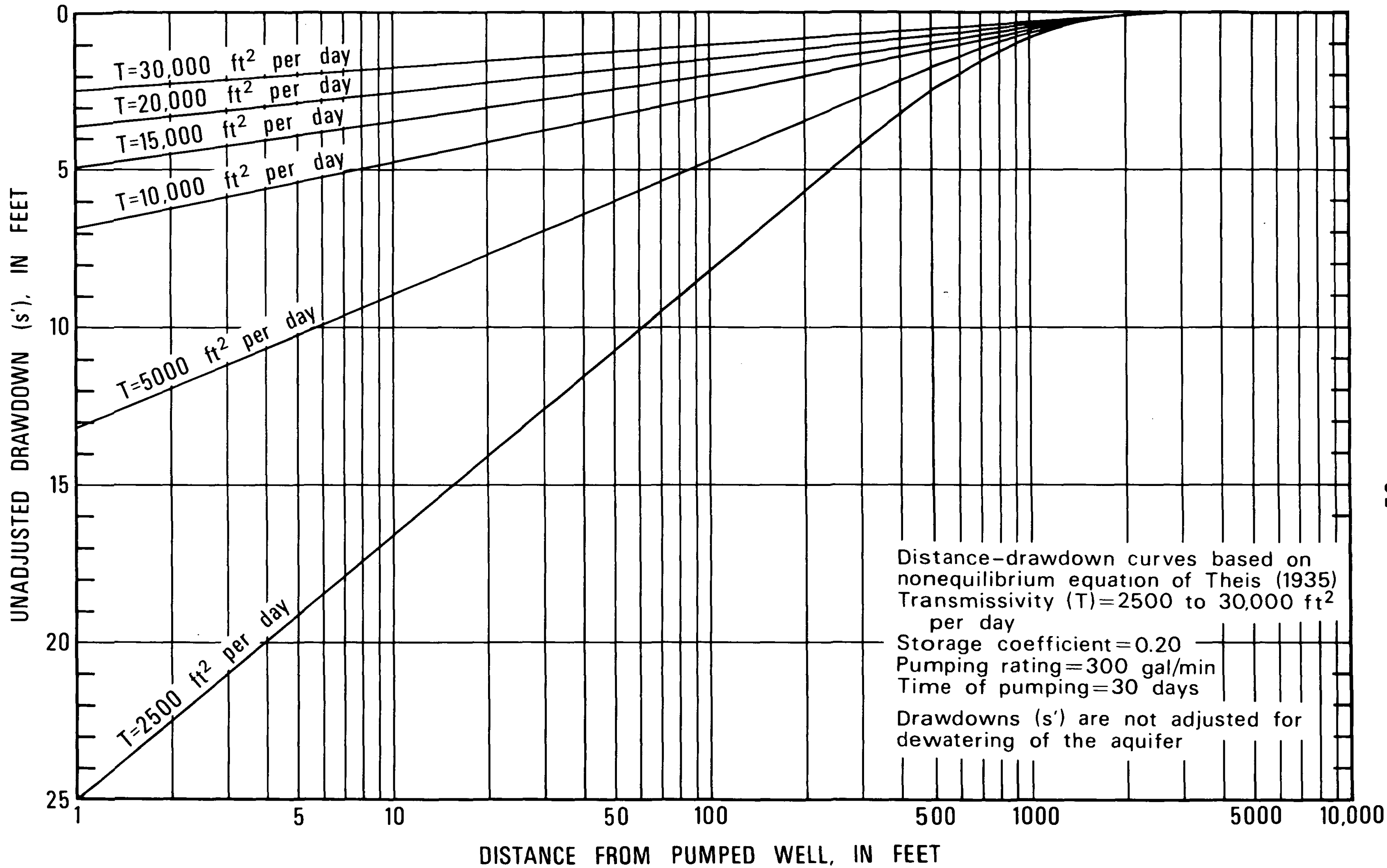


Figure 12.--Theoretical relation of drawdown to distance from a well.

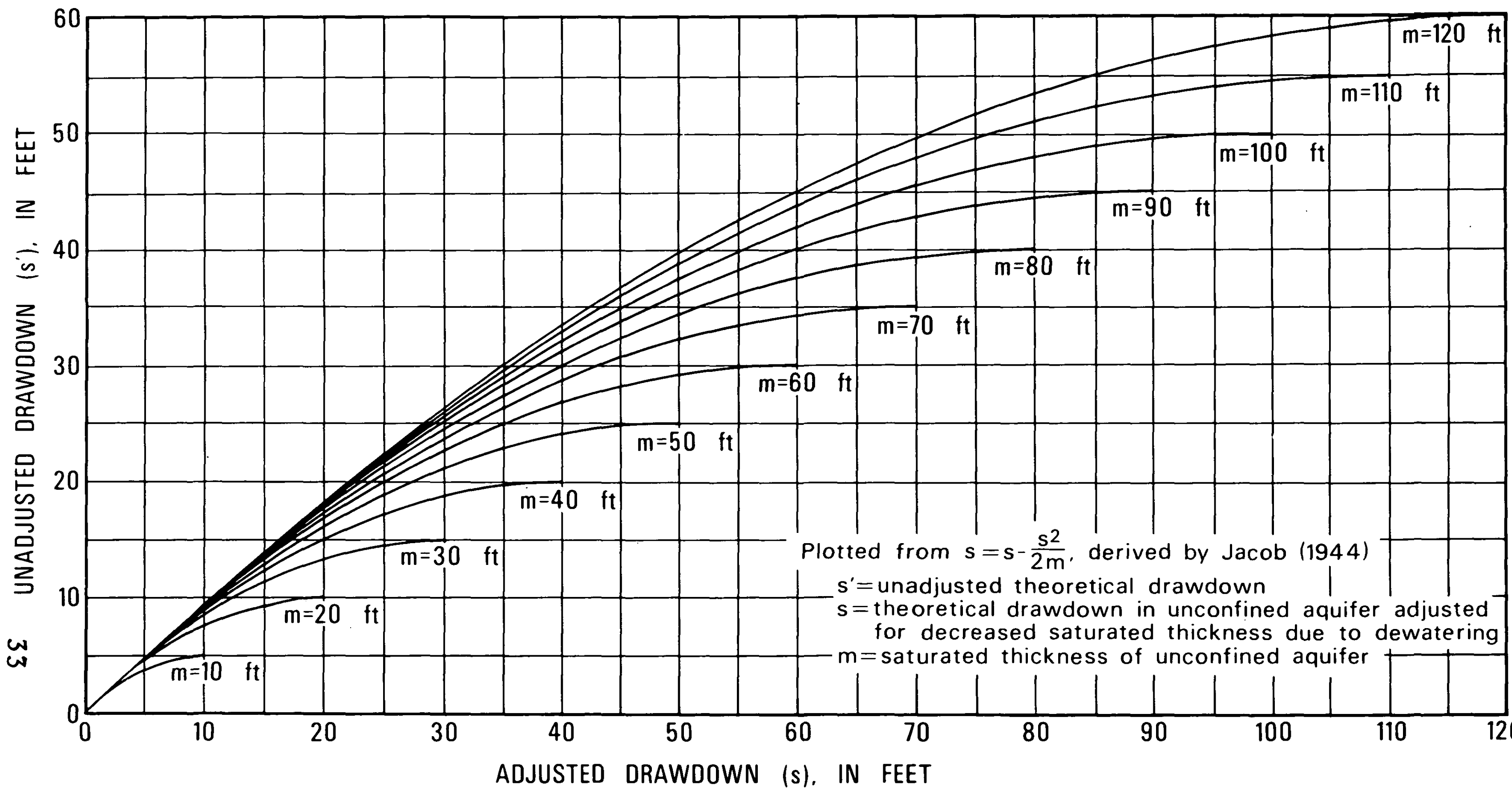


Figure 13.--Theoretical curves for adjustment of drawdown.

3. From figure 12, unadjusted drawdown 200 feet from the center of the well is 2.0 x (600 ÷ 300) = 4.0 feet.

4. From figure 13, adjusted drawdown is also about 4 feet.

Example 2. Two wells having anticipated yields of 1,200 gal/min are planned in an area of an unconfined aquifer where saturated thickness is 70 feet, transmissivity is 15,000 ft^2/day, and storage coefficient is 0.20. The wells will be 100 percent efficient and open to the full saturated thickness of the aquifer. How far apart should the wells be placed if the drawdown midway between them after 30 days of pumping is not to exceed 2 feet?

1. 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. The adjusted drawdown caused by <u>each</u> well midway between the two wells should, therefore, not exceed 1/2 x 2 = 1 foot.

2. From figure 13, unadjusted drawdown caused by <u>each</u> well will also be about 1 foot.

3. To use figure 12, which is based upon a pumping rate of 300 gal/min, the appropriate value of unadjusted drawdown for <u>each</u> well is 1 x (300 ÷ 1200) = 0.25 foot.

4. From figure 12, the distance at which the unadjusted drawdown is 0.25 foot, where T is 15,000 ft^2/day, is about 1,400 feet. The distance between the wells should, therefore, be at least 1,400 x 2 = 2,800 feet.

Variations from the theoretical relationships described above are to be expected. Few wells are 100 percent efficient and open to the full saturated thickness of the aquifer. Hydraulic properties of the aquifer may vary substantially within short distances. Furthermore, hydrologic boundaries may cause increased or decreased drawdowns (fig. 14). Of particular importance would be the nearness of a well to exposed or shallow till, a stream or lake, or other pumped wells.

Long-term pumping may affect the water system in several ways, most being related to the concepts depicted in figure 14. Large demands may cause water-table declines in response to

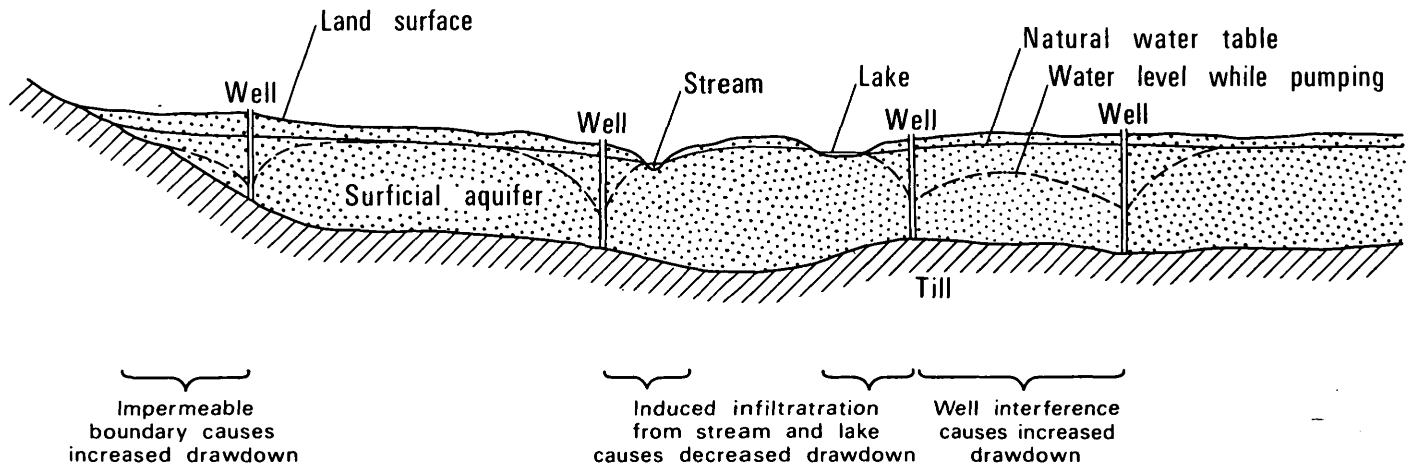


Figure 14.--Schematic cross section illustrating effects of natural boundaries and nearby wells on cones of depression.

withdrawals from storage. Some water which was originally discharged to streams or lakes or as evapotranspiration may be diverted to pumping centers, thereby, lessening the draft on storage. Sufficiently heavy pumping near streams or lakes may induce infiltration directly from these sources. Development near a permeable boundary may alter the natural underflow; underflow could be increased across the northern boundary, for example.

Based on the water budget alone, a maximum of 295 ft^3/s is theoretically available for long-term pumping from the aquifer as a whole, without depletion of aquifer storage. Practical sustained yield, however, would be considerably less because much of the natural discharge cannot be intercepted by pumping. The complexities of the system and the intensity of development will determine the degree to which different areas can support long-term withdrawals.

Model Analyses

The model provides a tool that can be used to approximate the probable effects of ground-water development. Pumping is superimposed on the steady-state model as an additional component of discharge in order to simulate the effects of development. An additional component of recharge, in the form of irrigation water returning to the aquifer, could have also been introduced. However, with proper irrigation practices this quantity is assumed to be small relative to withdrawal rates.

Modeled Development Patterns

This report describes the results of three simulation programs involving pumpage patterns, as shown in figure 15. The programs are identified as follows:

Program 1.--A 10-year simulation of present development with a total pumping rate of 3.3 ft^3/s.

Program 2.--A 20-year simulation of hypothetical future development with a total pumping rate of 60 ft^3/s.

Program 3.--A 20-year simulation of hypothetical future development with a total pumping rate of 120 ft^3/s.

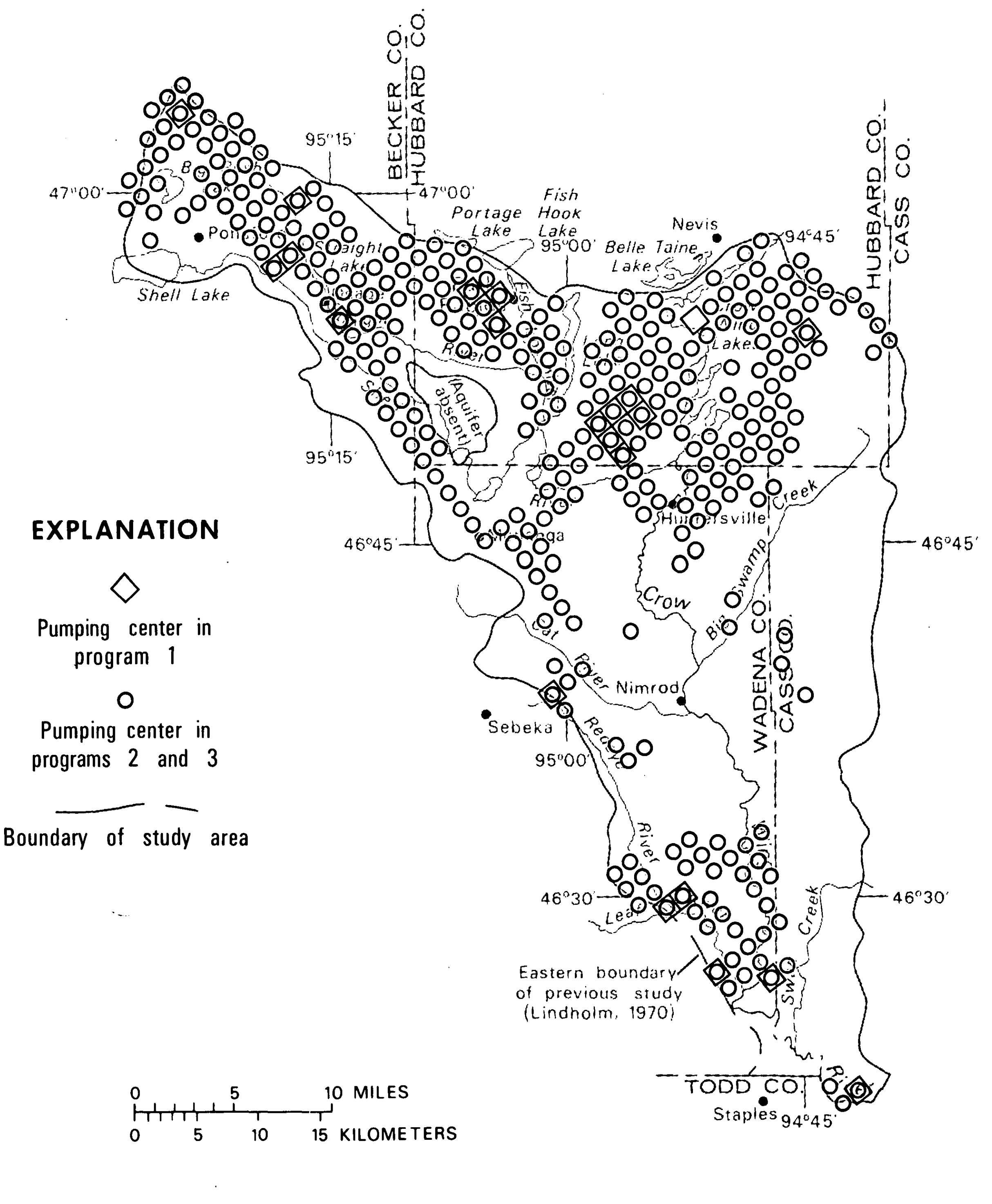


Figure 15.--Pumping centers modeled in programs 1, 2, and 3.

Each simulation includes withdrawals for the municipality and irrigation. Pumpage from the municipal withdrawal center (Park Rapids) was modeled in all three programs as a constant rate of 0.44 ft^3/s. This rate is higher than current usage to allow for some increase in water demands.

Program 1 simulates withdrawals from 23 pumping centers, as presently distributed in the surficial aquifer. Irrigation pumpage was made equivalent to an application of 8 inches of water per year on the irrigated land (about 3,000 acres).

Programs 2 and 3 each simulate hypothetical development patterns comprised of 320 pumping centers. The location of pumping centers was determined by the distribution of irrigable land underlain by surficial outwash capable of supplying well yields exceeding 500 gal/min (pl. 3). It is likely that most irrigation will develop where such rates are available. About 130,000 acres of irrigable land satisfy this criterion. A pumping center may represent one or several wells. The rate of withdrawal assigned to any given pumping center depends on what part (1, 2, 3, or 4 quarters) of that particular square mile is irrigable and can produce at least 500 gal/min from the surficial aquifer.

Withdrawals in program 2 may be considered equivalent to (1) 4 inches of water per year applied to the entire 130,000 acres, or (2) 8 inches of water per year applied to 65,000 acres (development uniformly half as dense). Withdrawals in program 3 may be considered equivalent to (1) 8 inches of water per year applied to the 130,000 acres, or (2) 16 inches of water per year applied to 65,000 acres (development uniformly half as dense).

Though actual pumping patterns cannot be predicted, the three simulations are based on a nearly complete range of possible irrigation-development densities. Therefore, at any given time, a given part of the study area can probably be related to some part of the model analysis, depending on the proportion of land under irrigation and the sources of irrigation water. For example, assume that half the land in a certain part of the area was to be irrigated with water obtained from the surficial aquifer. If the application rate was to be 8 inches per year, the results of program 2 would then be the most relevant for that particular area. For development patterns or application rates different from those in the model analyses, expected aquifer response should be accordingly different, the interpretation being guided by the results of programs 1, 2, and 3.

Simulated Water-Table Declines

Model results include the amount of water-table decline in response to modeled pumping. The declines represent regional changes, that is, those caused by pumping throughout the aquifer. The local effects of pumping individual wells were discussed previously.

The average irrigation season is estimated to be 100 days, consisting of cyclical pumping periods alternating with periods of water-level recovery. The total actual pumping time during the season is assumed to be 30 days. To facilitate modeling, rather than simulate pumping in a cyclical manner, the same amount of water that is actually withdrawn from the real aquifer in 30 days is withdrawn from the model aquifer in 365 days. The long-term water-table declines resulting from these two different methods of withdrawal are comparable, as shown by the relationship curves shown in figure 16. Therefore, simulated water-table declines can be considered as close approximations for the pumping patterns that are modeled.

Depending on well locations in the aquifer system and development density, time between pumping periods may not be sufficient to permit complete water-table recovery. This results in cumulative water-table declines with time. If ground-water development remains unchanged, declines would eventually cease when enough natural recharge and discharge is intercepted to supply the amount being pumped. In such a situation, the adjustment of the system to development will have resulted in a new steady-state condition.

Program 1 (present development) shows no significant regional water-table declines over the 10-year simulation period. The largest decline was 1.1 feet near Park Rapids, an amount that could be easily overshadowed by fluctuations related to climate. Little additional decline would occur beyond 10 years, if development is unchanged.

In program 2, the model shows water-table declines of up to 6 feet at the end of a 20-year simulation period (fig. 17). Here again, little further change would result under the fixed development pattern modeled in program 2. Although the indicated declines would probably not be critical in much of the aquifer, possible problem areas can be identified (west of Park Rapids; northeast of Ponsford; east of Huntersville). Declines of several feet could significantly affect yields in shallow wells or yields in places where the original saturated thickness is substantially reduced.

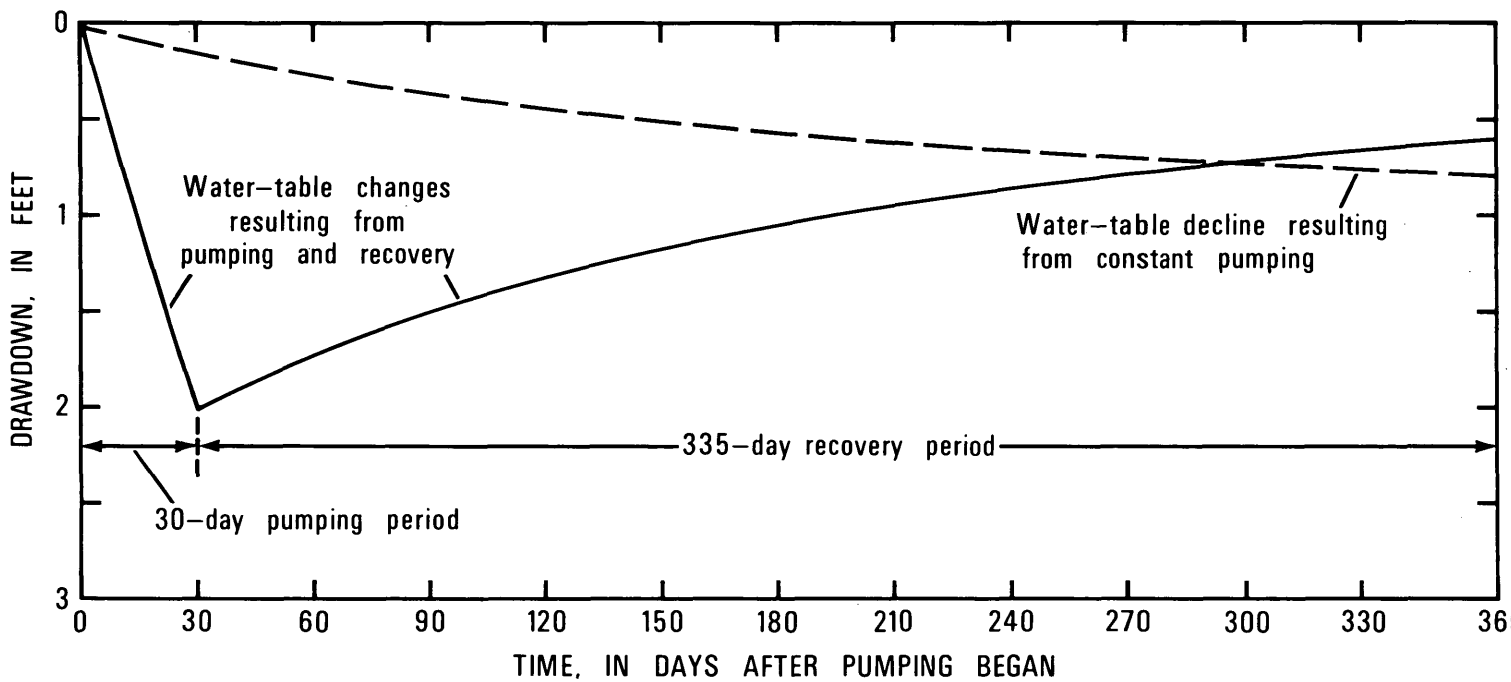


Figure 16.--Relation between regional water-table changes resulting from cyclical and constant pumping.

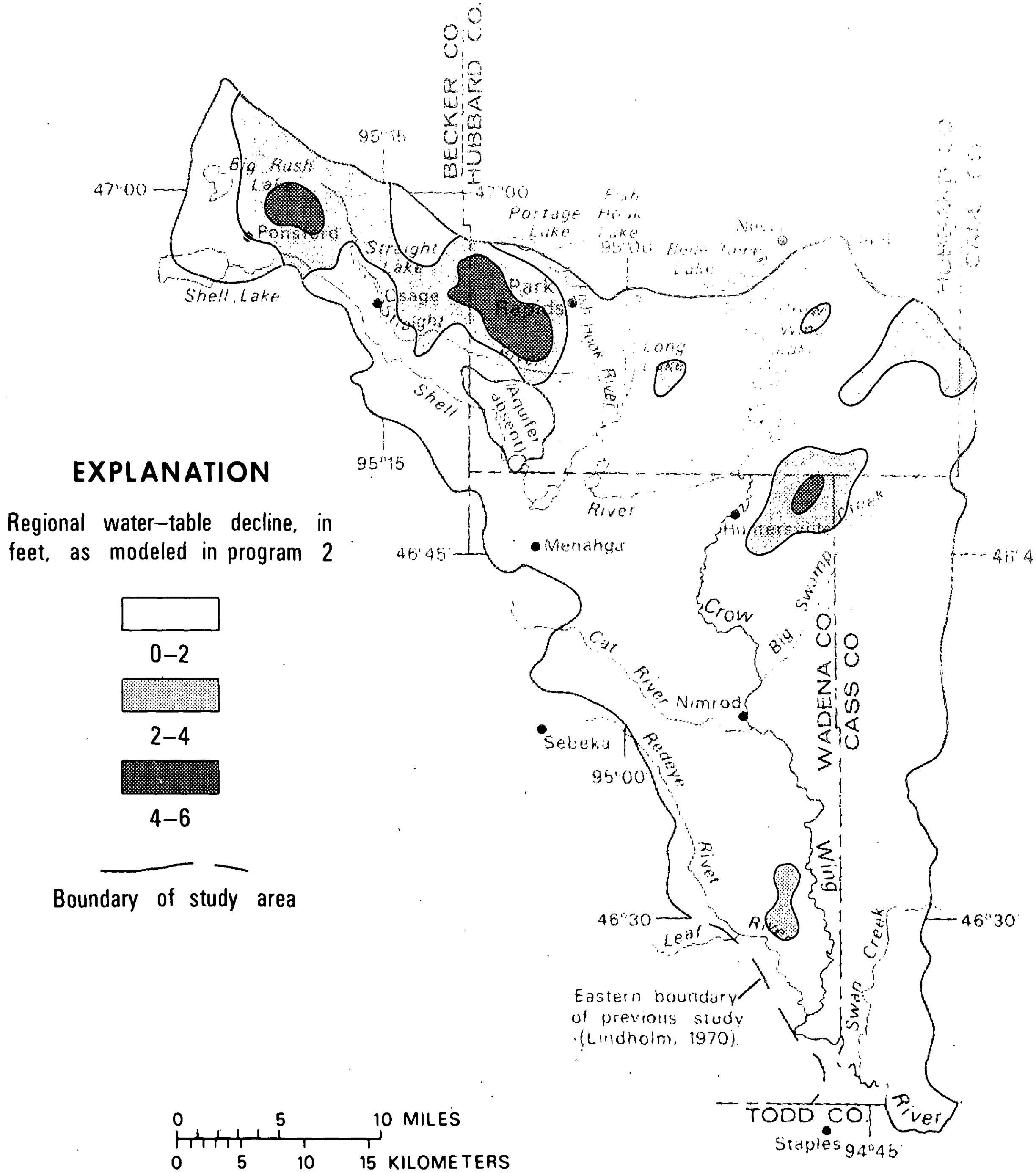


Figure 17.--Simulated water-table declines resulting from 20 years of pumping, as modeled in program 2.

In program 3, simulated water-table declines (fig. 18) are about twice as great as in program 2. Excessive lowering would occur over larger areas. Declines would be most severe near impermeable boundaries and away from larger streams or lakes. The small declines indicated near Long Lake and Crow Wing Lakes exemplify the stablilizing influence of surface-water bodies, even in heavily pumped areas.

Simulated Water-Budget Changes

Pumped water may come from storage within the aquifer or from resulting changes in inflow and outflow rates. The relative amounts derived from each source, under a given development pattern, vary with time (fig. 19). An explanation of the sources of water identified in figure 19 follows:

Storage - represents water removed from storage in the aquifer.

Streams - represents intercepted base flow to streams or induced infiltration from streams.

Lakes - represents intercepted discharge to lakes or induced infiltration from lakes.

Evapotranspiration - represents water diverted from discharge as evapotranspiration.

Underflow - represents increased ground-water flow across the northern boundary of the study area owing to increased gradients toward pumping centers.

Pumping from storage results in the water-table declines described previously. Storage provides most of the water pumped at the beginning and very little at the end of each simulation. Most long-term pumpage is intercepted stream base flow. Pumpage derived from other sources would vary considerably, depending on location because underflow, evapotranspiration, and discharge to lakes are each active only in small parts of the area.

Results of program 1 indicate that present development will cause no significant changes in the surficial aquifer system. Figure 19 shows that all components of the budget except underflow contribute water to the pumpage, but the small withdrawal rate in program 1 requires only small adjustments in the system.

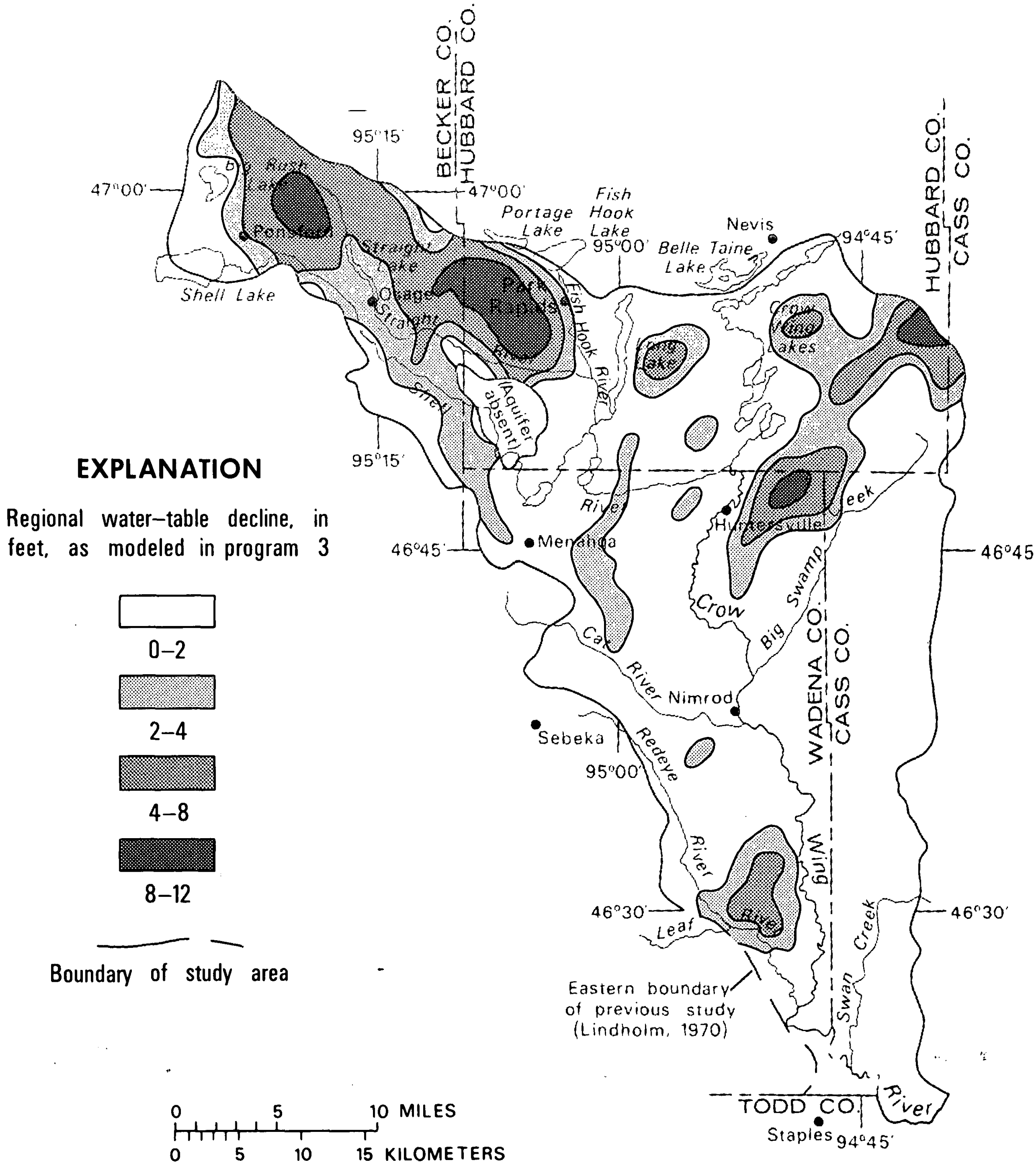


Figure 18.--Simulated water-table declines resulting from 20 years of pumping, as modeled in program 3.

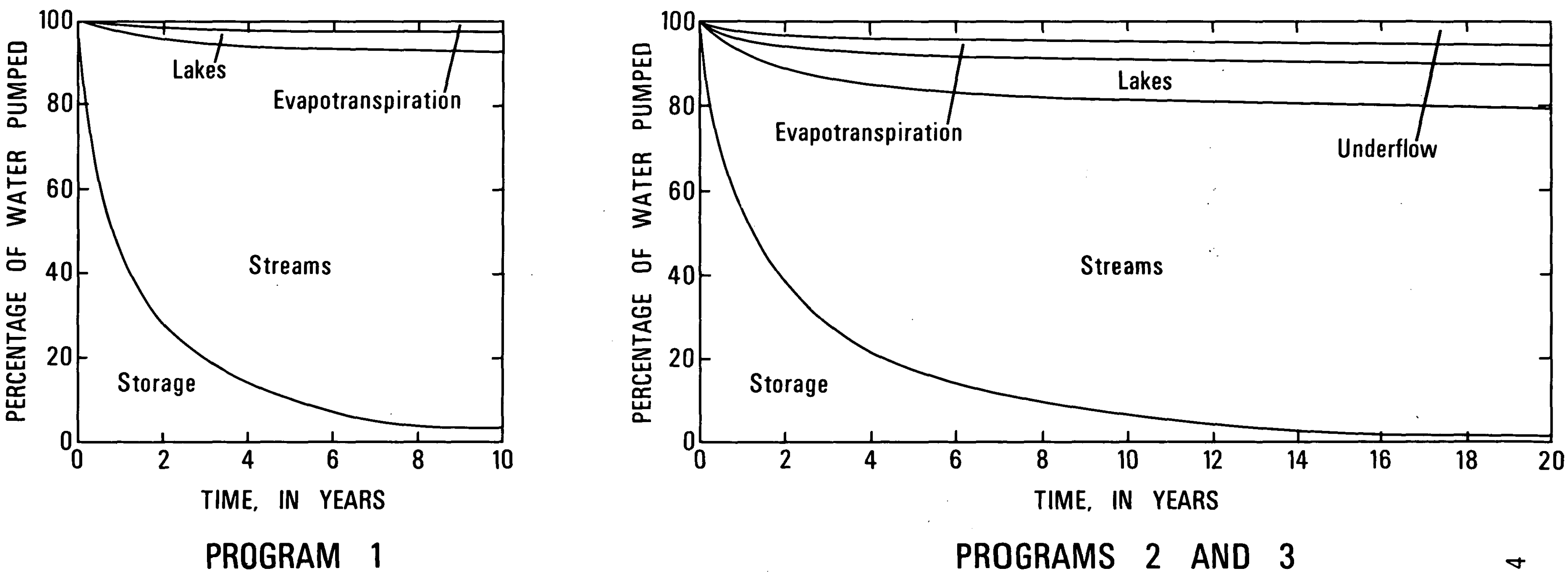


Figure 19.-- Simulated sources of water during 10 years of withdrawal, as modeled in program 1 and 20 years of withdrawal, as modeled in programs 2 and 3.

In programs 2 and 3, the percentages of water from each source at any given time are nearly the same and therefore are shown as a single graph.

Base flow to streams is reduced to 78 percent of its natural steady-state value in program 2 and to 56 percent in program 3. (Refer to table 4 for steady-state values.) In both simulations, only a few scattered nodes (part of Shell River southeast of Ponsford and parts of two small tributaries to the east side of Crow Wing River) were indicated to have more than their entire base flow (contributed within that particular node) intercepted. This suggests that, although ground-water pumping will reduce streamflow, it will probably not induce enough infiltration directly from streams to cause significant reaches of stream to go dry.

Ground-water discharge to lakes is reduced to 86 percent of its natural value in program 2 and to 72 percent in program 3. The effect on a specified lake depends on the relative importance of ground water in maintaining the lake level. Most large lakes have sufficient stream inflow, along with nonintercepted ground-water inflow, to maintain levels. Possible exceptions are as follows: (1) Big Rush Lake could be seriously depleted by development, as modeled in programs 2 and 3, (2) the levels of Twin Lakes (northeast of Menahga) and Shell Lake could decline slightly in response to pumping, as modeled in programs 2 and 3, and (3) the level of Blueberry Lake (north of Menahga) could decline in response to pumping, as modeled in program 3. Lakes and ponds that rely mostly on ground water for inflow might decline appreciably, particularly in areas of substantial water-table declines. (See figs. 17 and 18.)

The simulations show that diverted evapotranspiration forms a relatively small part of pumpage, because most expected development is not in areas of shallow water table.

Most increased underflow resulting from pumping would occur across the boundary of the northwestern part of the aquifer. In this area, modeled underflow increased about 20 percent in program 2 and 50 percent in program 3. Slight increases in underflow were indicated in the Belle Taine Lake area.

Qualifications of Results

The model identifies the capability of different parts of the surficial aquifer to support large-scale development.

Results are based upon sufficiently wide ranges in pumping intensities and withdrawal rates to provide useful references, as development is changed. Nevertheless, it is important that application of the model results take into account several qualifications.

Estimated average values of inflow and outflow were used to simulate the aquifer system. The real system will be influenced by climatic variations that need to be considered when evaluating hydrologic changes in the system. Furthermore, programs 2 and 3 are based on selected hypothetical patterns of development. Because actual development will undoubtedly differ, the model results should not be viewed as predictions, but rather as guides to estimate the effects that a given development pattern might have in a given area. It should also be recognized that the model simulates regional response to selected volumes of withdrawal, and problems of local well hydraulics should be treated separately. Finally, return flow of irrigation water to the aquifer was not included in this analysis; if the amount of return flow is significant, expected water-level declines could be smaller than those described here.

SUMMARY

Surficial outwash is the largest single source of ground water in the Pineland Sands area. The extent of buried outwash aquifers is unknown; however, available data suggest that they too may be favorable sources for supply in much of the area.

The surficial outwash aquifer varies considerably in water-yielding capability, depending on saturated thickness and texture of materials. Well yields of 500 gal/min are obtainable in much of the aquifer and exceed 2,000 gal/min in some northern parts of the aquifer. The water is chemically suitable for irrigation. Dissolved-solids concentration and hardness are generally greater in the northwestern half of the aquifer than in the southeastern.

The aquifer is recharged mostly from snowmelt and rainfall in the spring. It discharges mostly within relatively short distances to streams and lakes or as evapotranspiration in areas where the water table is shallow. Model analysis indicates that the natural system is not significantly affected by the present degree of development.

Simulations of hypothetical pumping show that considerable development of the surficial aquifer could be safely supported. If irrigation development were to include all irrigable land underlain by surficial outwash capable of individual well yields exceeding 500 gal/min, the water table and some lake levels would be adversely affected in some heavily pumped areas. In general, streamflow and levels of most large lakes would not be expected to be greatly affected. The model programs discussed above can be a useful tool in aiding decisions about development and management of ground water in the Pineland Sands area. However, decision makers should be ever aware of the limiting assumptions used to simulate the complex hydrologic systems in the area.

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