# Availability of Ground Water For Irrigation from Glacial Outwash in the Perham Area, Otter Tail County, Minnesota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2003

*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* HAROLD O. REEDER

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## CONTENTS



## ILLUSTRATIONS

# TABLES

# AVAILABILITY OF GROUND WATER FOR IRRIGATION FROM GLACIAL OUTWASH IN THE PERHAM AREA, OTTER TAIL COUNTY, MINNESOTA

By HAROLD O. REEDER

ABSTRACT

The Perham study area includes about 350 square miles of surficial deposits of glacial outwash in the central part of Otter Tail County in west-central Minnesota. The aquifer characteristics have a wide range, as follows: Transmissivity values range from nearly 0 along the perimeter of the area to more than 100,000 gallons per day per foot in the central parts of the area; storage coefficient values range from 0.1 to 0.2; and the saturated thickness of the upper outwash material ranges from nearly 0 to more than 100 feet. Most of the aquifer material is fairly well sorted and is in the particle-size range of fine to coarse sand.

Wells penetrating the full thickness of the aquifer and developed to 100-percent efficiency can be expected to yield 1,200 gallons per minute for 30 days and to have drawdowns of less than two-thirds the aquifer thickness in much of the area; however, well yields vary widely within short distances. Yields of 300 gallons per minute or less can be expected from wells drilled near the edges of the area and in the general area east and southeast of Otter Tail Lake.

Results from the mathematical analyses show that the amount of streamflow leaving the area will not be depleted within the 10-year analysis period, if not more than 6 inches of water per year is used on all the irrigable land in the outwash area. If pumpage and its effects on the streams is assumed to be prorated proportionately along the full length of the streams within the area, then the levels of lakes along these streams generally will not be lowered appreciably. However, owing to the heterogeneity of the aquifer and the other variable factors involved, some reaches of the streams may cease to flow when full ground-water development is approached, which, in turn, would result in a decline in some lake levels. Lakes and ponds not connected to streams in the area are expected to be lowered considerably or to be dried up completely as pumping becomes more extensive in years to come.

If irrigation wells and other large-yield wells in the study area are spaced 1 mile or more away from streams and lakes, the effect of ground-water pumping on the streams will be small, and the lake levels will be affected very little. However, the lakes and ponds are expected to approach normal levels during periods of above-normal precipitation and during periods of no pumping.

# INTRODUCTION

The present study of ground water in the Perham 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 of the Minnesota Department of Conservation.

## PURPOSE OF INVESTIGATION

This investigation was one of several studies made primarily to obtain information on the water resources of sandy soil areas in Minnesota, where irrigation might be feasible by using ground water from surficial aquifers to supplement precipitation. Crop yields in unirrigated areas are generally poor because the normal rainfall is insufficient to supply crops during the main part of the growing season and because the sandy soils have a low water-holding capacity. The purpose of the study was to investigate the adequacy of both the quantity and the quality of ground water in the upper sand-and-gravel aquifer for irrigation, to determine the areal extent and thickness of these deposits; to determine the potential yield that can be anticipated from ground-water development for irrigation on a long-range basis; to predict the effects of this development on the local water system; and to provide guidelines to local planners and irrigators in the development of the water resources in the area.

## LOCATION AND EXTENT OF AREA

The study area includes about 350 square miles in the central part of Otter Tail County in west-central Minnesota (fig. 1). The boundary of the study area is based primarily on the type of soil and on the extent of the surficial deposits of glacial outwash sand. The major towns in the area are shown in figure 1. About 90 lakes, each having a surface area of 10 acres or more (Minnesota Division of Waters, Soils, and Minerals, 1969, p. 306–327), lie within the study area and cover about 24 percent (84 square miles) of the area. The largest lakes, in square miles, are Otter Tail, 21.7; West Battle, 8.9; Rush, 8.3; and Big Pine, 7.5. Also, swamps cover an additional 10 to 15 percent of the study area.

Most of the study area is in the Otter Tail River watershed, but a small part southeast of Otter Tail Lake is in the Crow Wing River watershed (fig. 1), as outlined in the Hydrologic Atlas of Minnesota (Minnesota Division of Waters, 1959, Units VIII and XVI).

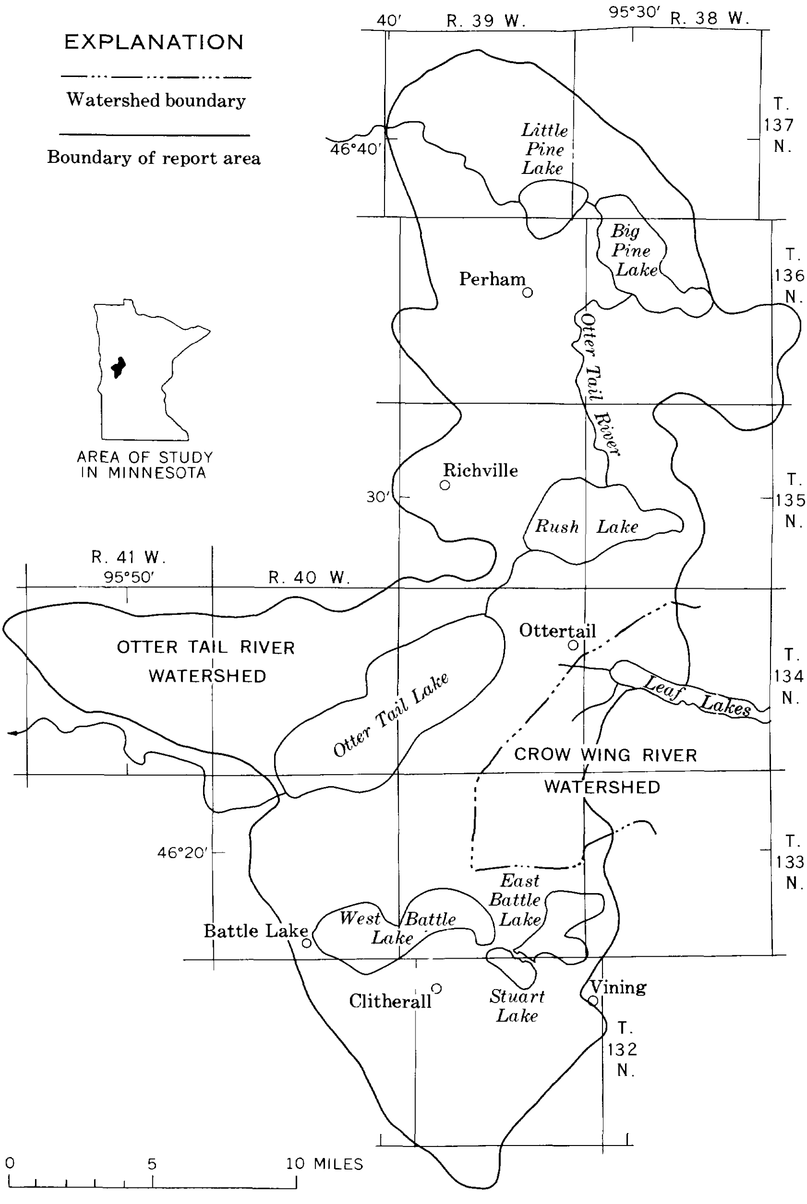



**FIGURE 1.**—Index map showing location and areal extent of the Perham study area in west-central Minnesota.

## PREVIOUS INVESTIGATIONS

Upham (1888) first summarized the geology and natural history of Otter Tail County and included some ground-water data. Later, Allison (1932, p. 143–152) discussed Otter Tail County generally in his study of the geology and water resources of northwestern Minnesota. The area was included in the report on the glacial geology of Minnesota and adjacent States by Leverett (1932). The U.S. Geological Survey, in cooperation with the Minnesota Division of Waters, Soils, and Minerals, is engaged in an appraisal of the water resources of the 39 watersheds in the State. As part of this study, hydrologic atlases were prepared of the Otter Tail River watershed (Winter and others, 1969) and of the Crow Wing River watershed (Lindholm and others, 1972). These atlases include all the present study area (fig. 1).

## METHODS OF PRESENT INVESTIGATION

Many farmers and other residents were visited to determine the present source of water supplies and to collect information on existing wells, such as diameter, depth, water level, and other pertinent data. Particular emphasis was placed on locating wells in which the depth to water could be measured, so that the direction of ground-water movement could be determined. Data were collected on about 200 wells, including more than 100 wells in which the depth to water was determined. Twenty-three existing wells were selected for the periodic measurements used to determine the seasonal fluctuations in water levels. Water levels in several additional existing wells were measured two or three times during the study to determine the yearly fluctuations only.

Fifty-nine test holes were drilled with a power auger in November 1967 and in June 1968 for a total footage of about 4,300 feet. About 2,200 feet of pipe and sandpoints were installed in 44 of the augered holes. The test holes with pipe were developed with forced air for use as observation wells. Recording gages were installed in five of the test holes and in one existing well to obtain a continuous record of water-level fluctuations. This augering was in addition to the 59 test holes augered in 1965 for the Otter Tail River watershed study (Winter and others, 1969). Information obtained from test drilling includes thickness and extent of the upper sand aquifer, depth to water, grain size of the material penetrated, and estimated water-bearing characteristics of the material. Twenty-eight samples of materials from auger holes and 37 samples from near the land surface in road cuts and sand pits were sent to the U.S. Geological Survey laboratory in Denver, Colo., for permeability, specific-yield, and grain-size determinations.

Of the 44 augered test holes in which sandpoints were installed, 13 were placed near existing irrigation wells for use as observation wells during pumping tests. Pumping tests were run at eight sites to determine aquifer characteristics.

Streamflow measurements were made at six sites in October of 1967 and at 12 sites in June and in August of 1968 to determine natural ground-water discharge to the streams and to determine rates of inflow and outflow. Also, levels of lakes and streams were measured periodically at 16 sites.

Six ground-water samples were analyzed by the U.S. Geological Survey. These samples were collected during pumping tests made of irrigation wells in the summer of 1968. Seven other ground-water samples from the area were analyzed by the Survey during the watershed study in 1965.

## WELL-NUMBERING SYSTEM

The system of numbering wells and test holes is based on the U.S. Bureau of Land Management's system of subdivision of public lands. The Perham area is in the fifth principal meridian and base line system. The well number, in addition to designating the well, locates its position in the land network. The first segment of a well number indicates the township north of the base line; the second, the range west of the principal meridian; and the third, the section in which the well is located. The lowercase letters a, b, c, and d, following the section number, locate the well within the section. The first letter denotes the 160-acre tract, the second denotes the 40-acre tract, and the third, 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 designate the wells within one 10-acre tract.

Figure 2 illustrates the method of numbering a test hole. Thus, the number 136.39.19abd1 identifies the first well or test hole designated in the SE¼NW¼NE¼ sec. 19, T. 136 N., R. 39 W.

## ACKNOWLEDGEMENTS

Many well owners and other residents, well drillers, and public officials provided data used in the preparation of this report. The author thanks these people for providing information and assistance. Special appreciation is extended to those irrigators who permitted the use of their wells, equipment, and land for conducting pumping tests; to those residents who recorded precipitation data; and to those who permitted installation of water-level-recording instruments.

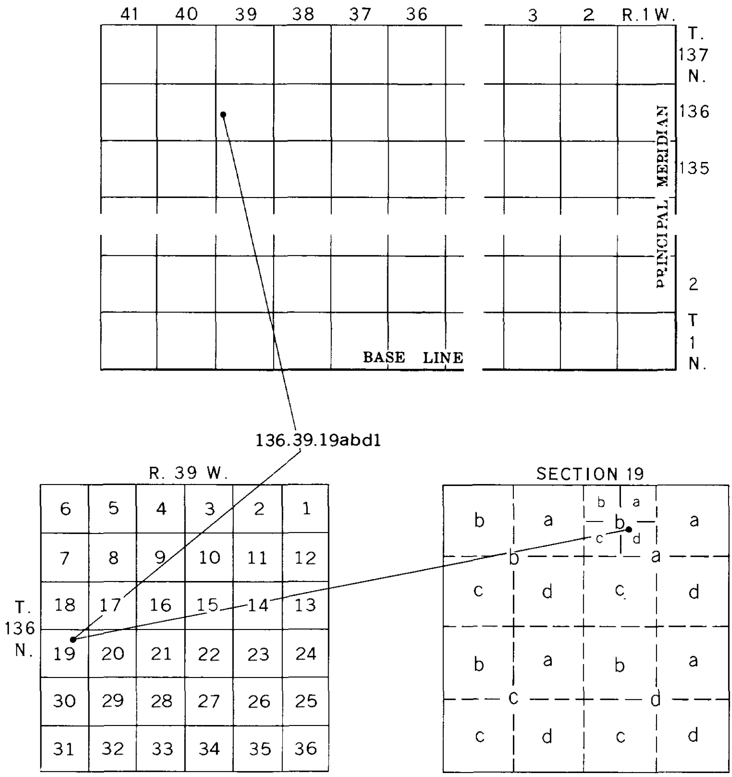



FIGURE 2.—System of numbering wells and test holes in Minnesota.

## HYDROGEOLOGY

This study was primarily of water in the upper sand of the glacial outwash. The upper outwash consists mostly of sand, but also contains various gradations of sand and gravel and, in some places, lenses of clay. The outwash sand and gravel is overlain by sandy loam and loamy sand at the surface and is underlain in most places by clay ranging in thickness from a few feet to several tens of feet. The thickness of the upper outwash sand above the first massive clay layer ranges from 0 to more than 100 feet. Few test holes were drilled through the first massive clay into the sand below because the primary purpose of the study was to determine properties of the sand above the first massive clay.

Grain-size determinations were made on 43 of the 65 samples of the outwash material collected. The materials in most of the 43 samples were fairly well sorted and ranged in particle size from fine (0.125–0.25 mm (millimeter) diameter) to coarse (0.5–1.0 mm) sand. One sample consisted predominantly of very coarse (1–2 mm) sand, but ranged in size from coarse sand to very fine (2–4 mm) gravel. Several samples, however, were poorly sorted and ranged in size from fine sand to very fine gravel. Almost all the samples contained some particles the size of clay and silt (less than 0.0625 mm).

The total thickness of the glacial drift (the upper outwash and the underlying layers of clay and sand) above the bedrock is known only generally; however, the drift is thinnest near Perham and Big Pine Lake, where bedrock is only about 200 feet below land surface. (See Winter and others, 1969.)

As this study was made primarily of the upper outwash sand, a map was prepared of the altitude of the base of the upper sand —that is, the contact between the upper sand and the first massive clay layer (pl. 1*A*). The configuration of the base of the sand shows three areas of fairly thick, or deep, sand deposits that are separated at depth by narrow subsurface ridges of finer grained material. One of the sand deposits covers the northern third of the area; a smaller area is in the vicinity of Rush Lake; and the third area is in the southwestern part of the area, in the vicinity of Otter Tail Lake.

At least one sand layer exists in places below the first massive clay layer. Large potential water supplies in the deeper sand have been proved in a few wells. A possible solution to obtaining ground-water supplies where the upper sand is absent, or where the water in it is inadequate, is the deeper exploration for water in the sand deposits below the massive clay.

A more complete description of the geology of the area can be found in the previous studies listed in "References." The most recent geologic map of the area was prepared by Winter, Bidwell, and Maclay (1969).

## THE GROUND-WATER TABLE AND GROUND-WATER MOVEMENT

The upper surface of the ground-water reservior throughout most of the Perham area is a free water surface (the water table). Under water-table conditions, the surface of the water is in contact with the overlying zone of aeration. In those places, the water level stands in a well at the depth at which water is found. In some places, however, ground water may be confined locally, such as where a clay lens extends down into the ground-water reservoir. The ground water in these confined areas is more characteristic of artesian conditions. Although local artesian conditions were recognized in places in the Perham area at least part of the time, the aquifer as a whole is characteristic of water-table conditions; therefore, the term "water table" or "water level" is generally used in this report in lieu of the term "piezometric surface."

The water table is not a flat smooth surface, but it generally is much smoother than the overlying land surface. Thus, appreciable differences in depth to water from one place to another in the wells finished in the same aquifer result generally from differences in the altitude of the land surface, rather than from differences in the altitude of the water table.

The depth to water in wells in the Perham outwash area generally is about 5–30 feet below the land surface, but ranges from 0 to about 70 feet, depending upon the topography of the area. The proximity of lakes or streams gives some visual indication of the depth to water at a particular place. Because of the irregularities in the land surface, a comparison of the form, or altitude, of the water table shown in plate 1*B* with that of the land surface at a particular place is a better way to predict the depth to water in a well to be drilled.

Depths to water were measured in augered test holes and in existing water-supply wells. Altitudes of the land surface at the wells were determined from topographic maps. Plate 1*B* shows altitudes of the water table and was prepared from data on the altitudes of wells, the depth to water as measured in the wells and test holes, and the altitudes of lake levels. Water is assumed to move downgradient perpendicular to the mapped water-table contours; hence, the direction of water movement can be inferred. However, the gradient of the water table alone is not indicative of the rate or the volume of water movement.

Ground-water movement, as indicated by the water-table contours on plate 1*B*, is generally toward the Otter Tail River—either toward the river channel or toward the lakes along the river—and, then, in the same general direction as the flow of the river. In the area east of Otter Tail Lake, ground-water movement is indicated toward the Leaf River and toward its tributary lakes.

Ground-water levels in the Perham area fluctuate in response to several natural phenomena and, also, in response to pumping for irrigation, commercial use, and other purposes. The major natural cause of ground-water fluctuations in the Perham area is the change in the relation between recharge and discharge. As water is recharged (or added) to the system, ground-water levels rise; and as water discharges from the system, water levels decline. In general, water levels in the area rise sharply during the spring thaw, when water is available and can move downward to the water table. Throughout the rest of the year, water levels gradually decline except as affected by precipitation. The magnitude of the seasonal fluctuation in the area from August 1967 through June 1969 generally did not exceed about 4 feet and, at most places, amounted to no more than 2 feet. Graphs of the depth to water in representative wells are shown in figure 3. In April 1969 a larger, much sharper rise in water levels occurred in all wells than in the spring of 1968 because of the greater amount of precipitation in the winter of 1968-69, which caused more water to be available for recharge during the spring thaw.

## RECHARGE

The primary source of recharge to the upper outwash sand in the Perham area is precipitation directly on the outwash deposits. The average annual precipitation in the area is about 24 inches (Baker and others, 1967).

As recharge to the ground-water reservoir can occur only after the soil-moisture deficiency is satisfied, the amount of recharge from a given rain is difficult to predict. The intensity and duration of a rain and the plant requirements, as well as soil type and grain size, also affect the amount of recharge. Consequently, recharge is not necessarily proportional to yearly precipitation, although, when the annual precipitation is large, recharge is generally greater than during relatively dry years.

The changes in water levels, as noted in observation wells and discussed previously indicate that most recharge to the ground-water reservoir generally occurs during the spring thaw, when water is available and can move downward to the water table. During that time of year the water requirements of plants are small. The rises of water levels in observation wells in April 1969 were multiplied by the specific yield, estimated to be 0.2, to determine the amount of recharge to the ground-water reservoir, expressed in inches. Figure 4 shows the generalized values of recharge from precipitation in the study area. In much of the area, an average of 5–6 inches of the annual precipitation reaches the ground-water reservoir (fig. 4).

Some ground-water recharge enters the area by underflow (ground water) moving into the area (See fig. 6.) Slope of the water table around part of the perimeter of the study area is

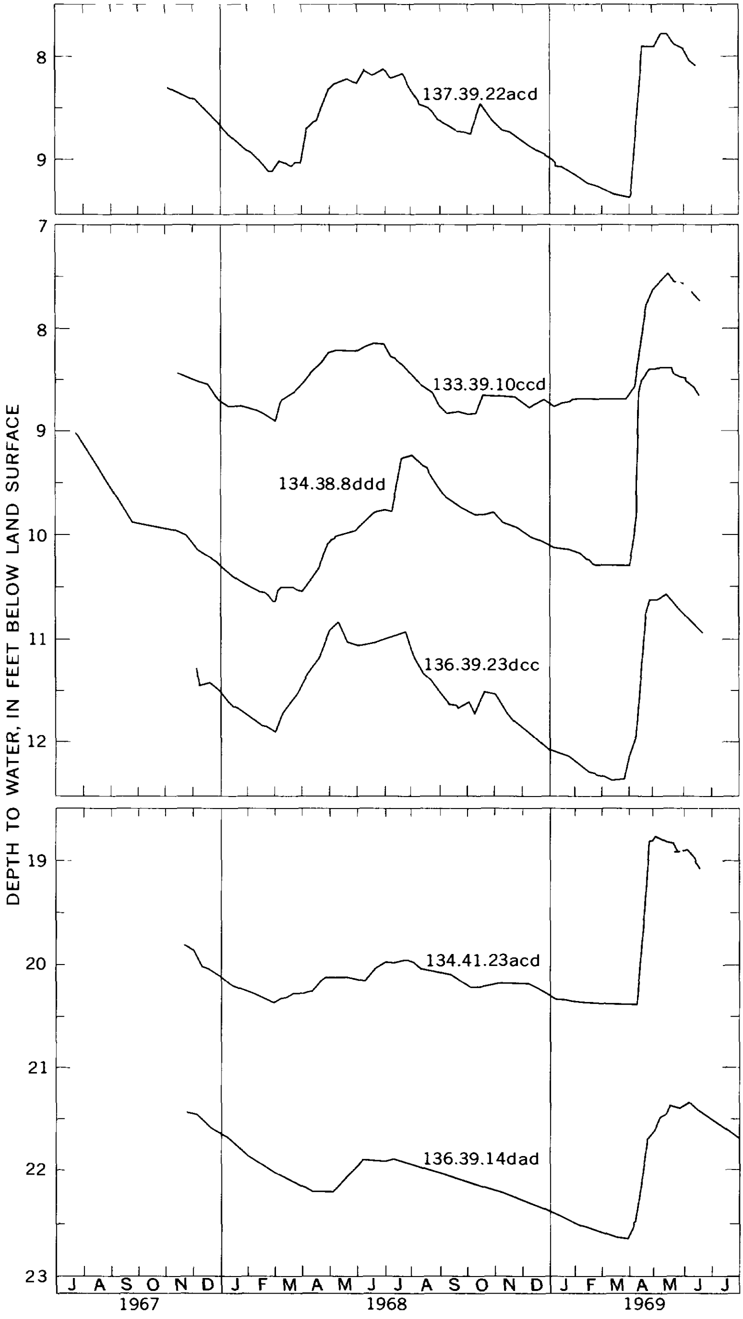



FIGURE 3.—Fluctuations in ground-water levels in the study area.

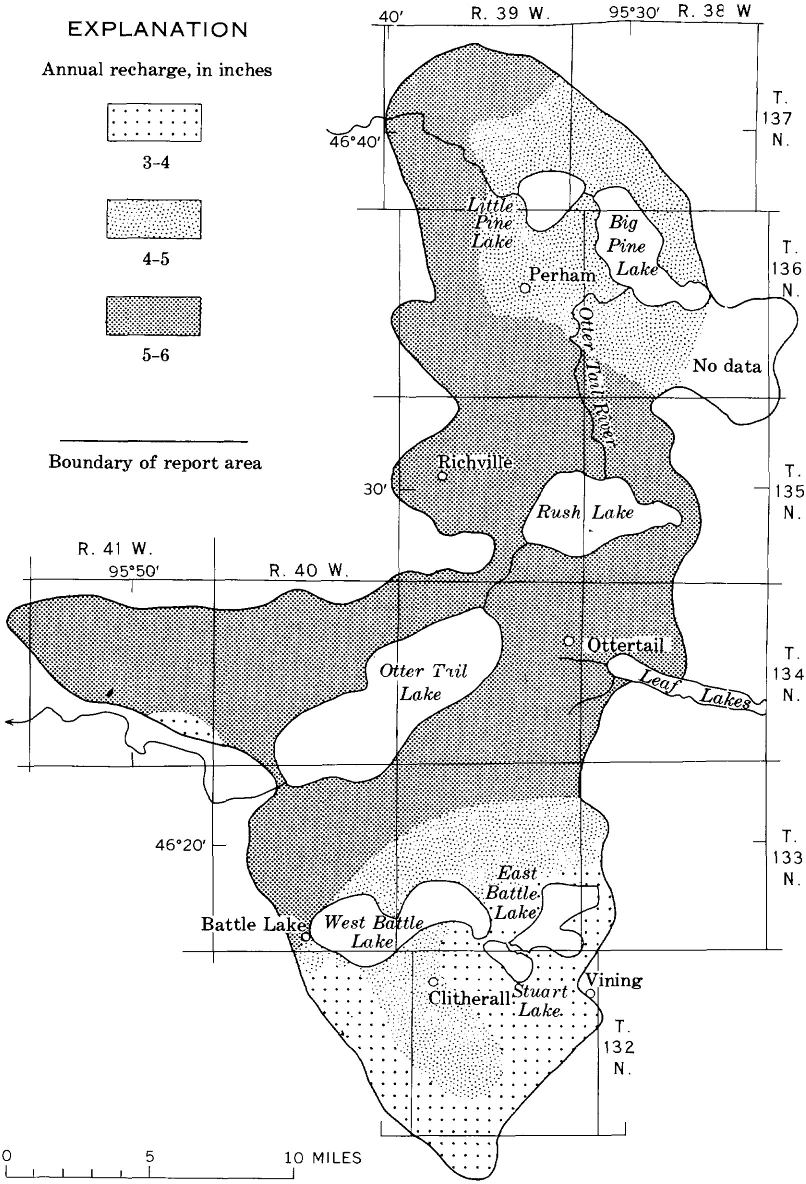



FIGURE 4.—Annual recharge, in inches, to the ground-water reservoir from precipitation.

indicative of ground-water movement (pl. 1*B*). However, the quantity of water moving is considered to be very small around most of the perimeter because of the much finer grained sediments, the low permeabilities of the till, and the small saturated thickness where sand occurs along the perimeter.

A significant amount of water apparently enters as underflow at the north-northwest end of the area. About 5,000 acre-feet of water per year is estimated to move into the area, primarily in T.137 N., R.39 W. (Gorman Township). (See fig. 6.)

Otter Tail River and several smaller streams bring water into the area but do not contribute significantly to ground-water recharge. In fact, the ground-water reservoir discharges water to streams within the area, so that more streamflow leaves the area than enters it. Streamflow measurements were made at 12 sites in the area during the study period. The total rate of measured streamflow entering the area was about 70 cfs (cubic feet per second) in October 1967, 240 cfs in June 1968, and 110 cfs in August 1968. These three measurements indicate the wide variability in the amount of streamflow from season to season and from year to year.

Some of the water pumped for irrigation probably returns to the ground-water reservoir by downward percolation, but the amount, at present, is considered to be negligible. However, as the practice of irrigation is used more and more in the study area over a longer period of time, some surplus irrigation water may return to the aquifer as recharge.

## DISCHARGE

Ground water is discharged from the area naturally and artificially. Natural discharge is that from streams, lakes, swamps, marshes, and underflow, as well as from evaporation and transpiration. Artificial discharge is that from pumping of wells.

Ground water moves to the streams and lakes, as shown by the water-table contour map (pl. 1*B*), where it discharges into the surface-water bodies. The Otter Tail River is the largest outlet from the area, although some water leaves the area through the Leaf River. The measured rate of stream-flow from the area in June 1968 was 370 cfs in the Otter Tail River and 10 cfs in the Leaf River, and in August 1968, the measured rate was 218 cfs in the Otter Tail River and 2 cfs in the Leaf River. Continuous measurement of streamflow from the area was not made.

Some ground-water discharge leaves the area by underflow. The primary area of ground-water underflow from the area is in the vicinity of the Otter Tail River at the southwest end of Otter Tail Lake, where underflow is estimated to be about 5,000 acre-feet of water per year. (See fig. 6.) Also, a small amount of underflow is discharged from the area in the vicinity of the Leaf River.

Much of the water discharged from the area is lost by evapotranspiration—that is, by a combination of direct evaporation of soil moisture and surface water and of moisture transpired by plants. In areas where the ground water is near the land surface, the water is evaporated directly from the land surface by capillary action. Also, the plant roots in a large part of the area reach the ground water reservoir and remove water by transpiration. Swamps, marshes, lakes, and streams that are supplied from ground-water sources have large water-surface areas exposed to the atmosphere, where large quantities of water are lost by evaporation. The average annual evaporation rate in the area from surface-water bodies, such as lakes, is 30 inches (Veihmeyer, 1964). Evaporation and transpiration losses from the ground-water reservoir can be reduced by lowering ground-water levels by pumping.

## TEMPERATURE

The temperature of ground water may differ from place to place areally in the same aquifer. However, because of the slow, nearly uniform movement of ground water, the temperature at any given place and depth below the zone of influence from seasonal changes in temperature at the ground surface generally remains relatively constant. Pumping may disturb the natural temperature gradients. The temperature of ground water immediately below the zone of influence from seasonal temperature fluctuation is generally expected to be a few degrees higher than the mean annual air temperature of the area. The mean annual air temperature in the central part of the Perham area is 40°F (4.4°C) (Baker and Strub, 1965).

The temperature of water in seven irrigation wells during pumping ranged from 7.8° to 9.4°C (46° to 49°F, respectively). Ground-water temperatures were also measured with a probe and remote reading meter in a number of the 2-inch-diameter observation wells in June and October of 1968. The temperatures at a depth of 50 feet in the observation wells ranged from 6.7°C (44°F) to 8.3°C (47°F). Above a depth of about 50 feet, however, the water temperatures had a wider range, depending largely on the time of year the measurements were made. In

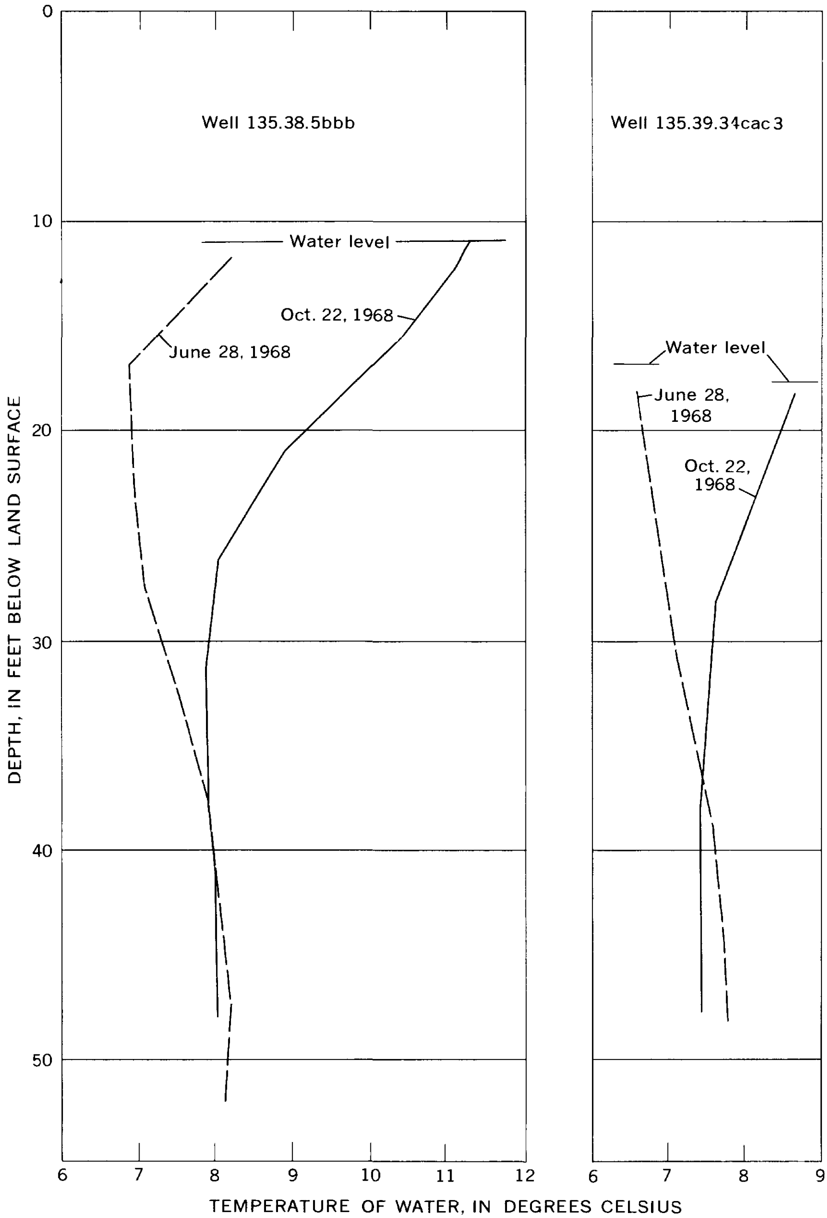



FIGURE 5.—Relation between ground-water temperature and depth below land surface in two observation wells.

general, however, the temperatures measured, in June, at depths of less than 50 feet were lower than those measured at 50 feet, but in October they were higher. Figure 5 graphically shows the relation between water temperature and depth below land surface in two typical observation wells.

## CHEMICAL QUALITY

Ground water dissolves some of the mineral matter from the rocks through which it moves. Table 1 lists 14 chemical analyses of water from the Perham area; six of the samples were collected from irrigation wells during pumping tests made in July and September of 1968, and eight were collected in 1964 and 1965 as part of the Otter Tail watershed study.

The dissolved solids in ground water in the study area consist predominantly of calcium, magnesium, and bicarbonate. Well-screen incrustation problems may occur, owing to these constituents. Several analyses of water showed relatively high concentrations of nitrate. Calcium, magnesium, and nitrate are essential plant nutrients and are desirable in reasonable concentrations. However, excessive concentrations of nitrate and chloride in ground water are indicative of pollution, probably from barnyard and domestic sewage, but, conceivably, also from the use of fertilizers. As the water-quality change resulting from use of fertilizers will probably become a more serious problem with the greater development of irrigation, several wells should be sampled periodically to detect possible adverse quality changes in the water.

Sodium, boron, and salinity can be harmful to plant growth. Small concentrations of boron in irrigation water is toxic to certain crops. However, all the water samples analyzed for boron had concentrations well below the amount considered to be toxic, even to boron-sensitive crops (Wilcox, 1955).

A generally significant factor in determining the suitability of water for irrigation is the concentration of sodium in the water. High concentrations of sodium in irrigation water tends to reduce the permeability of the soil, unless adequate leaching occurs. The sodium concentration in water in the Perham area is within satisfactory limits.

Water in the Perham outwash area meets Minnesota Water Pollution Control Commission standards for domestic consumption for all constituents, except for the few samples (table 1) that showed higher than desirable concentrations of iron and manganese, and one sample that showed excessive concentrations

TABLE 1.—*Laboratory chemical analyses of ground water in the Perham area, Minnesota*

[Results in milligrams per liter, except as indicated. Agency making analysis: USGS, U.S. Geological Survey; MDH, Minnesota Department of Health]

| Well location | Depth of well (ft) | (Date of collection) | Temperature (°C) | Agency making analysis | Silica ($SiO_2$) | Iron (Fe) | Manganese (Mn) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) | Bicarbonate ($HCO_3$) | Carbonate ($CO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Orthophosphate | Boron (B) | Dissolved solids | Hardness as $CaCO_3$: Calcium, magnesium | Hardness as $CaCO_3$: Noncarbonate | Sodium-adsorption-ratio | Specific conductance (micromhos at 25°C) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 133.40.15cdc | 54 | 9-14-68 | 9.4 | USGS | ---- | 0.02 | 0.07 | 50 | 16 | 1.1 | 2.2 | 218 | 0 | 14 | 1.0 | 0.1 | 3.3 | 0.09 | 0.02 | 218 | 189 | 10 | 0.03 | 360 | 8.0 |
| 133.40.34cdb | 71 | 6-20-64 | 13 | USGS | 26 | .02 | .01 | 61 | 30 | 6.4 | 3.0 | 282 | 0 | 25 | 12 | .2 | 20 | .04 | .03 | 356 | 275 | 44 | .2 | 544 | 7.7 |
| 134.39.1acd | 55 | 9-18-68 | 8.9 | USGS | ---- | .60 | .13 | 33 | 16 | 2.5 | 1.6 | 159 | 0 | 16 | 2.2 | .1 | 11 | .02 | .02 | 188 | 149 | 18 | .09 | 298 | 8.1 |
| 134.39.3bad | 24 | 9-16-65 | ---- | USGS | 20 | .15 | .06 | 59 | 16 | 2.2 | 1.2 | 202 | 11 | 10 | 3.7 | .1 | 23 | ---- | 0 | 254 | 212 | 28 | 0 | 403 | 8.4 |
| 134.40.32aaa | 200 | 9-16-65 | ---- | USGS | 23 | 1.5 | ---- | 35 | 19 | 9.6 | 3.0 | 227 | 0 | .2 | 1.2 | .2 | .5 | ---- | .10 | 208 | 165 | ---- | 0 | 343 | 8.1 |
| 135.39.35bbb | 56 | 9-11-68 | 8.3 | USGS | ---- | 1.9 | .28 | 38 | 20 | 3.1 | 1.8 | 170 | 0 | 28 | 2.6 | .1 | 21 | .02 | .03 | 223 | 178 | 39 | .1 | 347 | 8.0 |
| 136.39.14cc | 100 | 6-20-64 | 8.3 | USGS | 19 | .02 | .03 | 76 | 25 | 8.0 | 2.0 | 307 | 0 | 32 | 5.4 | .2 | 18 | .05 | .06 | 354 | 294 | 0 | .2 | 570 | 7.8 |
| 136.39.14dad | 68 | 7-30-68 | 9.4 | USGS | ---- | .03 | .06 | 60 | 23 | 4.5 | 1.8 | 224 | 0 | 51 | 9.0 | .1 | 15 | .01 | .01 | 311 | 245 | 62 | .1 | 485 | 7.9 |
| 136.39.19abd | 115 | 9-12-68 | 8.3 | USGS | ---- | .00 | .00 | 28 | 22 | 1.7 | 1.2 | 147 | 0 | 15 | 2.4 | .1 | 34 | .03 | .02 | 204 | 163 | 42 | .06 | 321 | 8.0 |
| 136.39.32cac | 105 | 7-25-68 | 7.8 | USGS | ---- | .22 | .39 | 21 | 21 | 1.9 | 1.8 | 145 | 0 | 19 | 2.8 | .1 | 10 | .00 | .02 | 176 | 139 | 20 | .07 | 285 | 8.0 |
| 136.39.35dad | 68 | 9-16-65 | ---- | USGS | 25 | .04 | 0 | 43 | 25 | 1.6 | 1.0 | 222 | 0 | 8.5 | 2.8 | .1 | 23 | ---- | 0 | 253 | 212 | ---- | 0 | 400 | 8.0 |
| 137.37.33baa | 180 | 7-12-65 | ---- | MDH | ---- | 5.9 | <.02 | 88 | 31 | 7.0 | 2.0 | 464 | ---- | <5 | .7 | .2 | 4.4 | ---- | ---- | 410 | 350 | ---- | ---- | ---- | ---- |
| 137.39.19dca | 40 | 7-12-65 | ---- | MDH | ---- | .09 | <.02 | 108 | 27 | 3.0 | 1.6 | 314 | ---- | 30 | 14 | .1 | 80 | ---- | ---- | 680 | 380 | ---- | ---- | ---- | ---- |
| 137.39.24bbc | 24 | 9-16-65 | ---- | USGS | 22 | .03 | ---- | 30 | 21 | 1.5 | 1.2 | 163 | 0 | 7.8 | 2.1 | .1 | 28 | ---- | 0 | 203 | 161 | 27 | 0 | 315 | 8.1 |

of nitrate and dissolved solids. Iron and manganese should not exceed 0.3 and 0.05 mg/l (milligrams per liter), respectively, according to the Minnesota Water Pollution Control Commission (1967, p. 8). Nitrate and total dissolved solids should not exceed 45 and 500 mg/l, respectively.

## AQUIFER CHARACTERISTICS

The thickness and character of the material forming a water-bearing bed, or principal aquifer, directly affect its hydraulic characteristics. The two principal hydraulic properties of aquifers that influence the yield of water to wells and the accompanying lowering of water levels are the transmissivity and the storage coefficient. The volumetric difference between the prepumping, or static, water level and the water-level surface resulting from the pumping is indicated by the size and depth of the cone of depression. In the Perham area the measurable effects of pumping for irrigation have not yet reached out very far (only a few hundred feet) from the pumped wells.

In the initial period of pumping, the discharge of a well is released from aquifer storage in the immediate vicinity of the well. As pumping continues, a greater percentage of the water released is from storage at greater distances from the pumped well. The increase in the volume of water released from storage at greater distances is accompanied by a decrease in the rate of water-level decline at the pumped well. The decline in water level will continue, at a decreasing rate, unless the discharge rate is changed. If the area of influence caused by pumping reaches relatively impervious boundaries, such as till adjacent to outwash, the rate of decline will increase. If the area of pumping influence reaches areas of discharge, such as streams and lakes, or reaches areas of recharge (which can also be streams and lakes), the rate of decline will decrease. The greater the storage coefficient, the less the water levels are lowered to supply a unit volume of water. Figure 6 shows the approximate locations of barrier boundaries (sand-till contact) of relatively impervious material, and major streams and lakes which act as recharge boundaries. Primary places of underflow into and out of the area are also shown.

In the Perham area, recharge to the aquifer supplying water to pumped wells can, in time, be increased by lowering water levels. Pumping can intercept natural discharge from the aquifer and, also, can induce recharge to the aquifer by increasing the gradient, or creating a gradient, toward the well, both of which

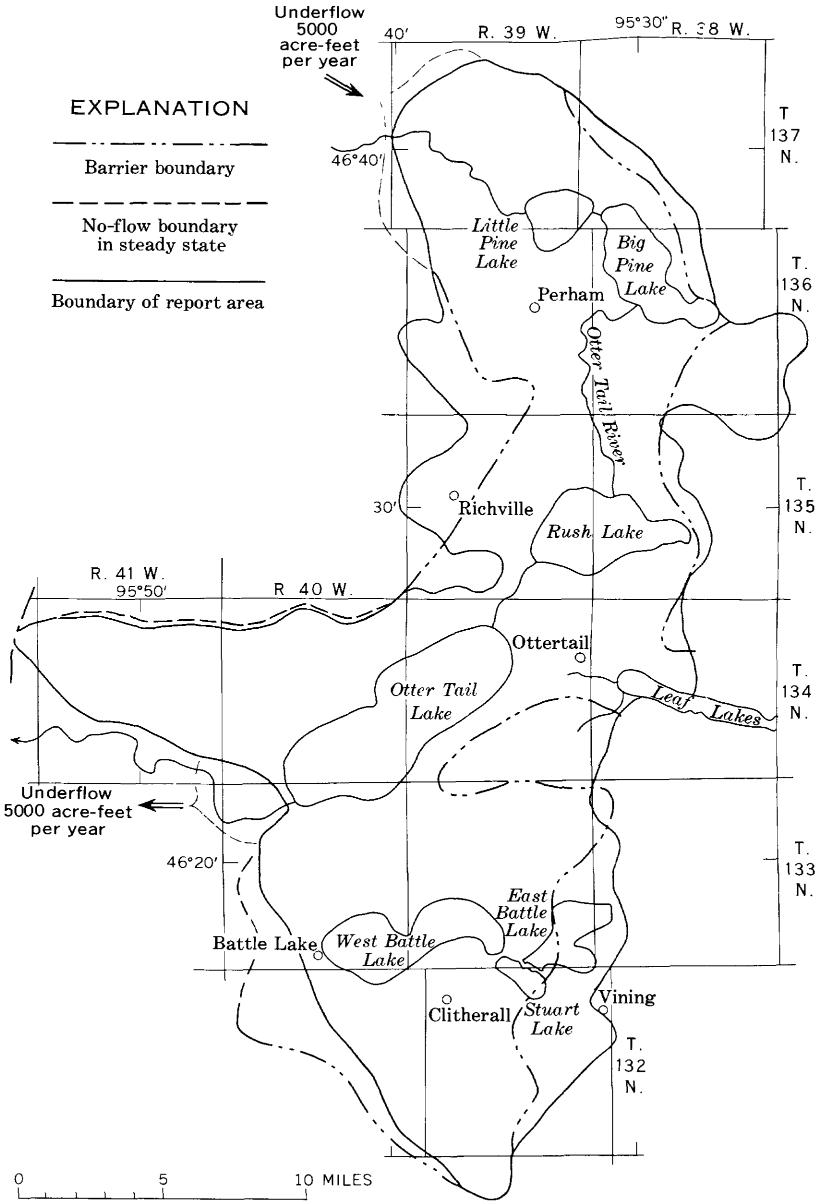



FIGURE 6.—Approximate locations of barrier boundaries (sand-till contact), recharge boundaries (major streams and lakes), and underflow into and out of the study area.

result in reducing streamflow. Development of ground-water supplies in the study area to date (1971) has accomplished this significantly only where the wells are within a few hundred feet of streams or lakes. As more wells are drilled, a significant decrease in streamflow is expected. Also, in the vicinity of swamps and other areas of natural ground-water discharge by evapotranspiration, water can be salvaged, by lowering water levels, and utilized possibly to a greater economic advantage than its use in the natural state.

The rate of decline in water level, the period of time that a given discharge rate can be sustained, and the effects on streamflow depend largely on the amount of water pumped, the spacing of wells, and the distance to boundaries. Concentration of large-yield wells in a small area causes water levels to decline more rapidly, and the length of time that the withdrawal rate can be maintained will be shortened substantially. Wider spacing and moderate pumping of wells allow water levels to decline over a large area without causing significant interference between wells. If the area of decline in the water level due to pumping extends to a hydraulic boundary, the water-level decline within the area of influence of pumping will increase near a barrier boundary, such as the sand-till contact. A recharge boundary, such as a stream or lake, within the area of influence of pumping will cause smaller water-level declines.

A prediction of the rate of decline in water levels and the effects on streams and lakes in the Perham area, with an assumed or given spacing of wells and pumping regimen, depends largely on accurate determinations of the transmissivity and the storage coefficient. Aquifer tests involving observations of the magnitude and rate of decline in water levels in response to pumping a well at a known rate commonly yield information from which the coefficients can be computed. The extent to which an aquifer departs from an ideal homogeneous aquifer and the construction and development of the wells govern the accuracy of aquifer-test results.

In addition to aquifer tests, the aquifer coefficients can be determined, or estimated, on the basis of laboratory analysis of samples of the aquifer material. Aquifer characteristics can be determined at more locations throughout the Perham area by this method, which has a more uniform application and avoids many of the effects on pumping-test results, such as presence of nearby boundaries, slow drainage of sediments, and so forth. The transmissivity map, discussed later in this report, was prepared primarily from results obtained by this method, but also includes some data obtained from the aquifer pumping tests. Both methods of determining aquifer characteristics are discussed in the following paragraphs.

### AQUIFER TESTS

Eight aquifer tests were made in the Perham area during the summer of 1968 to determine the transmissivity and the storage coefficient. The tests consisted of pumping an irrigation well at a uniform rate and observing the water-level changes before, during, and after the pumping period in the pumped well, where possible, and in nearby observation wells. The observation wells were constructed specifically for this purpose and were equipped with recording gages during the tests. The longest pumping period was 11½ hours.

The transmissivity and the storage coefficient were computed by several methods, and the results are listed in table 2. Due partly to the heterogeneity of the aquifer and partly to the short duration of the pumping tests, the results are somewhat inconclusive and are here utilized only as a basis for estimating transmissivity and storage coefficient, and also as a basis for checking other methods (to be discussed) for determining the aquifer characteristics. Only three of the eight tests were in wells tapping only the upper sand. The other five tests were in deeper wells that extend into the sand below a clay layer, and the test results probably were due to a combination of the upper and second sands and, therefore, are not shown on the transmissivity map.

TABLE 2.—*Results of aquifer tests in the Perham area, Minnesota*

| Location of pumped well | Aquifer depth (ft) | Aquifer thickness (ft) | Well depth (ft) | Pumping rate (gpm)[1] | Pumping time (hours) | Drawdown (ft) | Specific capacity (gpm per ft)[2] | Transmissivity (gpd per ft)[3] | Specific yield (field determination) | Aquifer tested |
|---|---|---|---|---|---|---|---|---|---|---|
| 133.40.15cdc1 | 20 | 102+ | 54 | 700 | 6.0 | 10.1 | 69 | 200,000 | 0.016 | Second sand. |
| 134.39.1acd1 | 20 | 92 | 55 | 610 | 5.5 | 8.6 | 72 | 250,000 | ------- | Do. |
| 135.39.34cac1 | 19 | 62 | 56 | 90 | 10.0 | 1.8 | 50 | 75,000 | ------- | Upper sand. |
| 135.39.35bbb1 | 29 | 55 | 56 | 650 | 6.7 | 6.9 | 94 | 200,000 | ------- | Second sand. |
| 136.39.2cda1 | 17 | 78+ | 84 | 335 | 11.5 | ------ | ---- | 50,000 | ------- | Upper sand. |
| 136.39.14dad1 | 22 | 64 | 68 | 790 | 10.7 | ------ | ---- | 200,000 | .12 | Do. |
| 136.39.19abd1 | 41 | 64 | 64 | 730 | 6.3 | ------ | ---- | 200,000 | .06 | Second sand. |
| 136.39.32cac1 | 67 | 38 | 105 | 830 | 2 | ------ | ---- | 200,000 | .002 | Do. |

[1] Gallons per minute.
[2] Gallons per minute per foot.
[3] Gallons per day per foot.

The storage coefficient, as determined from aquifer pumping tests, was low because of the short duration pumping, which did not allow sufficient time for adequate draining of the dewatered materials in the cone of depression (the volume between the non-pumping and pumping water levels). Storage coefficients from the tests ranged from 0.002 to 0.12.

### LABORATORY ANALYSES OF AQUIFER MATERIALS

The hydraulic conductivity (laboratory coefficient of permeability) and grain-size data were determined in the laboratory on representative samples from throughout the Perham area. The hydraulic conductivity of a material, multiplied by the saturated thickness of the material, gives the transmissivity. The hydraulic conductivity values shown in table 3 for the given

TABLE 3.—*Values of hydraulic conductivity for various grain sizes found in wells in the Perham area, Minnesota*

[Grain size of material based on the Wentworth scale]

| *Material* | *Hydraulic conductivity (gpd per sq ft)*[1] |
|---|---|
| **Well Sorted** | |
| Clay and silt | <1 |
| Sandy clay and silt | 1– 100 |
| Sand, very fine | 100– 200 |
| Sand, fine | 200– 500 |
| Sand, medium | 500–1,100 |
| Sand, coarse | 1,100–3,000 |
| Sand, very coarse | >3,000 |
| **Moderately Sorted** | |
| Sand, fine to medium | 100– 400 |
| Sand, fine to coarse | 100– 300 |
| Sand, fine to very coarse | 100– 200 |
| Sand, medium to coarse | 200–1,300 |
| Sand, medium to very coarse | 300–1,500 |
| Sand, medium to very fine gravel | 600–1,400 |
| Sand, coarse to very coarse | 1,500–2,000 |
| Sand, coarse to very fine gravel | 1,500–2,200 |
| **Poorly Sorted** | |
| Sand, with as much as 15 percent silt and clay | <100 |

[1] Gallons per day per square foot.

grain sizes were used for the Perham area. The correlations of hydraulic conductivities and grain-size data were extended, or applied, to all augered test-hole descriptions and data to derive the transmissivity of the aquifers at each test-hole site. An interpretation of the transmissivity of the aquifer, based on the aquifer thickness and grain-size data, is shown on plate 2*A*. The transmissivities obtained from the three aquifer tests made in wells in the upper sand substantiated the results obtained by use of the grain-size method. The highest transmissivities are generally along a line near the Otter Tail River, where the saturated thickness of the aquifer is great. Plate 2*B* shows the saturated thickness of the aquifer, as determined from drill logs of test holes and wells.

The specific yields determined from the laboratory analyses of drill-core samples averaged about 27 percent. The storage coefficient for the area would be expected to approach an average value of 0.27 for the area for long-term pumping, where sufficient time is allowed for the aquifer to drain between the nonpumping (static) and the pumping (cone of depression) water levels. However, this condition is not expected to be reached in the Perham area, and the storage coefficient for computation purposes is expected to be between 0.1 and 0.2 for the fairly short intervals of pumping expected. For purposes of computation in this report, a storage-coefficient value of 0.2 was used for the longer term pumping effects, and a value of 0.1 was used for the shorter term pumping effects. Modification of results are also discussed, giving magnitudes of corrections to be applied where the coefficient is determined to be different at a particular site than that given.

## COMPUTATIONS OF TRANSMISSIVITY BY THE GRADIENT–RIVER–GAIN METHOD

The transmissivity was also computed along a reach of the Otter Tail River, using the water-table-gradient component to the river and the gain in streamflow. The reach of the river used for transmissivity computations extends from the bridge on U.S. Highway 10 to the bridge on State Highway 14, where streamflow was measured in August 1968. The gradient to the river was determined in this reach from the water-table-contour map (pl. 1*B*). The transmissivity derived by this method was 60,000 to 70,000 gpd per ft (gallons per day per foot), which is the average shown on the transmissivity map (pl. 2*A*).

### SUMMARY OF TRANSMISSIVITY AND STORAGE COEFFICIENT

Several methods were used to determine the more probable values for transmissivity and the storage coefficient, and to determine the values for the upper sands throughout the Perham area. The computed transmissivities (shown on pl. 2*A*) were utilized to make further computations given in subsequent sections of this report. The transmissivity values (pl. 2*A*) ranged from near 0 generally around the perimeter of the area to more than 100,000 gpd per ft of aquifer in three areas, as shown.

The computed storage coefficient ranged widely because of the heterogeneity of the aquifer material at the different test sites, and because of non-ideal well construction. The storage coefficient for pumping intervals is believed to average between 0.1 and 0.2 in most of the Perham area. The storage-coefficient value used in computations in later sections of this report is 0.1 for the shorter term pumping effects and 0.2 for the longer term (several years' duration) pumping effects. However, if a different value is later determined to be more realistic, the water-level declines or drawdowns computed or predicted can be modified somewhat, as discussed in later sections of this report. Modification of the water-level change, or drawdown, due to changing the storage-coefficient value from 0.1 to 0.2 is relatively minor in most computations.

## ANALYSIS AND PROBABLE EFFECTS OF GROUND-WATER PUMPING

To determine the future effects of pumping, as reflected by the lowering of water levels in the study area, the previously discussed aquifer characteristics and geologic data were utilized. The future lowering of water levels can be predicted by using known or assumed values of aquifer characteristics, quantity of water required, and locations of wells. Factors given particular emphasis and consideration were the hydraulic characteristics of the aquifer, the hypothetical spacing of wells, the pumping rates, and the length of pumping season. All these values were determined, or estimated, in a range that is compatible with the known hydrologic data for the study area. As one or more factors may differ from those stated, various modifications of the data and adjustments of the results are discussed in following sections of the report. A mathematical model of the hydrologic system in part of the area was made to determine the effects of pumping on streamflow and the possible effects on lake levels. (See p. 32.)

Lakes hydrologically connected to the Otter Tail River and (or) its tributaries would be affected differently from those lakes and ponds not connected to the perennially flowing drainage system. Levels of lakes along the Otter Tail River and the flowing tributaries would not be affected significantly where ground-water levels are lowered, unless the streamflow stops. The source of water maintaining levels of lakes and ponds not connected to the major drainage system is from ground water and from precipitation. They have little or no other source. The major contributor of water maintaining a "stable" lake level is ground-water inflow. Pumping of wells could cause the lowering of ground-water levels, which, in turn, would cause these lakes and ponds to be lower in level or to dry up completely.

### THEORETICAL MAXIMUM YIELDS

The potential of an aquifer can be determined through quantitative analysis of the hydraulic properties. The quantitative values were calculated by use of the Theis (1935) nonequilibrium formula. Plate 3 shows the theoretical maximum possible yields that could be expected for 30 days of continuous pumping, with drawdowns limited to about two-thirds of the aquifer thickness. In this analysis, about 90 percent of the maximum yield was obtained, and the well was pumped at maximum efficiency when the drawdown equalled two-thirds of the aquifer thickness (Edward E. Johnson, Inc., 1966, p. 107–108). In computing the values indicated on plate 3, both the well interference and the possible change in the relation between recharge and discharge of the aquifer during pumping were disregarded. In preparing the map (pl. 3), well spacing was assumed to be such that interference between wells is negligible. The drawdowns at the wells, however, were corrected for decreasing transmissivity due to dewatering of the aquifer (Jacob, 1944). In order to obtain the yields indicated, a well must be constructed to fully penetrate the aquifer and must have a 100-percent efficiency. The map is intended to show only general trends and relative differences in water-yielding capacity for general areas, and local exceptions to the yield values shown are to be expected, owing to the local variations in transmissivity and storage. Also, 30-days' continuous pumping is considered to be an uncommonly long duration and probably would be necessary in the Perham area only in abnormally dry years.

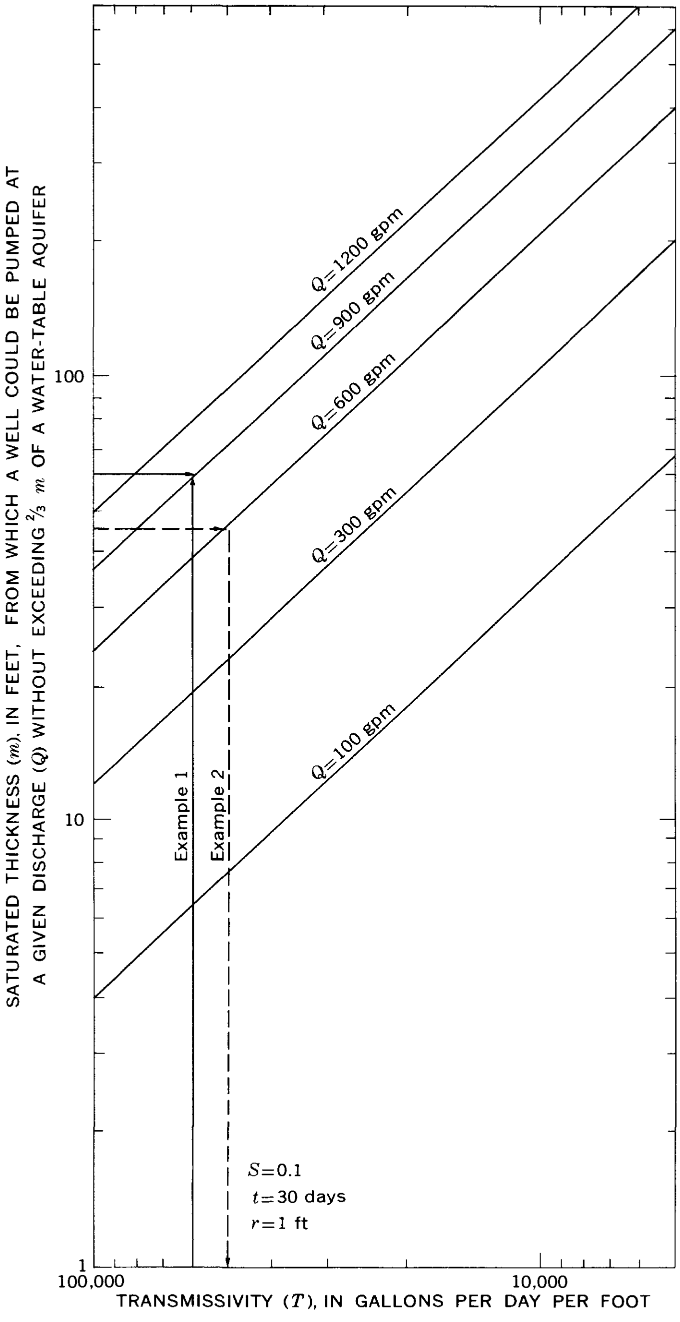
The areas of highest maximum yields generally are the same as the areas of highest hydraulic conductivity and greatest saturated thickness. Largest well yields—1,200 gpm (gallons per minute) or more—are expected to be available to individual wells in four areas: south of Big and Little Pine Lakes; south of Rush Lake; between West Battle Lake and the south end of Otter Tail Lake; and a narrow strip extending westward from the south end of Otter Tail Lake. Outward from these areas, the theoretical maximum possible yields are smaller in the upper sand, as indicated on the map. In these areas of smaller maximum yields, irrigators may have to utilize multiple-well systems or drill wells into deeper aquifers, which as yet, have not been extensively explored.

## RELATIONSHIP OF TRANSMISSIVITY, WELL YIELD, AND SATURATED THICKNESS

With the aid of figure 7, one can predict the theoretical maximum possible yield ($Q$) of a well to be drilled, the transmissivity ($T$) of the aquifer, or the required saturated thickness ($m$) of the aquifer, where two of the three factors are known. The saturated thickness of the aquifer can be determined from data on a test hole or can be estimated from the saturated-thickness map (pl. 2*B*). The transmissivity can be (1) determined from the test hole, (2) estimated from the hydraulic conductivity and the thickness of the materials penetrated by the test hole, or (3) taken from the transmissivity map (pl. 2*A*). The theoretical maximum possible well yield ($Q$) can be estimated from figure 7. Two examples describing the application of figure 7 are as follows:

Example 1. If the saturated thickness ($m$) of the aquifer is determined to be 60 feet and the transmissivity ($T$) is 60,000 gpd per ft, a fully penetrating well, with 100-percent efficiency, that is pumped continuously for 30 days can be expected to yield no more than about 900 gpm, with a drawdown not exceeding 40 feet, or two-thirds of the aquifer thickness. If the intersection of the horizontal and vertical lines falls between the diagonal lines for the theoretical maximum possible well yield ($Q$) the $Q$ value can be interpolated logarithmically.

Example 2. Assume that it is planned to drill a fully penetrating irrigation well with maximum development, and that the theoretical maximum well yield ($Q$) needed to irrigate a field, or to operate a sprinkler system, is 600 gpm. The saturated thickness ($m$) of the aquifer is determined, from a test hole, to be 45 feet; then, the transmissivity ($T$) of the aquifer at the well must be at least 50,000 gpd per ft to operate the well


SATURATED THICKNESS (m), IN FEET, FROM WHICH A WELL COULD BE PUMPED AT A GIVEN DISCHARGE (Q) WITHOUT EXCEEDING ⅔ m OF A WATER-TABLE AQUIFER
Q=1200 gpm
Q=900 gpm
Q=600 gpm
Q=300 gpm
Q=100 gpm
Example 1
Example 2
S=0.1
t=30 days
r=1 ft
100
10
1
100,000
10,000
TRANSMISSIVITY (T), IN GALLONS PER DAY PER FOOT

for 30-days' continuous pumping with a drawdown that does not exceed two-thirds of the saturated thickness. If the production well is drilled on the basis of test-hole data alone, it should be test pumped to determine the transmissivity of the aquifer, in order to assess the probable outcome of the investment and to determine whether the well will satisfy the specified water requirements.

Although figure 7 was prepared on the basis of a storage coefficient ($S$) of 0.1, the reader should note that if, later, the storage coefficient value is determined to be 0.2 at a particular site, the illustration is correct within about 5 percent. That is, if the storage coefficient value is 0.2, the required saturated thickness ($m$) determined from figure 7 should be decreased 5 percent from that indicated on the diagram.

## WELL INTERFERENCE

Well interference, caused by overlapping cones of depression of wells closely spaced (on the order of a few hundred feet), is common in areas of high yield and high pumping efficiency. Some well interference at any well spacing is necessary for optimum development of an aquifer. The yield from a particular well, or the pumping efficiency of the well, decreases as the interference increases and can become critical if the interference causes the drawdown in a well to exceed two-thirds of the aquifer thickness. The drawdown at a point within the area of influence of one or more wells is the sum of the drawdowns caused by the individual wells. Figure 8 shows the generalized shape of the cones of depression for two wells separately and also shows the effect of additional drawdown caused by overlapping cones of depression at two closely spaced wells. Figures 9 and 10 can be used to determine approximate drawndowns in the water-table aquifer between 1 and 1,000 feet from a pumping well. Because the drawdown decreases, the saturated thickness of the aquifer, theoretical

FIGURE 7.—Theoretical curves showing relationships of transmissivity, well yields, and saturated thickness required for drawdowns not exceeding two-thirds of the aquifer thickness (based on the Theis (1935) nonequilibrium method and computed by the Theis (1963) method and the Jacob (1944) equation). Curves were derived by using a variant of the Jacob (1944) equation in which $s' = s^2/2m$, and $m = 9/4\ s'$, where $m$ = saturated thickness, in feet, of a water-table aquifer; $s'$ = theoretical drawdown, in feet, in an equivalent artesian aquifer; and $s$ = drawdown, in feet, in a water-table aquifer. ($S$ = storage coefficient; $t$ = time, in days; and $r$ = radial distance, in feet, from center of well.)

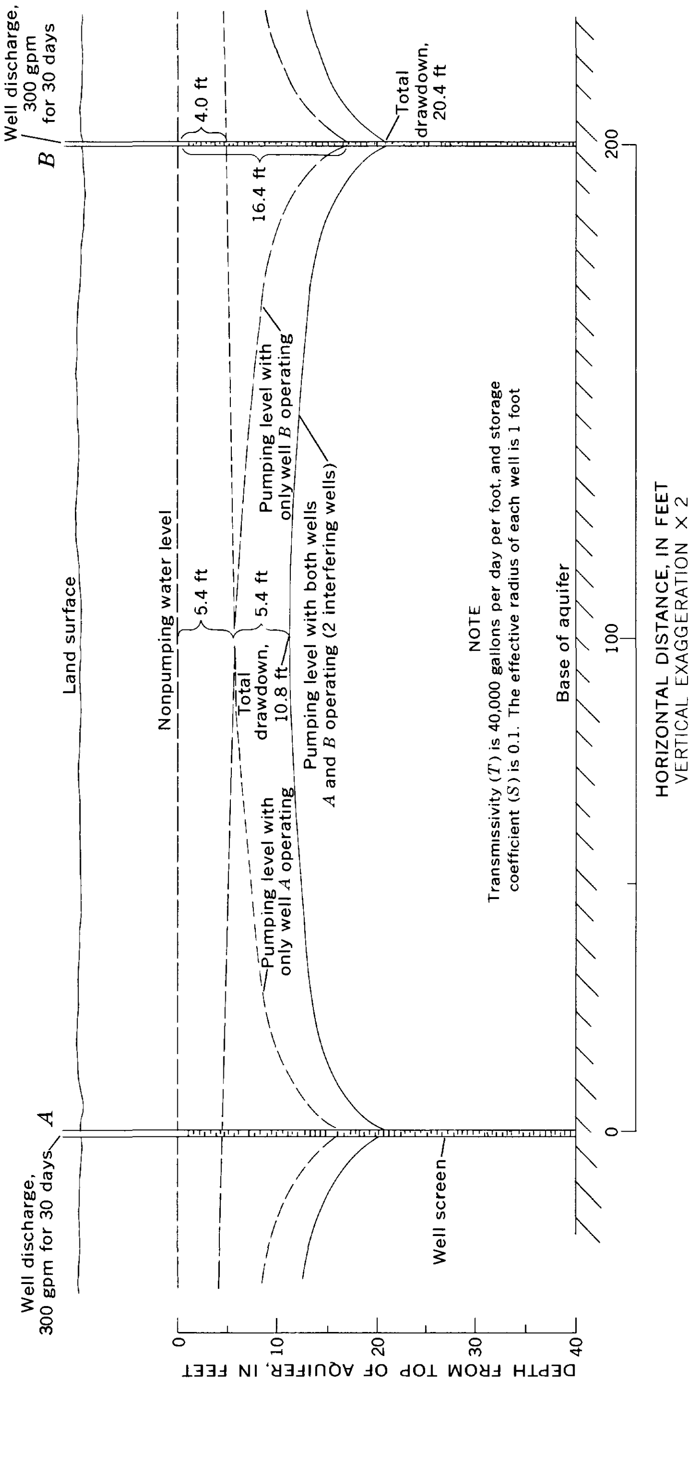



FIGURE 8.—Cones of depression caused by hypothetical wells pumping from a water-table aquifer.

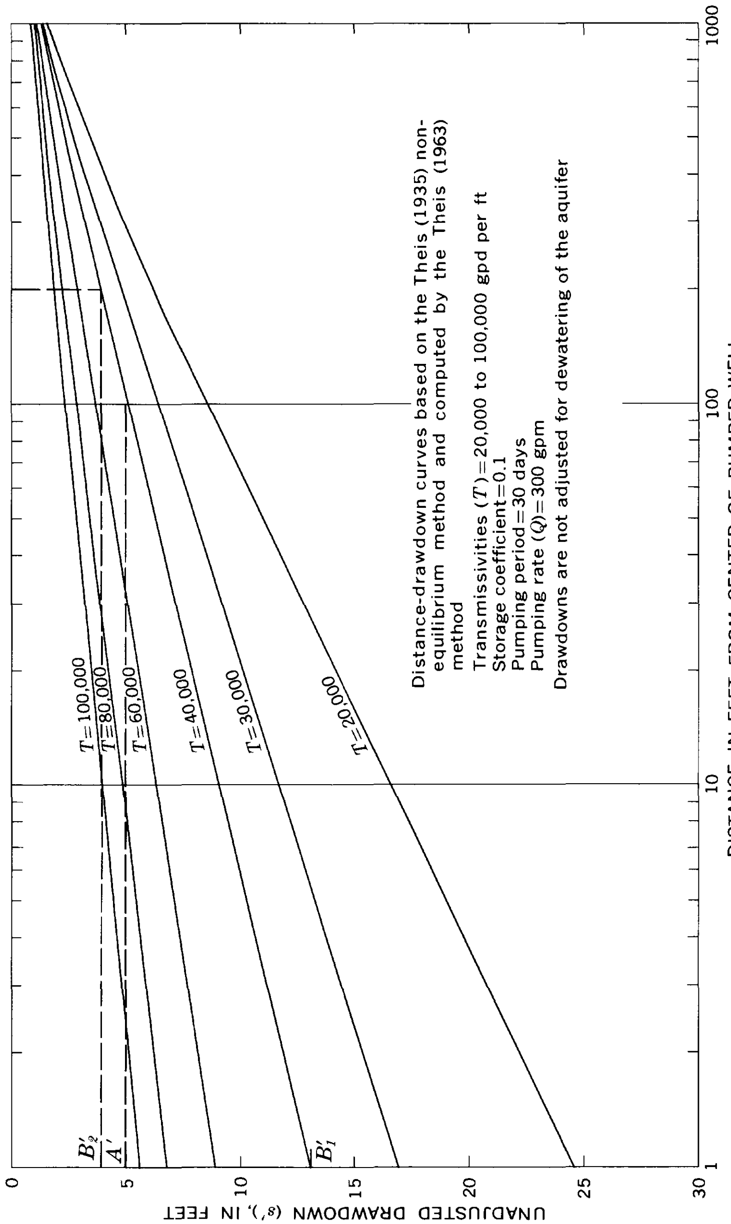



FIGURE 9.—Theoretical relation between drawdown and distance from a pumped well at the end of 30-days' continuous pumping at the rate of 300 gallons per minute.

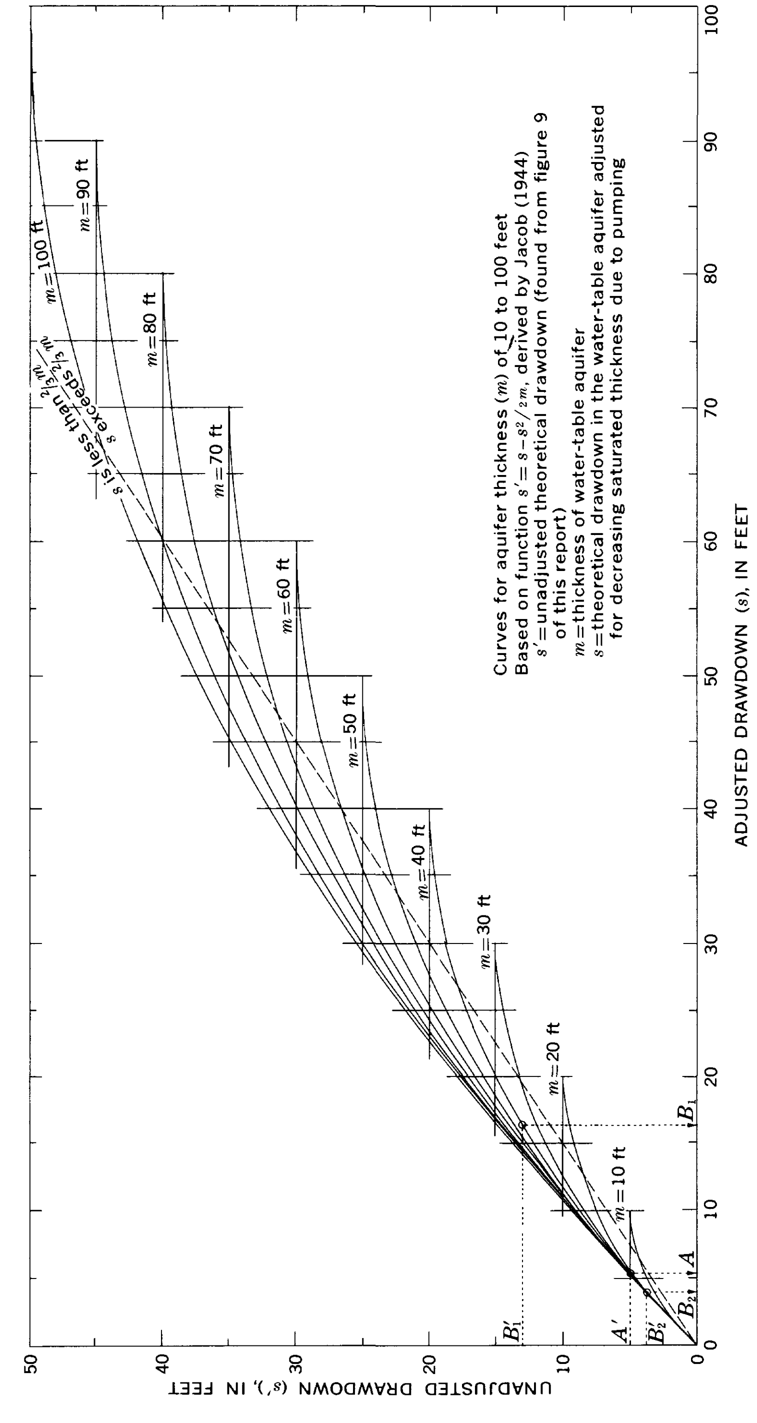



FIGURE 10.—Theoretical curves for adjustment of the drawdown data from figure 9 to compensate for dewatering of the water-table aquifer.

drawdowns (fig. 9) calculated by the Theis (1935) nonequilibrium formula must be adjusted for the decreased transmissivity. Adjustment of drawdown for dewatering of the aquifer can be made by using an equation derived by Jacob (1944), shown graphically in figure 10. To best explain use of figures 9 and 10 for estimating or predicting well interference, a hypothetical problem is presented and solved as follows:

*Example.*—Two wells, 200 feet apart, are each pumping 300 gpm from a 40-foot-thick water-table aquifer having a transmissivity of 40,000 gpd per ft and a storage coefficient of 0.1. Each well fully penetrates the aquifer and is 100-percent efficient.

A. Find the drawdown midway between the two wells after 30-days' continuous pumping.

1. The curve for 40,000 gpd per ft (fig. 9) shows that the unadjusted drawdown 100 feet from one well would be about 5.0 feet ($A'$). The 40-foot aquifer-thickness ($m$) curve (fig. 10) shows that the adjusted drawdown would be about 5.4 feet ($A$).
2. The drawdown midway between the interfering wells would be the sum of the drawdowns 100 feet from each well, or about 10.8 feet.

B. Find the drawdown 1 foot from the center of each well after 30-days' continuous pumping.

1. The curve for 40,000 gpd per ft (fig. 9) shows that the unadjusted drawdown at one well would be about 13.0 feet ($B'_1$). The 40-foot aquifer-thickness curve (fig. 10) shows that the adjusted drawdown would be about 16.4 feet ($B_1$).
2. The curve for 40,000 gpd per ft (fig. 9) shows that the unadjusted drawdown 200 feet from the other well would be about 3.8 feet ($B'_2$). The 40-foot aquifer-thickness curve (fig. 10) shows that the adjusted drawdown would be about 4.0 feet ($B_2$).
3. The drawdown at either well when influenced by the other would equal the sum of the adjusted drawdowns computed in steps 1 and 2 above (or about 20.4 ft).

Although the curves shown in figure 9 and applied in the example problem are for a well discharge of 300 gpm, they are also applicable to different discharges. Drawdown varies directly with discharge; for example, if 600 gpm is the anticipated or obtained yield, drawdowns can be determined by doubling the drawdown values indicated in figure 9 before adjustment for dewatering of the aquifer. Also, if the storage coefficient value

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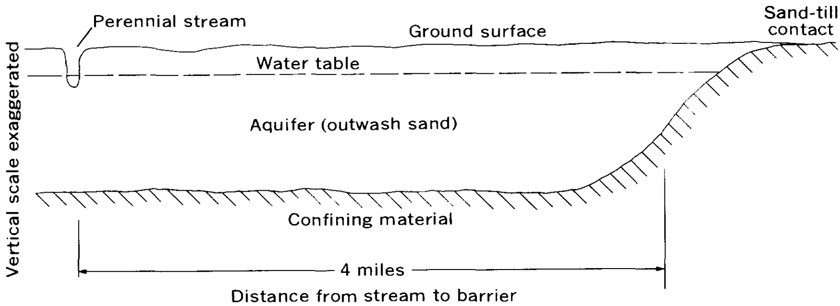
is later determined to equal 0.2, rather than 0.1, the drawdown would be slightly smaller—on the order of a few tenths of a foot smaller—than those shown. The theoretical curves for adjustment of drawdown (fig. 10) would remain the same for either storage coefficient value.

## MATHEMATICAL MODEL OF THE HYDROLOGIC SYSTEM IN PART OF THE AREA

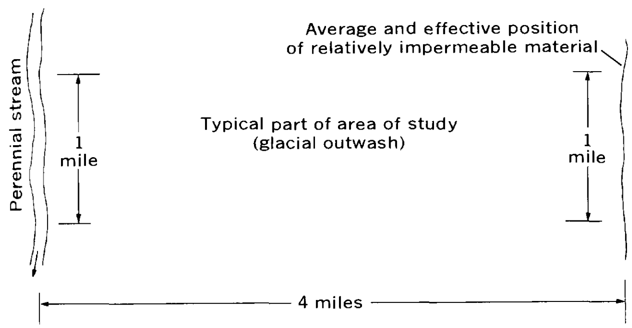
Ultimately, all pumpage will cause a net decrease in streamflow —that is, over a period of perhaps several years, and depending on the degree of ground-water development, pumpage will decrease streamflow to some degree. Ground-water pumpage that exceeds streamflow over a longer period of time (many years) will eventually cause streams to cease to flow during dry periods and lake levels to decline.

The configuration of the study area, the wide range in quantitative characteristics of the aquifer, and the probable variation in pumping rates so complicate the hydrologic system as to preclude the practicality of mathematically modeling the entire area. However, a small mathematical model typical of the hydrologic system in part of the area was utilized to determine the effects of pumping on streamflow and the possible effects on lake levels. Lake levels will not be affected significantly, unless streamflow is stopped. Thus, determining whether pumping will dry up the streams was necessary.

The effects on streamflow due to pumping ground water can be determined, in part, from the following model and computations: Assume that a strip of the outwash aquifer, 1 mile wide, extends from the sand-till contact (a barrier boundary, in effect) to the Otter Tail River (assumed to be a recharge, or no drawdown, barrier). For purposes of mathematical computation, it was assumed that streamflow in the Otter Tail River would not decrease; however, where data showed the amount of pumpage supplied from the river to exceed the amount of streamflow, the river ceased to flow and lake levels declined. The real aquifer was idealized as being parallel to the Otter Tail River and as being of infinite extent along the river. Because the average distance between the Otter Tail River and the outer edge of the aquifer (the sand-till contact) is approximately 4 miles, the aquifer strip was modeled as 4 miles long (fig. 11). Although the real aquifer extends to both sides of the river, the river was assumed to act as a barrier, and only one side of the river was modeled. Assume an infinite aquifer that is parallel to the stream and uniformly




SECTION VIEW OF REAL SYSTEM (IDEALIZED)




PLAN VIEW OF A PART OF REAL SYSTEM (IDEALIZED)

A part of a strip aquifer, extensive along the length of the stream. The aquifer is present on both sides of the stream, but for simplicity only one side is illustrated

FIGURE 11.—Real system (idealized) for which a mathematical model was prepared.

developed the same way as the strip modeled. The strip of the aquifer modeled, then, is perpendicular to the river, is 1 mile wide and 4 miles long, and is bounded on one end by a recharge boundary (river) and on the other end by a barrier boundary. The sides, in effect, are barrier boundaries that produce the same quantitative effect as would an infinite aquifer along the river.

The assumed development of the model has a well spaced 1 mile from the river and three additional wells in a line perpendicular to the river and spaced at 1-mile intervals from the first well, as shown in figure 12. The greatest drawdown to be expected, therefore, occurs at the well farthest from the river. Use of the theory of image wells allows the simulated effects of pumping on the small strip of modeled aquifer to be projected to simulate water-level fluctuations in a larger part of the aquifer (Ferris,

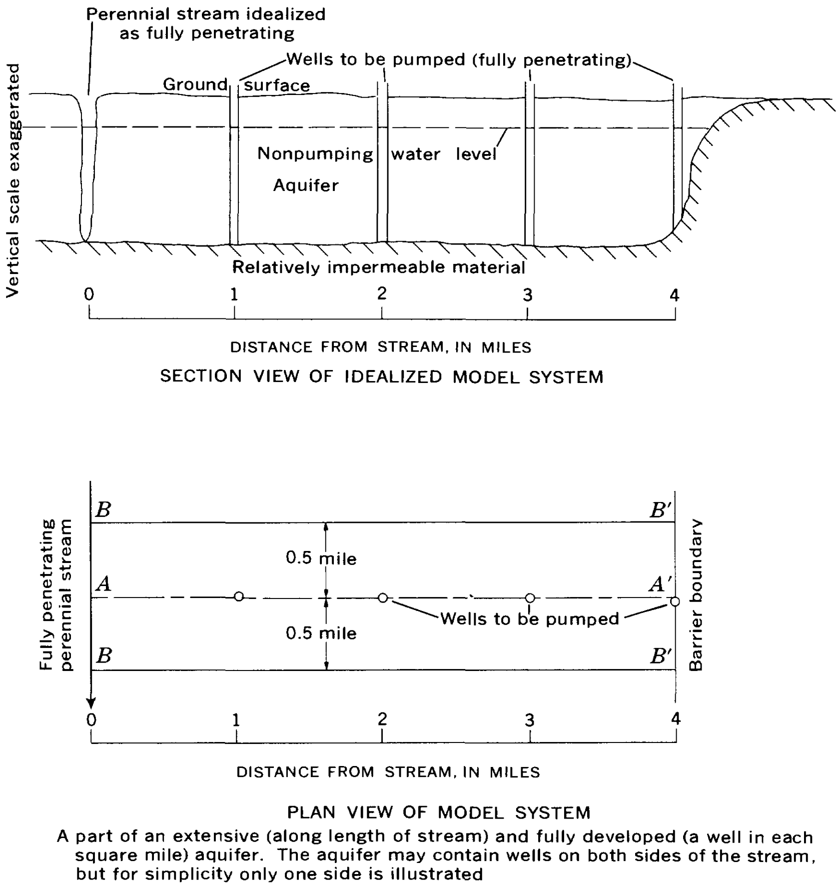



FIGURE 12.—Idealized system of mathematical-model computations, showing positions of pumped wells.

1948; Ferris and others, 1962). Actual computations were made by using the technique described by Conover and Reeder (1963).

For purposes of computation in the model, the quantitative aquifer characteristics were idealized as follows: Transmissivity (*T*) of 50,000 gpd per ft, an average value in the cross section of the modeled aquifer strip; and storage coefficient (*S*) of 0.2, a value for long-term pumping computations. On the basis of the above computed values for the various factors involved, computations were made of the lowering of water levels at the end of 30-days' pumping (fig. 13), at the end of 1 year with continuous pumping during the first 30 days (fig. 14), and at the end of 10 years plus one 30-day pumping season (fig. 15). The latter

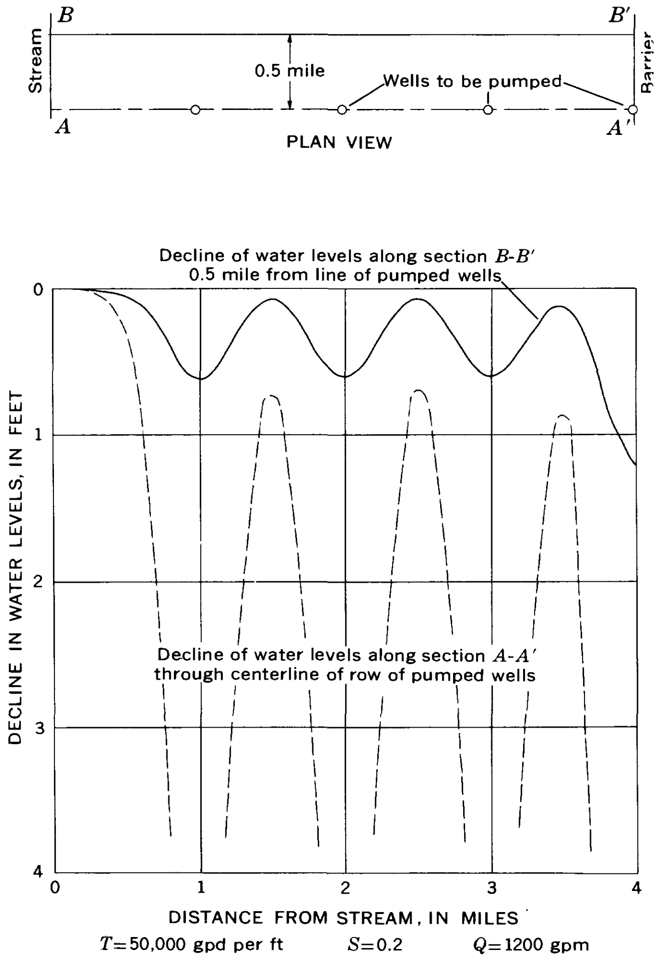



FIGURE 13.—Water-level declines at end of 30-days' continuous pumping, as computed from the mathematical model.

represents the water-level decline that resulted at the end of the 11th pumping season. In the above computations each well was assumed to be pumped at a constant rate of 1,200 gpm for only 30 days of each year. This rate is equivalent to about 160 acre-feet per year per well, or 6 inches of water per year on a half section of land (320 acres), or 3 inches of water per year on a full section.

The above computations showed that well interference (the overlapping of water-level declines due to pumping) would occur

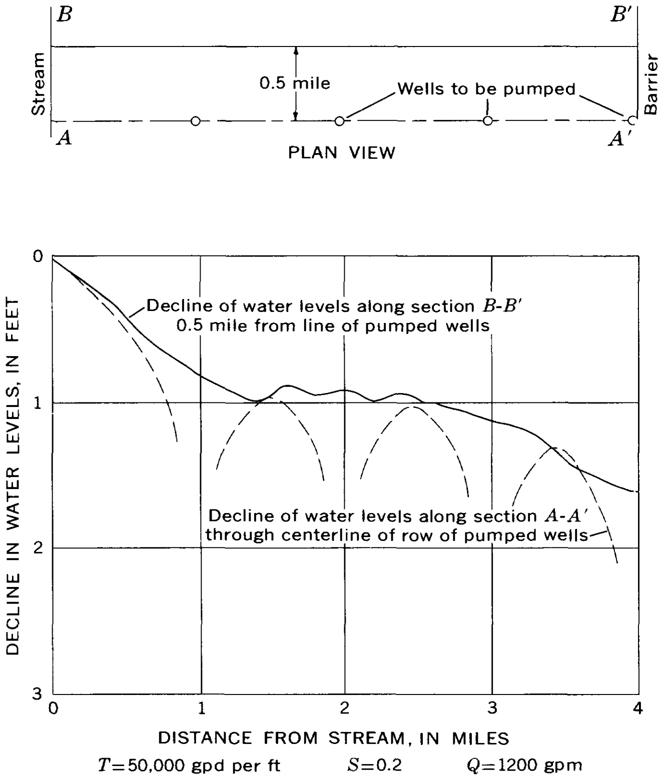



FIGURE 14.—Water-level declines at the end of 1 year with continuous pumping during first 30 days (only), as computed from the mathematical model.

within the 30-day pumping period with well spacing of 1 mile. Drawdowns at the pumped wells were discussed in the preceding section of this report and are not shown in this computation. However, figure 13 includes a graph of the water-level changes along the line of pumped wells, and shows that water-level declines of half a foot or more can be expected midway between the pumped wells 1 mile apart in a line. At the end of 1 year after the beginning of the first 30-day pumping season (just before the beginning of the pumping season of the second year), water levels at the pumped wells will recover, or rise, but the water levels midway between the pumped wells will continue to decline and reach net declines of 1 foot or more (fig. 14). Figures 13 and 14 also include graphs, or cross section, showing water-level declines on a line half a mile from the line of pumped wells. Water levels will decline as much as half a foot in 30 days (fig.

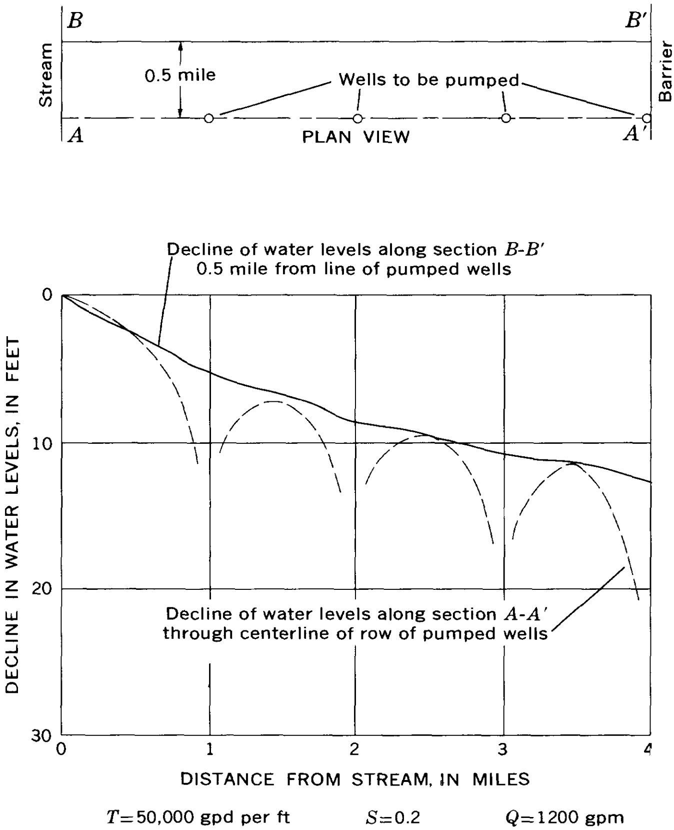



FIGURE 15.—Water-level declines at the end of 10 years and 30 days (end of the eleventh 30-day pumping season of each year), as computed from the mathematical model.

13). One year after the beginning of the 30-day pumping period, the cones of depression of the pumped wells will overlap and spread, causing declines along this line of as much as 1 foot (fig. 14).

Figure 15 shows water-level declines after the 11th pumping season (10 years plus 30 days) along the line of pumped wells. Declines will be greater farther from the river, but the pumping can be expected to cause general declines of 10 feet or more. Figure 15 also shows corresponding water-level declines along a line half a mile from the line of pumped wells which will range from near 0 at the river to more than 10 feet 4 miles from the river.

The results of the computations shown in figures 13, 14, and 15 are representative of conditions which prevailed in the winter and spring of 1967–68, when water-levels were relatively static (fig. 3). Natural general declining water levels, such as from 1967 to early 1969, coupled with water-level declines resulting from pumping for irrigation, as computed above, can lead to larger declines than the conditions for which these computations were made. Artificially induced water-level declines due to pumping will be superimposed upon the natural water-level fluctuations due to recharge and discharge.

These computations can be used only as a guide, as they are based on a hypothetical development. They show the approximate order of magnitude of the water-level declines caused by pumping for irrigation that can be expected with further development of the aquifer. Also, if all land is developed to the extent of applying 6 inches of water per year on all the study area, the water-level declines computed from the above mathematical model must be multiplied by 2.

The study area includes about 190 square miles of land, excluding lakes, underlain by the outwash sand. If all the land were to be developed (by applying 6 inches of water per year, or 320 acre-feet per square mile), a total of about 60,000 acre-feet per year of ground water would be required. The natural ground-water contribution to stream discharge from the study area is about 40,000 acre-feet annually. Surface-water flow into the area averages (50-percent recurrence, Winter and others, 1969) 35,000 acre-feet annually. The total amount of water available to the Otter Tail and Leaf Rivers at the outlets from the area prior to ground-water development, then, is about 75,000 acre-feet annually. The 75,000 acre-feet of streamflow at the outlets exceeds the 60,000 acre-feet maximum allowed pumpage and indicates that streamflow would not be depleted by pumping of ground water at the maximum-allowed rate of development, except possibly during abnormally dry years, when streamflows would be low. If pumpage is assumed to be prorated proportionately along the length of the streams within the study area, the levels of lakes along the drainage system of the Otter Tail and Leaf Rivers generally would not be appreciably lowered. However, because of the heterogeneity of the aquifer, the nonuniform pumping development, and other variable factors involved, some reaches of the Otter Tail River conceivably could cease to flow and some lake levels could decline. (A more detailed study would be required to fully evaluate individual lakes.) The lakes and ponds not connected to the drainage system by channels are expected to be lowered considerably or to be dried up completely as pumping progresses. This condition is not expected to occur for many years, however. Precipitation and natural recharge, not taken into account in the above evaluation, will relieve the adverse hydrologic conditions considerably. As ponds, swamps, and some lakes become lowered or go dry as a result of pumping, more water will be available for direct use on crops, owing to the salvage of ground water that previously would have been lost to evaporation and transpiration through less economically productive vegetation.

The computations also suggest that, with extended ground-water pumping, the natural gradient of water flow will be reversed, causing water to flow from the rivers and lakes, rather than toward them, as was the direction of flow caused by the natural gradient prior to any ground-water pumping in the area.

### PUMPED WATER DERIVED FROM STREAMS OR LAKES

As an additional check on the method of evaluation, the amount of pumped water diverted from streamflow can be computed for a well (or group of wells) and can be projected for the entire reach of the Otter Tail River in the study area. The graph in figure 16, based on an equation developed by Theis (1941, p. 736), shows the percentage of water from a pumped well that is diverted from a nearby stream or drain. The effect on the streamflow due to 30-days' pumping in the Perham area can be computed from the graph, as can the rate of pumping for the well. The graph (fig. 16) is based on the range in transmissivity and storage coefficient values in the Perham area. For example, for a transmissivity value of 100,000, which is common near the Otter Tail River in the study area, a pumped well 0.1 mile from the river or a lake will divert 85 percent of the pumped water from the stream or a lake at the end of 30-days' continuous pumping. If the well pumps at a rate of 1,000 gpm, 850 gpm is diverted from streamflow and 150 gpm is supplied from ground-water storage. The graph also shows that a similar pumped well 1 mile from a surface-water supply (river or lake) will divert only 6 percent of the water from the river or lake and will derive 94 percent of its yield from ground-water storage. A curve is also included in the figure for use in areas where the transmissivity is 50,000 gpd per ft, all other values remaining the same.

If irrigation, or other large-yield wells in the study area are spaced 1 mile or more away from streams or lakes, the effect on

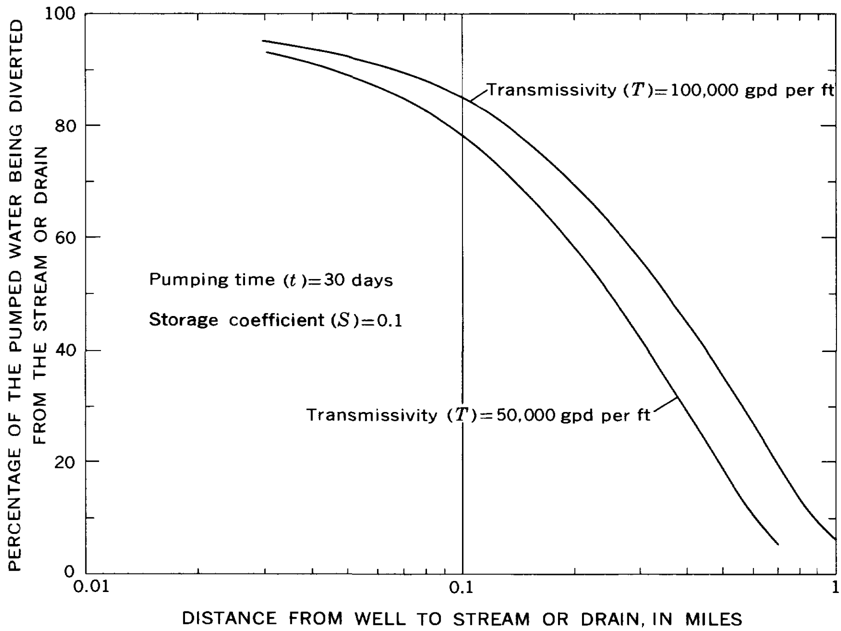



FIGURE 16.—Percentage of pumped water being diverted from stream or drain at the end of 30-days' continuous pumping. After Theis (1941).

the streams from ground-water pumping will be small, and lake levels will be affected very little. However, there is also considerable merit in a greater utilization of the water resources of the area by allowing levels of some lakes to fluctuate without stringent controls being applied to maintain the lake levels. Water in such lakes is expected to seek normal levels during periods of precipitation and periods when wells are not pumped.

In the previous section of this report the mathematical model of the hydrologic system in part of the area represents pumping from only one side of the stream and represents pumping along each mile of river length. The percentage of water diverted from the stream due to pumping the modeled wells on both sides of the stream for 30 days would be about 6 percent for the 2 wells 1 mile from the river, and would be less than 1 percent for the other wells. This amounts to less than 0.5 cfs (cubic feet per second) per river-mile, or less than 20 cfs for the reach of the Otter Tail River within the study area, after 30 days of continuous pumping. For the same example of pumping at the same rate for 30 days each year, in 10 years the percentage of water diverted from surface waters would be much greater, but the average annual rate of pumping would be smaller, resulting in a relatively moderate increase in the yearly amount of diversion from the streams. The amount of pumped water diverted from the streams would be about 1.25 cfs per river-mile, or about 60–70 cfs total diversion (which amounts to about 50,000 acre-ft per year). Although this is a crude estimate of the total water diversion, it compares favorably with the 60,000 acre-feet previously indicated to be the ultimate requirement for full ground-water development.

### DISCUSSION OF ANALYSIS

The values have been stated on which each of the above mathematical analyses was made; however, the following discussion should help to evaluate the analyses results. Several factors may cause the computed results to be different from the actual results as additional wells are drilled and the area is further developed.

1. The computations were necessarily based on the assumption that the aquifer is homogeneous throughout, both areally and in depth. Test augering, laboratory analyses, and aquifer tests indicated that the character of the water-bearing material varies greatly within short distances, as shown on the transmissivity map (pl. 2*A*) and saturated-thickness map (pl. 2*B*), and possibly with depth. For the computations, average values of the aquifer characteristics were used.
2. For purposes of computation, it was assumed that pumped water is derived from storage—that is, no natural recharge to, or discharge from, the aquifer occurs except for that to or from the streams and lakes. Further, it was assumed that there is no ground-water recharge from return flow from irrigation, except for that which returns through the rivers and lakes. These assumed conditions would prevail during years of below-normal precipitation, when little or no water is available for ground-water recharge. The graphs in figure 3 show relatively small water-level rises in the spring of 1968, indicating that recharge was very little. Recharge from normal or above-normal precipitation is expected to nearly offset the water-level drawdowns resulting from pumping, as shown by the large rises in water levels in the spring of 1969 (fig. 3).
3. Wells were assumed to be pumped continuously at a uniform rate. Although this does not actually happen, the assump-

tion remains reasonable for long-term computations. Also, a continuous pumping period of 30 days per year for irrigation in the Perham area was recognized to be a condition that would probably be reached only during abnormally dry years; nonetheless, it was used in the computation as a factor to evaluate the irrigation potential of the area.

4. The boundaries and thickness of the aquifer in the mathematical model of a part of the aquifer are idealized. The model is a hypothetical (although representative) presentation of a part of the real system. The idealization of the model was necessary for computation, owing to the great increase in complexity in dealing with a large number of wells and image wells if complex boundaries are used.

As additional data become available it may become apparent that any of the factors or variables should be changed. Adjustments of the results, as discussed, can generally be made. As the pattern of development and more individual well yields are known, a more complete evaluation of the system would be desirable.

## CONCLUSIONS

The Perham study area, made up of glacial outwash, is in Otter Tail County; it includes parts of the Otter Tail River and Crow Wing River watersheds. About 24 percent of the 350-square mile study area is occupied by about 90 lakes, each of which has a surface area of 10 acres or more.

The availability of ground water in the upper outwash aquifer varies greatly within short distances. The saturated thickness of the permeable outwash deposits ranges from 0 near the edges of the study area to more than 100 feet in the central parts of the area. Most of the aquifer material is fairly well sorted and ranges in particle size from fine (0.125 to 0.25 mm) (millimeters) to coarse (0.5 to 1.0 mm) sand.

A large part of the ground water in the Perham area is derived from precipitation within the area, although some water is derived from ground-water underflow into the area. The ground-water movement in the upper outwash aquifer is generally toward the Otter Tail River and toward the lakes along the river, and, then, movement is in the same general direction as the flow of the river. Ground water is the source of supply to lakes and ponds and is the base flow of the streams. Thus, a large part of the ground water discharged from the area is by streamflow, although some ground water leaves the area as underflow, primarily along the Otter Tail River, and some is discharged by evapotranspiration.

The chemical quality of the water in the Perham area is generally suitable for irrigation. Dissolved solids in the ground water consist predominantly of calcium, magnesium, and bicarbonate and, where present in excessive amounts, can cause well-screen incrustation problems. Water in the Perham outwash meets the chemical standards of the Minnesota Water Pollution Control Commission for domestic consumption, except that higher than desirable concentrations of iron and manganese occur locally. Also, some local pollution is indicated by excessive concentrations of nitrate.

The transmissivity is determined largely by the saturated thickness of the aquifer. Transmissivity values range from near 0 near most of the perimeter of the area to more than 100,000 gpd per ft of aquifer in three locations in the middle part of the area. The storage coefficient values range from about 0.1 to 0.2 for the pumping durations anticipated.

The above aquifer characteristics indicate that wells penetrating the full thickness of the aquifer and developed to 100-percent efficiency can be expected to yield 1,200 gpm for 30 days of continuous pumping, with drawdowns of less than two-thirds of the aquifer thickness in much of the area. However, yields vary widely within short distances, and yields of less than 300 gpm can be expected near the boundaries of the area and in the general area east and southeast of Otter Tail Lake.

Results of the mathematical analyses show that the streamflow from the area will not be depleted within the 10-year analysis period of 100-percent ground-water development if not more than 6 inches of water per year is used on all the irrigable land in the outwash area. If pumpage and its effect on the streams can be assumed to be prorated proportionately along the full length of the streams within the area, the levels of the lakes along the drainage system of the Otter Tail and Leaf Rivers, in most years, will not be lowered appreciably. However, because of the heterogeneity of the aquifer, the nonuniform pumping development, and other variable factors involved, some reaches of the streams will possibly cease to flow as full ground-water development is approached and will cause some lakes to decline. This condition, however, is not expected to occur for many years. A more detailed study would be required to evaluate the effects of lowered ground-water levels on individual lakes. Also, those lakes and ponds not connected to the drainage system by channels are expected to be lowered considerably or to be dried up completely as pumping increases.

If irrigation wells and other large-yield wells in the study area are spaced 1 mile or more away from streams and lakes, the immediate effect on the streams from the pumping of ground water will be small, and the lake levels will be affected very little, whereas the long-term effect will be a decrease in both streamflow and lake levels. The greater decline in ground-water levels because of distance from a surface-water source might cause a greater decline in the level of a lake not connected to a permanent stream. There is considerable merit to greater utilization of the water resources in the area by allowing the levels of some lakes and ponds to fluctuate without maintaining stringent controls of the lake levels. Water in such lakes and ponds is expected to seek normal levels during periods of precipitation and during periods when wells are not pumped.

Data from several wells that penetrate the first massive clay later and bottom in the second sand indicate that, where present, the deeper aquifers have great potential for development and should be explored.

Restudy of the Perham area at a later time would be desirable, to document new development, and the results and changes caused by the ground-water development, and to explore the deeper aquifers that were, necessarily, scarcely touched upon in the present study. The information obtained in the present study should be of value as background data for a future study of the area.

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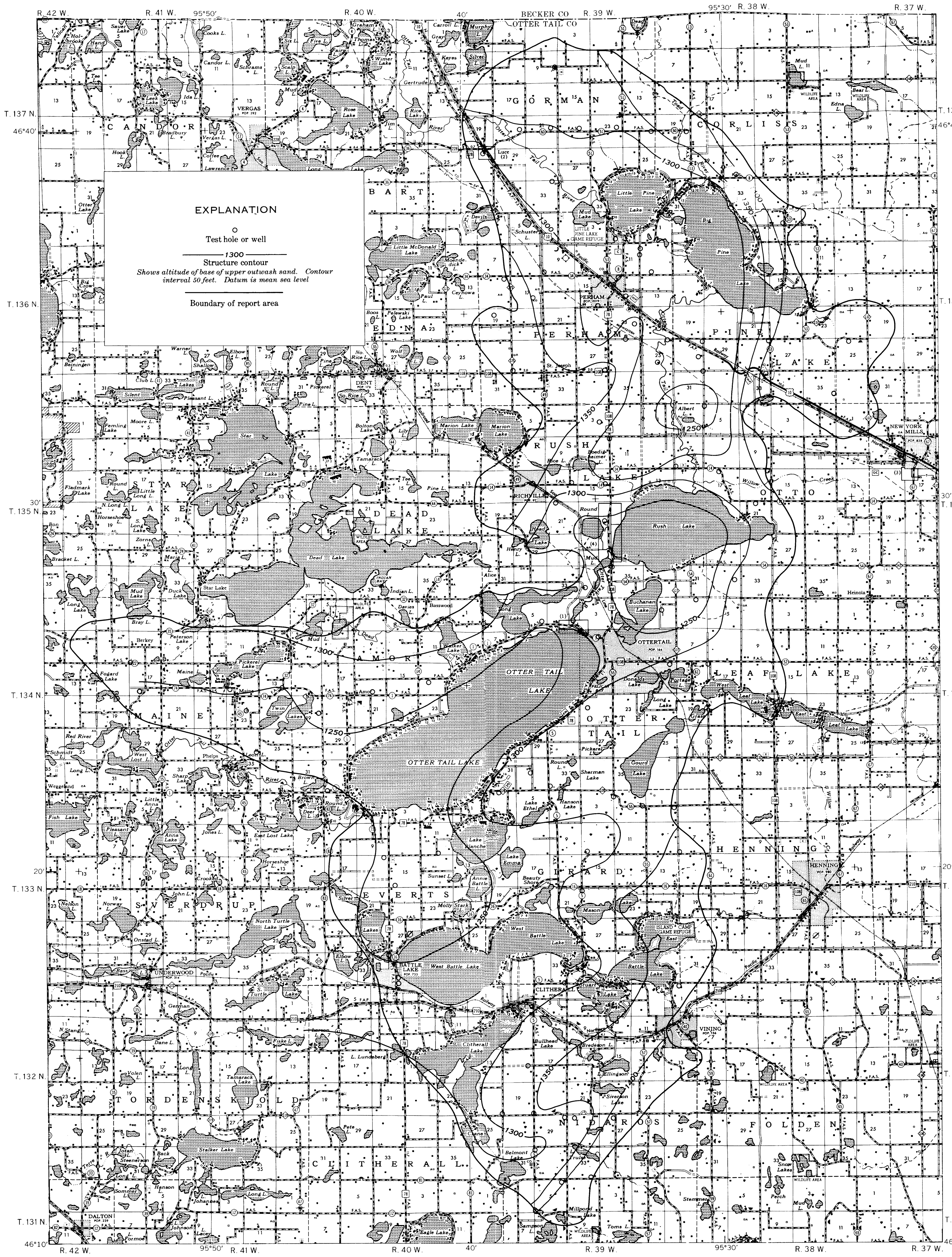
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

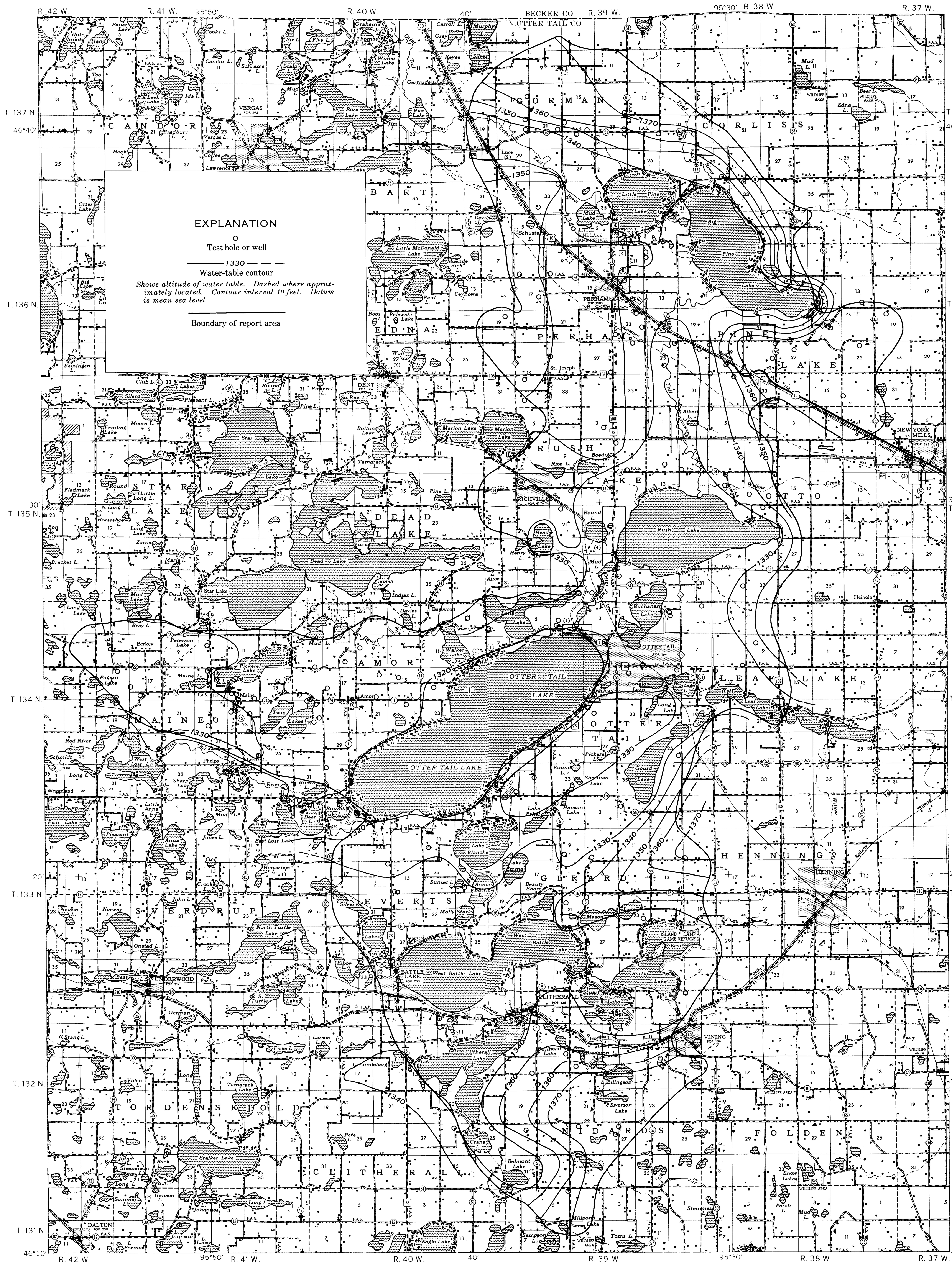
PREPARED IN COOPERATION WITH THE
WEST-CENTRAL MINNESOTA RESOURCE CONSERVATION AND DEVELOPMENT COMMITTEE
AND THE
MINNESOTA DEPARTMENT OF CONSERVATION, DIVISION OF WATERS, SOILS, AND MINERALS

WATER-SUPPLY PAPER 2003
PLATE 1




Base from Minnesota Department of Highways county road maps, 1966

*A.* Altitude of the base of the upper outwash sand




*B.* Altitude of the water table

SCALE 1:125 000

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2 0 2 4 6 8 10 KILOMETERS

APPROXIMATE MEAN DECLINATION 1972

# MAPS SHOWING CONFIGURATION OF THE BASE OF THE PRINCIPAL AQUIFER AND THE WATER TABLE IN THE PERHAM AREA, OTTER TAIL COUNTY, MINNESOTA

443-121 O - 72 (In pocket)

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PREPARED IN COOPERATION WITH THE
WEST-CENTRAL MINNESOTA RESOURCE CONSERVATION AND DEVELOPMENT COMMITTEE
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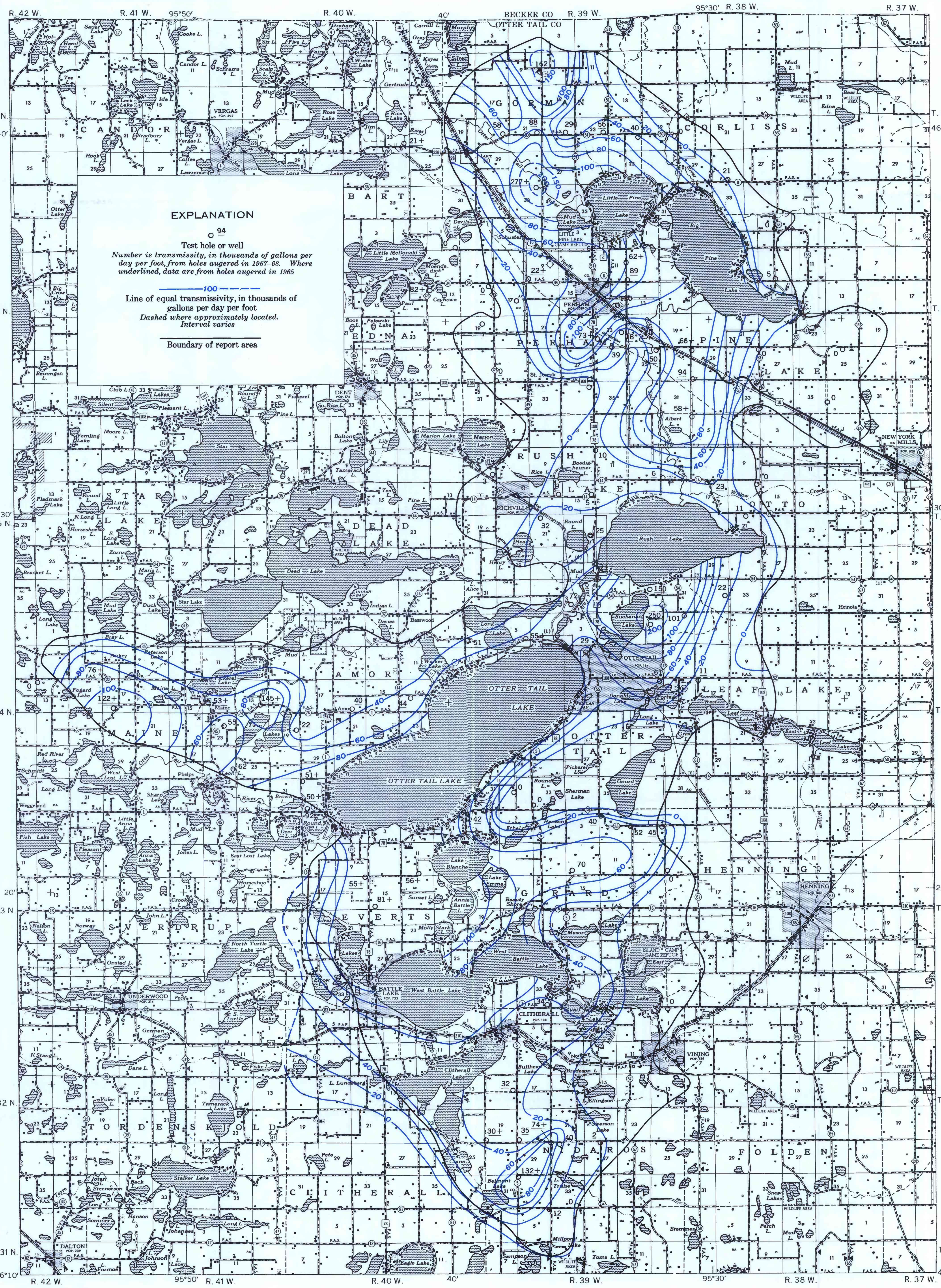
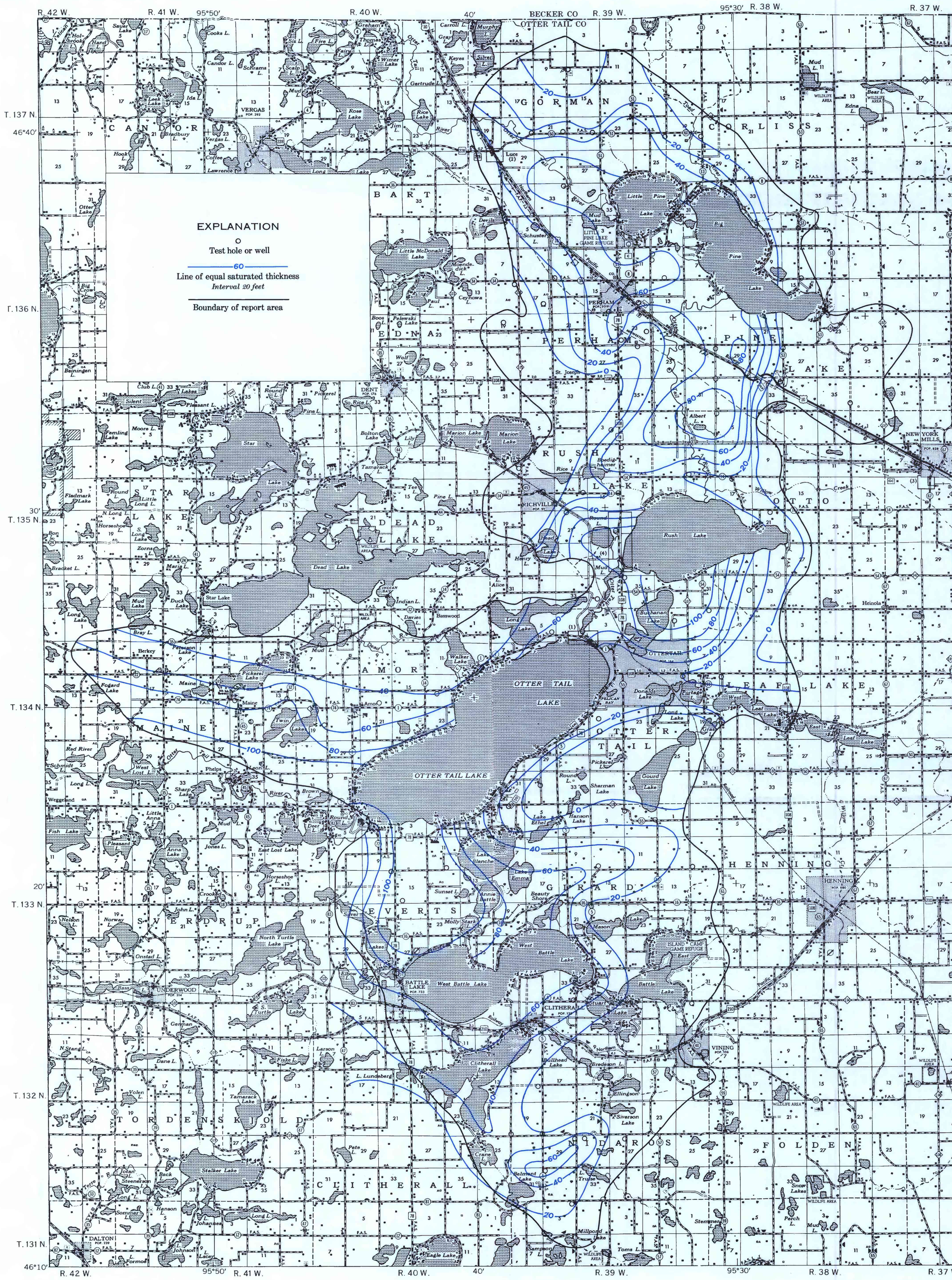
WATER-SUPPLY PAPER 2003
PLATE 2




Base from Minnesota Department of Highways county road maps, 1966

*A.* Transmissivity




*B.* Saturated thickness

TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1972

SCALE 1:125 000
2 0 2 4 6 8 10 MILES
2 0 2 4 6 8 10 KILOMETERS

# MAPS SHOWING THE TRANSMISSIVITY AND THE SATURATED THICKNESS OF THE PRINCIPAL AQUIFER, PERHAM AREA, OTTER TAIL COUNTY, MINNESOTA

443-151 O - 73 (In pocket)

PREPARED IN COOPERATION WITH THE
WEST-CENTRAL MINNESOTA RESOURCE CONSERVATION AND DEVELOPMENT COMMITTEE
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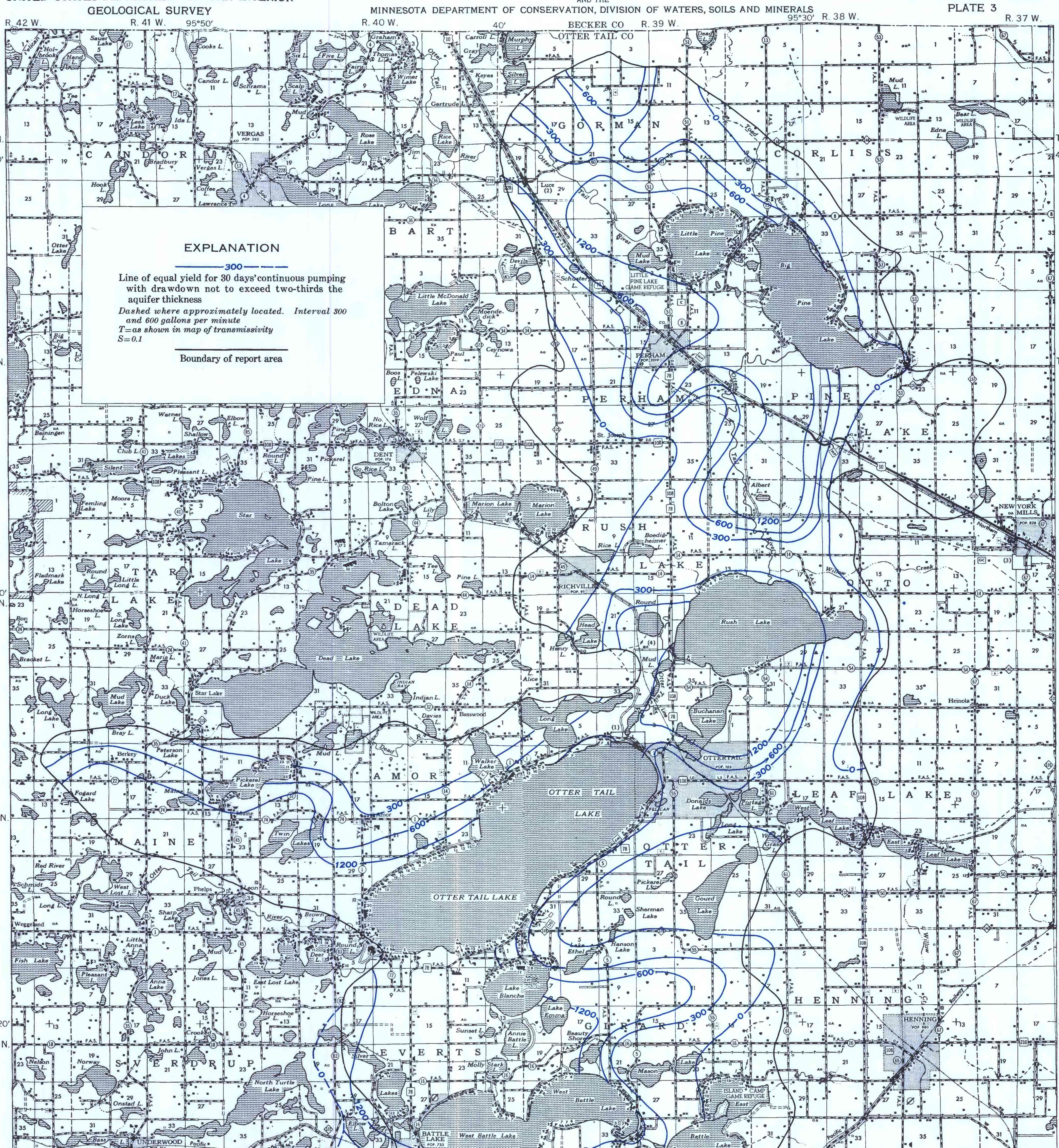


Base from Minnesota Department of Highways county road maps, 1966

TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1972

SCALE 1:125 000

2 0 2 4 6 8 10 MILES

2 0 2 4 6 8 10 KILOMETERS

# MAP SHOWING THEORETICAL MAXIMUM POSSIBLE YIELDS FROM THE PRINCIPAL AQUIFER IN THE PERHAM AREA, OTTER TAIL COUNTY, MINNESOTA

443-121 O - 72 (In pocket)