GROUND-WATER RESOURCES

Of

BENSON AND PIERCE COUNTIES, NORTH DAKOTA

by

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U.S. Geological Survey

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SELECTED FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) OF METRIC UNITS

A dual system of measurements — English units and the International System (SI) of metric units — is given in this report. SI is a consistent system of units adopted by the Eleventh General Conference on Weights and Measures in 1960. Selected factors for converting English units to SI units are given below.

Multiply English units	By	To obtain SI units
Acres	0.4047	hectares (ha)
Acre-feet	1,233	cubic metres (m^3)
	1.233×10^{-6}	cubic kilometres (km^3)
Feet	.3048	metres (m)
Feet per day (ft/d)	.3048	metres per day (m/d)
Feet per mile (ft/mi)	.18943	metres per kilometre (m/km)
Feet squared per day (ft^2/d)	.0929	metres squared per day (m^2/d)
Gallons	3.785	litres
Gallons per day (gal/d)	3.785×10^{-3}	cubic metres per day (m^3/d)
Gallons per minute (gal/min)	.06309	litres per second (l/s)
Gallons per minute per foot [(gal/min)/ft]	.2070	litres per second per metre [(l/s)/m]
Inches	25.4	millimetres (mm)
	.0254	metres (m)
Miles	1.609	kilometres (km)
Miles per hour	.44704	metres per second (m/s)
Million gallons (Mgal)	3,785	cubic metres (m^3)
Million gallons per day (Mgal/d)	3,785	cubic metres per day (m^3/d)
Square miles (m^2)	2.590	square kilometres (km^2)

GROUND-WATER RESOURCES OF BENSON AND PIERCE COUNTIES, NORTH DAKOTA

By P. G. Randich

ABSTRACT

Ground water is obtainable in Benson and Pierce Counties from aquifers in preglacial rocks of Cretaceous age and from aquifers in glacial drift of Pleistocene age. Aquifers in the preglacial rocks are more widely distributed, but those in the drift provide higher yields to wells and better quality water.

Aquifers in the preglacial rocks occur in the Dakota Group and the Pierre and Fox Hills Formations. The Dakota underlies the entire area at depths between 1,400 and 2,200 feet (430 and 670 metres) below land surface. The Dakota aquifer is capable of yielding large quantities of water, but the water contains about 4,000 milligrams per litre dissolved solids. Flowing wells are obtainable in places.

The Pierre Formation is an aquifer where it is fractured and directly underlies glacial drift, mainly in Benson County. The Fox Hills Formation is restricted to the western part of the area. Only small quantities of water are generally obtainable from the Pierre and Fox Hills, although in places the Fox Hills may yield as much as 100 gallons per minute (6.3 litres per second) to individual wells. Water from both aquifers is soft and contains high concentrations of sodium.

Nine major aquifers were identified in the glacial-drift deposits. These are classified into buried-valley, buried-outwash, and surficial-outwash aquifers. The aquifers contain a total of nearly 1.8 million acre-feet (2.2 cubic kilometres) of available ground water. They have been named the New Rockford, Spiritwood, Kilgore, Maddock, Leeds, Warwick, Esmond, Pleasant Lake, and Tokio aquifers. The largest and potentially most productive aquifer is the New Rockford, which underlies about 80 square miles (210 square kilometres) in southwestern Benson and Pierce Counties. A well in the aquifer was test pumped for 5 days at a rate of 1,420 gallons per minute (90 litres per second) in order to determine the hydraulic properties of the aquifer. The New Rockford aquifer is tapped by only a few small-capacity wells. It should yield as much as 1,500 gallons per minute (95 litres per second) to properly constructed wells located in the central part.

The glacial-drift aquifers yield water that differs considerably in chemical quality, depending on aquifer depth and position in the ground-water flow system, but the water is satisfactory for most uses.

About 3.2 million gallons per day (12,100 cubic metres per day) of ground water is pumped for municipal, domestic, and livestock uses in the two-county area.

INTRODUCTION

The present study of ground-water resources in Benson and Pierce Counties (fig. 1) was made cooperatively by the U.S. Geological Survey, the North Dakota State Water Commission, the North Dakota Geological Survey, and the Benson and Pierce Counties Water Management Districts.

Purpose of Investigation

This investigation was one of a series of studies to obtain information on the ground-water resources in North Dakota. The purpose of the study was to determine the general quantity and quality of ground water available for municipal, domestic, livestock, industrial, and irrigation uses. Accordingly, the report contains descriptions of the location, areal extent, thickness, and nature of the major aquifers; estimates of the quantities of water stored in these aquifers; estimates of the potential yields of wells tapping the aquifers; and descriptions of the chemical quality of the ground water.

Physiography and Drainage

Benson and Pierce Counties have an area of 2,512 mi^2 (6,506 km^2) in north-central North Dakota; they are within the Drift Prairie section of the Central Lowland physiographic province.

The area is generally of moderate to low relief. Total relief is about 460 feet (140 m) — ranging from about 1,400 feet (426 m) above msl (mean sea level) on the Sheyenne River at the south boundary of Benson County to 1,865 feet (568 m) near Harlow in north-central Benson County. The prominent land features are glacial in origin — moraines, ice-contact features, lake plains, and outwash plains.

Drainage is fairly well developed in some parts of the counties, but poorly developed in others. Drainage to the east consists of the Sheyenne River and its tributaries (Red River of the North basin), and to the west consists of intermittent streams of the Souris River basin (fig. 1). The Devils Lake basin lies between the basins of the Red and Souris Rivers. Because there has been no outflow from the Devils Lake basin in historic time, it is generally regarded as a closed basin. The basin divides generally coincide with the crests of major end moraines.

The land surface contains numerous undrained depressions, commonly referred to as sloughs or prairie potholes. Although each depression represents a small closed basin, some fill up and spill over — especially during rapid spring thaws that follow winters of above normal snowpack.

Climate

Benson and Pierce Counties are in a region of cool-temperature continental climate. The mean annual temperature at Maddock in Benson County ranges from 36°F (2.2°C) to 39.5°F (4.2°C). The mean monthly temperature ranges from 5.3°F (−14.8°C) in January to 69.6°F (20.9°C) in July (National

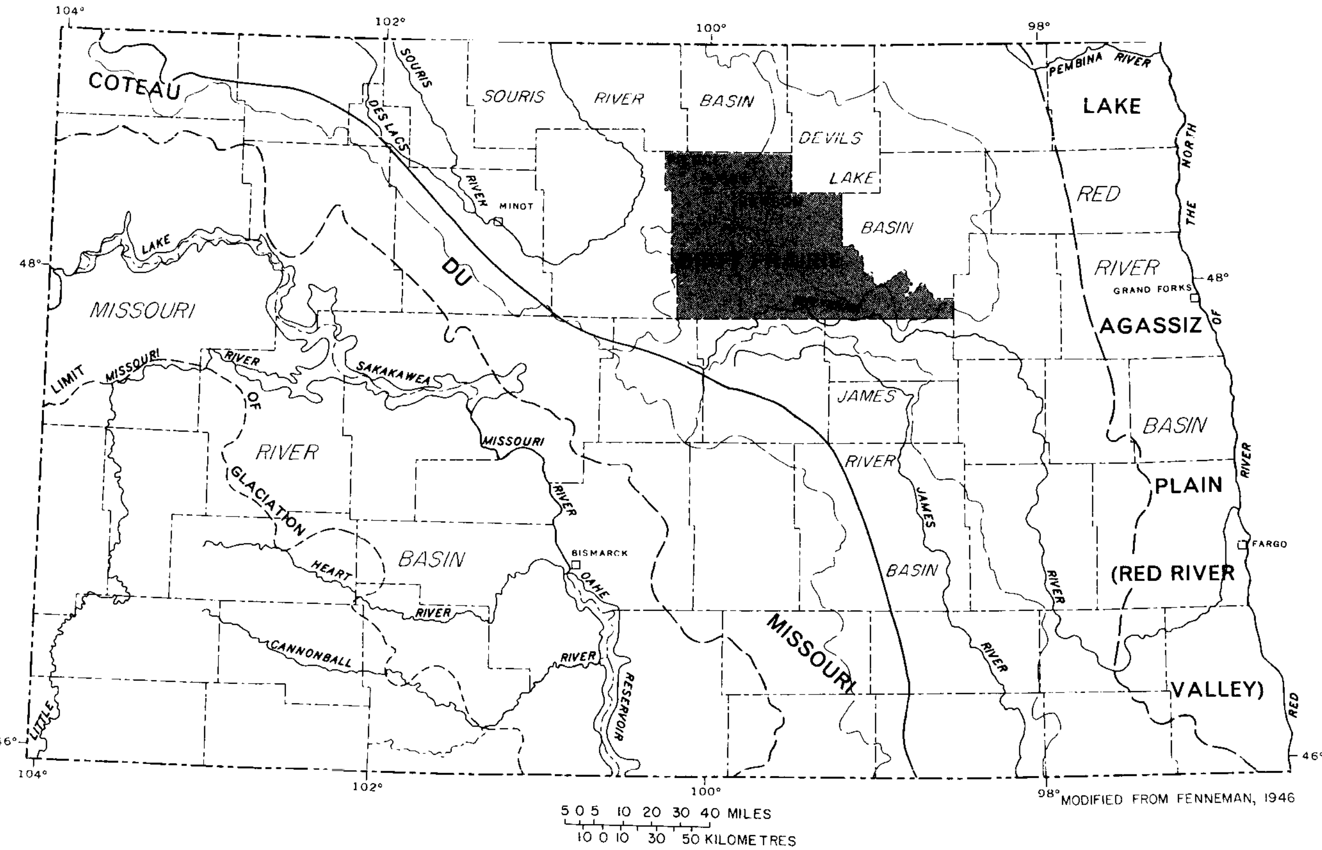


FIGURE 1.—Physiographic and drainage-basin divisions in North Dakota and location of report area.

Weather Service, 1931-68). The mean monthly temperature at Maddock is 26°F (3.3°C) for the period November through March, and 62°F (16.7°C) for the period June through August. The prevailing wind is from the northwest, except June through August when southeast winds predominate. The average wind velocity is about 10 miles per hour (4 m/s). Wind velocity is greatest in the spring and least in the fall.

The mean annual precipitation is 16.5 inches (420 mm) at Maddock and 15.7 inches (400 mm) at Rugby (Pierce County). More than 75 percent of the precipitation occurs during the growing season from April through September. The mean annual snowfall in the area is generally between 34 and 38 inches (860 and 970 mm). The driest period of the year is November through February when about 0.5 inch (13 mm) of moisture is received each month as snow. The mean annual evaporation from lake surfaces in the area is about 30 inches (760 mm).

Frost accumulates 4 to 6 feet (1 to 2 m) below land surface in most parts of the area. Spring thaw usually starts in March, causing most of the peak flows in streams to occur in April.

Population and Economy

The population of North Dakota has decreased about 2.3 percent during the period 1960-70 (U.S. Bureau of the Census, 1971). Comparatively, the population in Benson and Pierce Counties has declined 13 and 14 percent, respectively, for the same period. Population figures and percentage of change for the two-county area are as follow:

	1960 population	1970 population	Percentage of change
Benson County	9,435	8,245	−13
Brinsmade	110	36	−67
Esmond	420	416	− 1
Knox	122	104	−15
Leeds	797	626	−22
Maddock	740	708	− 4
Minnewaukan[1]	420	496	+18
Oberon	248	151	−39
Warwick	204	168	−18
York	148	102	−31
Pierce County	7,394	6,323	−14
Balta	165	133	−19
Barton	80	34	−58
Rugby[1]	2,972	2,889	− 3
Wolford	136	81	−40

[1]County seat.

The 1970 census figures show that about 66 percent of the Benson County residents and about 50 percent of the Pierce County residents live in rural areas.

The economy is based mainly on diversified dryland farming and stock raising, with wheat, barley, flax, alfalfa, and hay as the main crops. Recreational activities in the Devils Lake area help broaden the economic base of the counties.

Data Numbering System

The wells, test holes, and other data-collection points mentioned in this report are numbered according to a system based on the location in the public land classification of the U.S. Bureau of Land Management. The system is illustrated in figure 2. The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre or 4-ha tract). For example, well 154-72-15DAA is in the NE¼NE¼SE¼ sec. 15, T. 154 N., R. 72 W. Consecutive terminal numerals are added if more than one well is recorded within a 10-acre tract.

Previous Investigations

The first worker concerned with the geology of the area was Warren Upham (1895), whose study results are published in his classic report on glacial Lake Agassiz. Simpson (1929) prepared the first areal report on the ground-water resources of the counties. His report contains brief discussions of the geology, ground-water resources, public water systems, and quality of ground water. Abbott and Voedisch (1938) listed chemical constituents of a few ground-water samples from the area. Detailed geologic studies have been completed for the Flora quadrangle (Branch, 1947), Oberon quadrangle (Tetrick, 1949), and Tokio quadrangle (Easker, 1949). Aronow and others (1953) described the geology and ground-water resources of the Minnewaukan area in Benson County. Swenson and Colby (1955) studied the chemical quality of surface water in the Devils Lake region. Robinove and others (1958) included the area in a statewide report on principal saline-water aquifers. Brookhart and Powell (1961) described the ground-water resources near Maddock in Benson County. Randich and Bradley (1962) described the ground-water resources in the vicinity of Leeds in Benson County. The North Dakota State Department of Health (1964) included chemical analyses from the area in a study of municipal water supplies in North Dakota. Paulson and Akin (1964) described the ground-water resources of the Devils Lake region. Their report contains geohydrologic interpretation and a large volume of data. Froelich (1965) reported on a ground-water survey of the Rugby area. His report contains geohydrologic interpretation of a 120-mi^2 (311-km^2) area in Pierce County. Mitten and others (1968) prepared a supplemental

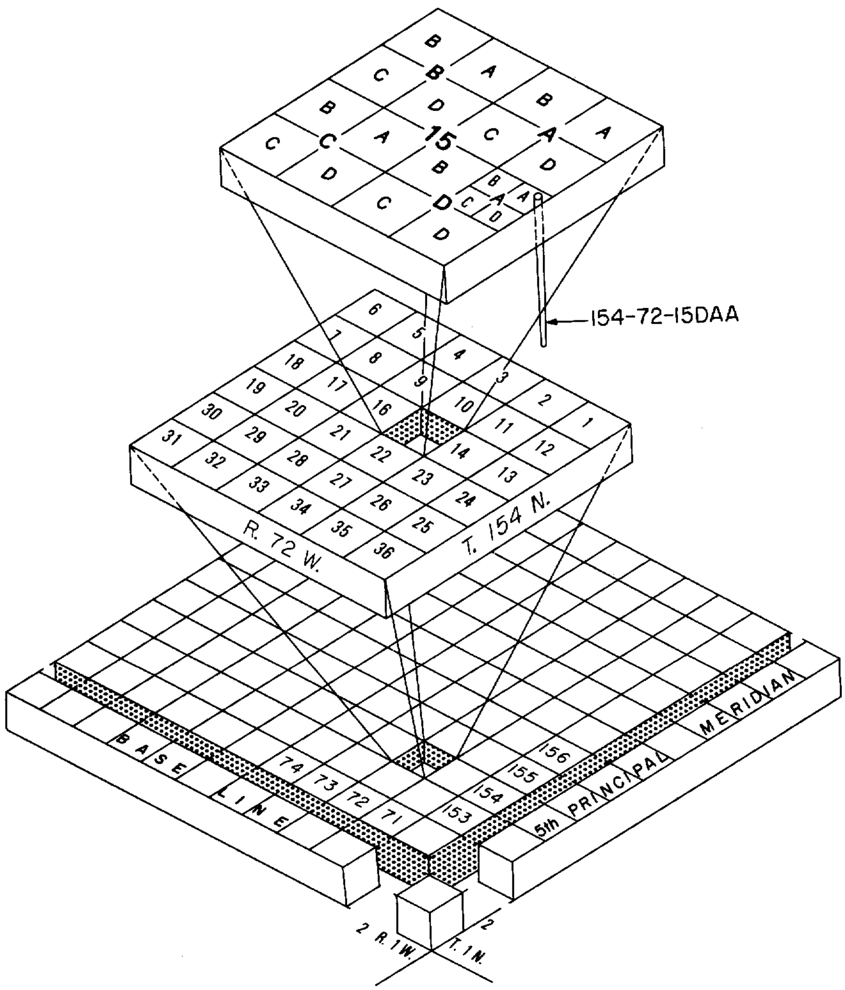


FIGURE 2.—System of numbering data sites.

report to Swenson and Colby's work (1955) on the chemical quality of surface waters in the Devils Lake basin. Randich (1972) prepared a hydrologic atlas outlining the general ground-water availability in Benson and Pierce Counties.

Acknowledgements

Appreciation is expressed to the residents and officials of Benson and Pierce Counties. Their ready cooperation made it possible to complete the study without unnecessary delays. C. E. Naplin, R. W. Schmid, M. O. Lindvig, L. L. Froelich, David Ripley, and L. M. Knutson of the North Dakota State Water Commission provided most of the test-drilling and aquifer-test data. T. F. Freers and C. G. Carlson of the North Dakota Geological Survey mapped the surface geology and provided auger test-hole data. Recognition is due Chevron Oil Co., C. A. Simpson and Son Drilling Co., and Frederickson's, Inc., for contributing drillers logs of seismograph holes and water wells, and for participation during aquifer tests.

HYDROGEOLOGIC SETTING

Preglacial Rocks

Benson and Pierce Counties are on the eastern flank of the Williston basin. The floor of the basin is formed of crystalline metamorphic and igneous rocks of Precambrian age. The overlying preglacial sedimentary rocks range in thickness from about 4,000 to 6,000 feet (1,220 to 1,830 m), and in age from Ordovician to Cretaceous. Rocks of pre-Cretaceous age generally are too deeply buried and contain water too highly mineralized to be of economic importance. Rocks of Cretaceous age contain major aquifers, but an understanding of their stratigraphic framework is essential to the interpretation of their ground-water potential.

In ascending order, the rocks of Cretaceous age can be divided into the Dakota, Colorado, and Montana Groups.[1]

The Dakota Group of Lower Cretaceous age has been further divided into the Lakota, Fuson, Fall River, Skull Creek, Newcastle, and Mowry Formations (Hansen, 1955). However, the Dakota has not been subdivided in the study area. Interpretation of 30 oil-test logs shows that the Dakota Group averages about 300 feet (90 m) in thickness and contains two sandstone intervals that are important aquifers. These intervals probably are equivalent to the Lakota and Newcastle Formations; which consist primarily of loosely cemented quartz sandstone and siltstone separated by about 200 feet (60 m) of thinly bedded shale and siltstone.

[1] The stratigraphic nomenclature used in this report is that of the North Dakota Geological Survey and does not necessarily follow the usage of the U.S. Geological Survey.

The Niobrara Formation of the Colorado Group was identified at the base of a test hole drilled into a buried valley near the southeastern corner of Benson County. It was found to be a calcareous light-gray shale with very calcareous white specks (fossil fragments). Rocks in the Colorado Group are not believed to contain significant aquifers.

The Pierre and Fox Hills Formations of the Montana Group directly underlie the glacial drift in most of Benson and Pierce Counties. The line of contact between the two formations trends northerly approximately through the center of the two-county area (fig. 3). The surfaces of the two formations contain numerous valleys and other erosional features (pl. 1, in pocket) carved by preglacial and interglacial streams. The bedrock topography defines the location and extent of the buried valleys and depressions containing major glacial aquifers in Benson and Pierce Counties. More detail is shown on this map than the one in Part I of this report (Carlson and Freers, 1975) because the bedrock topography in most cases imposes hydraulic controls on the glacial aquifers. These controls are confining and recharge boundaries, which affect potential yields and chemical quality of the ground water in the glacial aquifers.

The Pierre Formation is older than the Fox Hills and underlies it where both formations are present. The Pierre consists of olive-gray to grayish-black fissile bentonitic shale. This formation, which underlies nearly the entire area, ranges in thickness from 0 to about 1,000 feet (300 m). In places, where it directly underlies glacial drift, the upper 10 to 30 feet (3 to 9 m) is fractured and generally is oxidized to a brown color. The fracturing is attributed to preglacial erosion with subsequent glacial loading, and the brown color to oxidation and hydration of iron-bearing minerals. The fractured shale forms an aquifer of considerable importance. Drilling action for the fractured zone is similar to that for a gravel. Sample returns from hydraulic-rotary drilling are chunky blocks ranging in size from 0.5 to 2.0 inches (13 to 51 mm).

The Fox Hills Formation generally is covered by deposits of glacial drift, but crops out in isolated small exposures in the western part of the two-county area. The formation ranges in thickness from 0 to 290 feet (88 m). It dips westward at about 10 ft/mi (1.9 m/km). The formation outcrops are generally dark greenish gray weathering to light brown. Two samples collected at outcrops (153-70-36DCC and 153-72-27DAA) averaged 86 percent very fine to fine-grained sand.

Glacial Deposits

Glacial drift of Pleistocene age underlies Benson and Pierce Counties (fig. 4). The maximum known thickness of the deposits is 382 feet (116 m), but the average (fig. 3) probably is about 100 feet (30 m). The contact between the glacial drift and bedrock is commonly marked by a layer of boulders. In Benson and Pierce Counties, the glacial drift can be subdivided into six general types of deposits on the basis of lithology and inferred origin. These are ground moraine, end moraine, lake deposits, ice-contact deposits, buried-valley deposits, and outwash deposits (fig. 4).

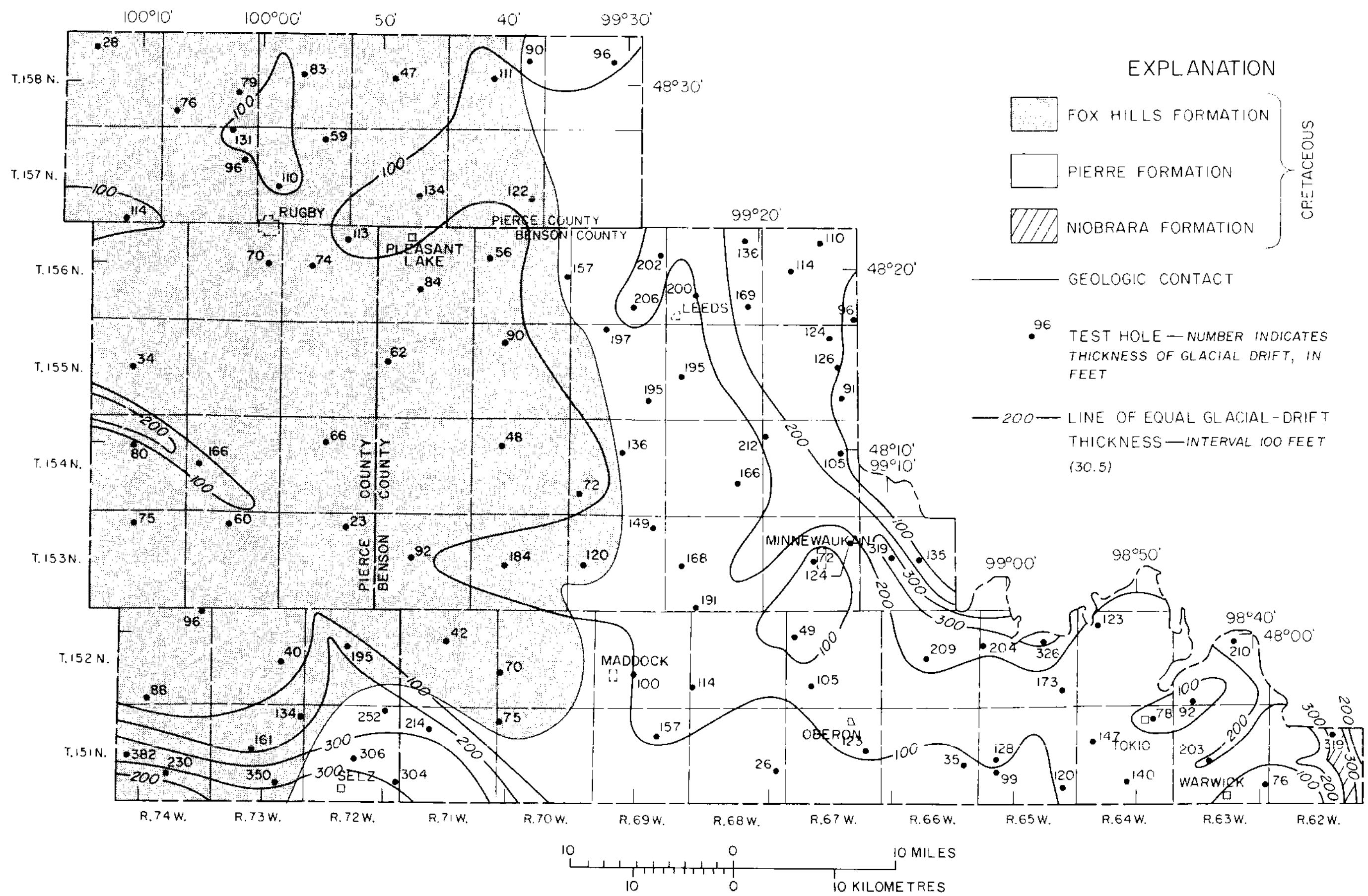


FIGURE 3.—Bedrock formations and thickness of glacial drift.

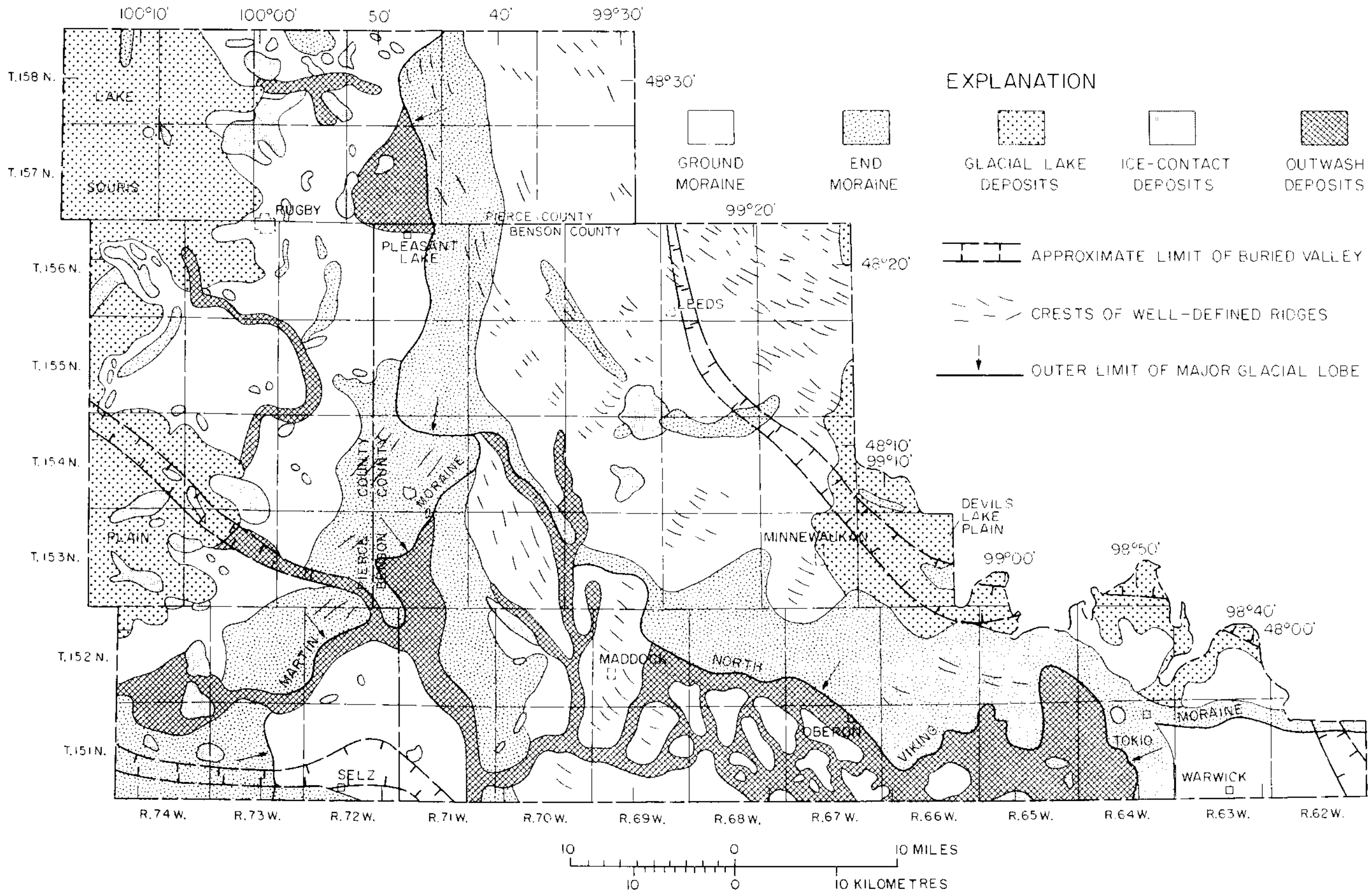


FIGURE 4.—Generalized surficial geology and locations of buried valleys.

Ground moraines are characterized by gently rolling "swell and swale" topography of low relief. The deposits are composed chiefly of till. Generally the upper 10 to 30 feet (3 to 9 m) is yellowish-brown — caused by oxidation of minerals containing iron. They are most extensive in the northeastern and central parts of the area, but widely scattered tracts exist in the southern part also. In northeastern Benson County the deposits contain abundant glaciofluvial sand and gravel lenses.

End moraines are characterized by "knob and kettle" topography of moderate local relief and have a general linear form. These moraines mark outer positions of glacial ice sheets (fig. 4) and are composed of till and associated glaciofluvial sand and gravel. In Benson and Pierce Counties, prominent hills are common at the junctions of end-moraine lobes. An appreciable amount of lag sand, gravel, cobbles, and boulders is common on top of these morainal hills. One such hill, located near Tokio in southeastern Benson County (sec. 8, T. 151 N., R. 64 W.), is called Devils Heart Butte by local residents. Bedrock highs (pl. 1) in the two-county area commonly coincide with, and perhaps contribute to, the topography and location of the end moraines (fig. 4).

Lake deposits of Pleistocene age underlie the Devils Lake plain in northeastern Benson County, and the more extensive Souris Lake plain in western Pierce County (fig. 4). These deposits consist mainly of clay, silt, and fine sand. Some gravel is present along former shorelines. The deposits are characterized by relatively flat topography, but sand dunes have formed locally. These sand dunes are mostly subdued and stabilized by vegetation.

The principal types of ice-contact features in the area are eskers, kames, crevasse fillings, and kame terraces. They were formed by glacial melt water flowing around, through, and beneath cavernous or fissured ice. The deposits are characterized by hilly topography and almost unpredictable lithology. The ice-contact deposits generally consist of poorly sorted and stratified sand and gravel with varying mixtures of clay, silt, cobbles, and boulders.

Buried valleys, which were part of a regional preglacial and interglacial drainage system, underlie parts of the area (fig. 4). They are many miles in length, 1 to 7 miles (1.6 to 11 km) wide, and 200 to nearly 400 feet (60 to 120 m) deep (pl. 1). In places these valleys underlie recognizable topographic lows, such as Devils Lake and East Devils Lake in Ramsey County. However, in most places they are completely filled by glacial deposits. The buried-valley deposits consist chiefly of interbedded sand and gravel (which generally form major aquifers) and lesser amounts of clay and silt. Massive blocks of till or bedrock locally were pushed into the deeper parts of the valleys by advancing glaciers and form hydraulic confining barriers within the aquifers.

Outwash deposits were built by streams extending beyond the ice fronts (fig. 4). They are characterized by gently undulating to nearly flat topography and consist chiefly of sand and gravel, in part interbedded with and (or) covered by considerable amounts of clay and silt. Coarse gravel and cobbles generally are abundant near the contact of end moraines and outwash. The gravel grades to finer materials with increasing distance from the end moraines.

AVAILABILITY AND QUALITY OF GROUND WATER

General Concepts

Part of the precipitation on the earth's surface is returned to the atmosphere by evaporation, part runs off into streams, and the remainder infiltrates into the ground. Some of the water that enters the soil is held by capillarity, to replace the water that was evaporated or transpired by plants during a preceding dry period. After the soil and plant requirements have been satisfied, any excess water will percolate downward to the saturated zone. After the excess water enters the saturated zone, it becomes available to wells.

Ground water moves under the influence of gravity from areas of recharge to areas of discharge. Ground-water movement is generally very slow, possibly only a few feet per year. The rate of movement is dependent upon the hydraulic conductivity and porosity of the material through which the water moves and the hydraulic gradient. Gravel and well-sorted medium or coarse sand generally are highly conductive, and deposits of these materials commonly are productive aquifers. Fine-grained materials such as silt, clay, and shale usually have low conductivity and may act as barriers that impede the movement of ground water into or out of more conductive material.

The water level in an aquifer fluctuates in response to variations in the rate of recharge and discharge. Some aquifers near or at land surface are recharged each spring and early summer by precipitation. Recharge to these aquifers normally is sufficient to replace losses caused by natural discharge and by pumping of wells, although there may be several years in which net gains or losses in ground-water storage occur. Aquifers confined by thick deposits of fine-grained materials such as clay or silt are recharged very slowly. Replenishment of these aquifers is by seepage from the confining fine-grained materials, and laterally from unconfined areas of the aquifer. The rates of recharge may increase as heads in the aquifers are lowered by pumping. However, head declines may continue for several years before sufficient recharge is induced to balance the rate of withdrawal. In some cases, this balance may never be achieved without a decrease in the rate of withdrawals. The decrease in discharge plus the increase in recharge is termed capture.

In parts of Benson and Pierce Counties, surface-water bodies are in hydraulic connection with ground water in shallow aquifers. The aquifers either may receive recharge from these streams and lakes or may discharge into them, depending on head relationships, which vary both in time and space.

Ground water contains variable amounts of dissolved mineral matter. Water in the form of precipitation begins to dissolve mineral matter in the air and continues to do so as it infiltrates the land surface and percolates through the soil. The amount and kind of dissolved mineral matter in water depends upon the solubility and types of rocks and soil material encountered, the pressure and temperature of the water and rock formations, and the amount of carbon dioxide and soil acids in the water. Water that has traveled a long distance from the recharge area through several types of rock formations with varying pressures and temperatures, generally is more highly mineralized than water that has been in transit for only a short time.

Numerous references are made in this report to ground-water quality types, such as sodium bicarbonate type, calcium bicarbonate type, etc. These classifications are derived from inspection of chemical analyses and represent the predominant cation (sodium, calcium, or magnesium) and anion (bicarbonate, sulfate, or chloride) expressed in milliequivalents per litre. Results of some analyses indicate that the water is a mixed chemical type in which two or more cations or anions are present in nearly equal concentrations.

The suitability of a water for various uses is determined largely by its physical properties and by the kind and amount of dissolved minerals. The chemical constituents, physical properties, and indices most likely to be of concern are: iron, sulfate, nitrate, fluoride, dissolved solids, hardness, temperature, specific conductance, sodium-adsorption ratio (SAR), and percent sodium. The source of the major chemical constituents, their effects upon usability of the water, and the limits recommended by the U.S. Public Health Service (1962) for drinking water on interstate carriers are given in table 1.

The quality of water used for irrigation is an important factor in productivity and quality of the irrigated crops. Salinity, sodium (alkali), and boron problems may result from the use of highly mineralized irrigation water. High salinity may result in the accumulation of salt in the soil to the extent that crops are injured. A sodium problem may develop if the amount of sodium in the irrigation water is high in comparison to the amount of calcium plus magnesium. Under such conditions, the soil is poorly permeable, sticky when wet, and hard and difficult to till when dry. Boron is required by all crops for normal growth, but injury may result if the amount in the irrigation water is more than 2,000 ug/l.

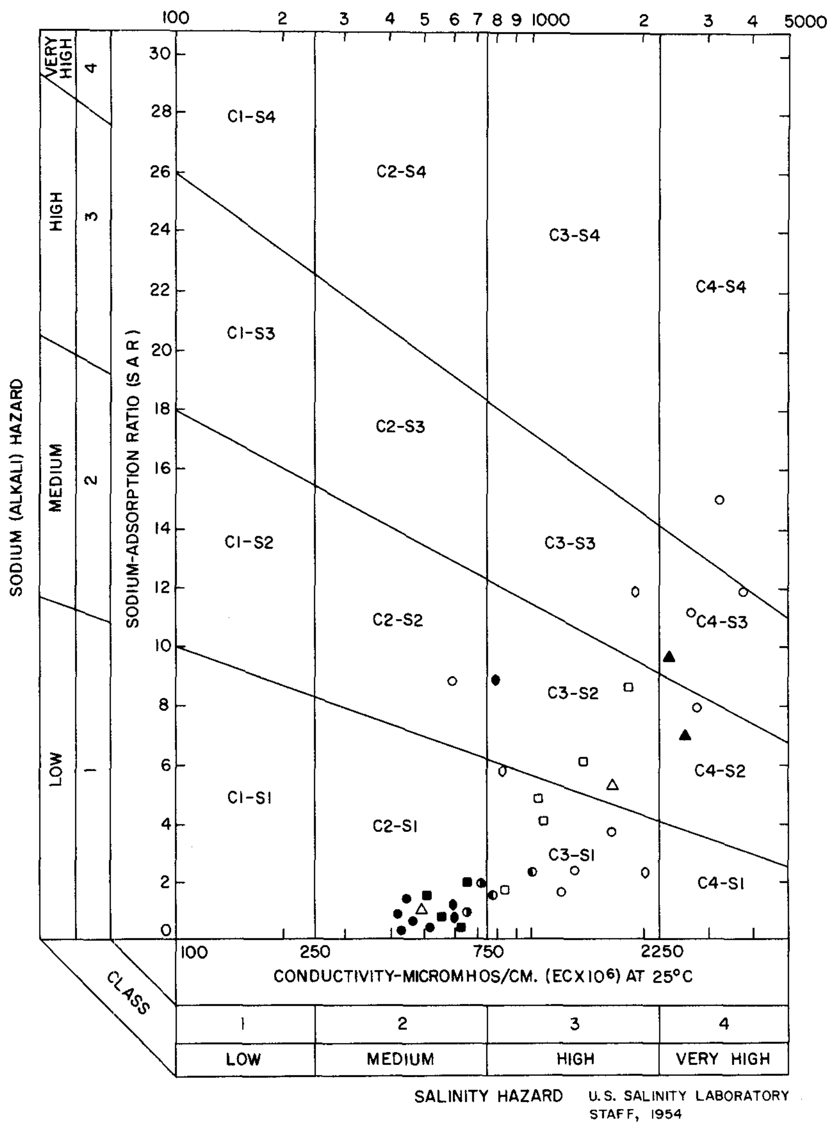
According to the U.S. Salinity Laboratory Staff (1954) the salinity hazard is related to the specific conductance of the water and the sodium hazard is related to the SAR. When judging the quality of an irrigation water according to the Salinity Laboratory Staff classification, it is assumed that the soil will take water readily and drain well; sufficient irrigation water will be applied to prevent salt accumulation in the root zone; and crops of proper salt and boron tolerance will be planted.

Salinity and sodium hazards of water from selected glacial-drift aquifers in Benson and Pierce Counties are shown in figure 5, using a classification developed by the U.S. Salinity Laboratory Staff (1954). Most of the aquifers yield water with a low sodium hazard (S1) and a medium (C2) to high (C3) salinity hazard. Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. Medium-salinity water (C2) can be used if a moderate amount of leaching occurs, and plants with moderate salt tolerance generally can be grown without special practices for salinity control. High-salinity water (C3) cannot be used on soils with restricted drainage. However, high-sodium or high-salinity waters have been used successfully for selected crops where ideal soil conditions and drainage exist.

TABLE 1. — Major chemical constituents in water — their sources, effects upon usability, and recommended concentration limits

(Modified after Durfor and Becker, 1964, table 2)

Constituents	Major source	Effects upon usability	U.S. Public Health Service (1962) recommended limits for drinking water
Silica (SiO_2)	Feldspars, ferromagnesian and clay minerals.	In presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat transfer.	
Iron (Fe)	Natural sources: amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, carbonates, and clay minerals. Manmade sources: well casings, pump parts, and storage tanks.	If more than 100 ug/l (micrograms per litre) iron is present, it will precipitate when exposed to air; causes turbidity, stains plumbing fixtures, laundry, and cooking utensils, and impart tastes and colors to food and drinks. More than 200 ug/l is objectionable for most industrial uses.	300 ug/l
Calcium (Ca)	Amphiboles, feldspars, gypsum, pyroxenes, calcite, aragonite, dolomite, and clay minerals.	Calcium and magnesium combine with bicarbonate, carbonate, sulfate, and silica to form scale in heating equipment. Calcium and magnesium retard the suds-forming action of soap and detergent. High concentrations of magnesium have a laxative effect.	
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, dolomite, magnesite, and clay minerals.		
Sodium (Na)	Feldspars, clay minerals, and evaporites.	More than 50 mg/l (milligrams per litre) sodium and potassium with suspended matter causes foaming, which accelerates scale formation and corrosion in boilers.	
Potassium (K)	Feldspars, feldspathoids, some micas, and clay minerals.		
Boron (B)	Tourmaline, biotite, and and amphiboles.	Many plants are damaged by concentrations of more than 2,000 ug/l.	
Bicarbonate (HCO_3)	Limestone and dolomite.	Upon heating of water to the boiling point, bicarbonate is changed to steam, carbonate, and carbon dioxide. Carbonate combines with alkaline earths (principally calcium and magnesium) to form scale.	
Carbonate (CO_3)			
Sulfate (SO_4)	Gypsum, anhydrite, and oxidation of sulfide minerals.	Combines with calcium to form scale. More than 500 mg/l tastes bitter and may be a laxative.	250 mg/l
Chloride (Cl)	Halite and sylvite.	In excess of 250 mg/l may impart salty taste, greatly in excess may cause physiological distress. Food Processing industries usually require less than 250 mg/l.	250 mg/l
Fluoride (F)	Amphiboles, apatite, fluorite, and mica.	Optimum concentration in drinking water has a beneficial effect on the structure and resistance to decay of children's teeth. Concentrations in excess of optimum may cause mottling of children's teeth.	Recommended limits depend on annual average of maximum daily air temperatures. Limits range from 0.6 mg/l at 32°C to 1.7 mg/l at 10°C.
Nitrate (NO_3)	Nitrogenous fertilizers, animal excrement, legumes, and plant debris.	More than 100 mg/l may cause a bitter taste and may cause physiological distress. Concentrations in excess of 45 mg/l have been reported to cause methemoglobinemia in infants.	45 mg/l
Dissolved solids	Anything that is soluble.	More than 500 mg/l is not desirable if better water is available. Less than 300 mg/l is desirable for some manufacturing processes. Excessive dissolved solids restrict the use of water for irrigation.	500 mg/l



EXPLANATION

- □ NEW ROCKFORD AQUIFER
- ◐ NEW ROCKFORD AQUIFER *(WESTERN PART)*
- ■ SPIRITWOOD AQUIFER NEAR WARWICK
- ○ SPIRITWOOD AQUIFER NEAR MINNEWAUKAN
- △ KILGORE AQUIFER
- 0 MADDOCK AQUIFER
- ▲ LEEDS AQUIFER
- ● WARWICK AQUIFER
- ♦ ESMOND AQUIFER
- ◑ PLEASANT LAKE AQUIFER

FIGURE 5.—Classification of water for irrigation use.

Ground Water in the Preglacial Rocks

Dakota Aquifer

The Dakota aquifer comprises two water-bearing beds of fine- to medium-grained quartz sandstone in the Dakota Group. The upper bed averages about 100 feet (30 m) in thickness and the lower bed 50 feet (15 m). The aquifer underlies Benson and Pierce Counties (fig. 6) at depths ranging from about 1,400 to 2,200 feet (430 to 670 m) below land surface.

The potentiometric surface of the Dakota aquifer slopes eastward from about 1,600 feet (490 m) above msl in western Pierce County to about 1,500 feet (460 m) above msl in eastern Benson County. Consequently, wells will generally flow if drilled in areas where the land surface is lower than these altitudes. Large cones of depression caused by pumping have formed in the potentiometric surface in areas of long-term withdrawal, such as near the city of Leeds.

Water from the Dakota aquifer in Benson and Pierce Counties contains about 4,000 mg/l dissolved solids, and is a sodium sulfate or a mixed sodium sulfate-chloride type. This water is unsuitable for irrigation because of high dissolved solids, sodium, and boron concentrations; however, it has been used satisfactorily for livestock and some domestic purposes without apparent ill effects. The temperature of water from flowing wells in the Dakota aquifer is about 65°F (18.5°C).

The Dakota aquifer yields as much as 100 gal/min (6 l/s) to wells in Benson and Pierce Counties. Because of its depth, mineralization, and the general availability of water in shallower aquifers, the water in the Dakota aquifer is not extensively used. However, should an economical desalinization process be developed, the Dakota aquifer may be an important source of water in the future.

Pierre Aquifer

Small quantities of water are generally available from fractures and silty layers in the upper part of the Pierre Formation. The fractures are most extensive in outcrop areas and where the formation directly underlies glacial drift (fig. 3).

Recharge to the Pierre aquifer is largely through the overlying glacial drift. Recharge is greatest where the aquifer is overlain by permeable drift aquifers or in areas where the drift is thin.

Water from the Pierre aquifer is generally of three types — sodium bicarbonate, sodium sulfate, and sodium chloride. The water generally contains high concentrations of iron and dissolved solids; however, the water is soft and is used for domestic and livestock purposes. Well yields range from 1 to 10 gal/min (0.06 to 0.6 l/s).

Fox Hills Aquifer

The Fox Hills aquifer consists of semiconsolidated sandstone in the upper part of the Fox Hills Formation. The lower part of the formation is mostly

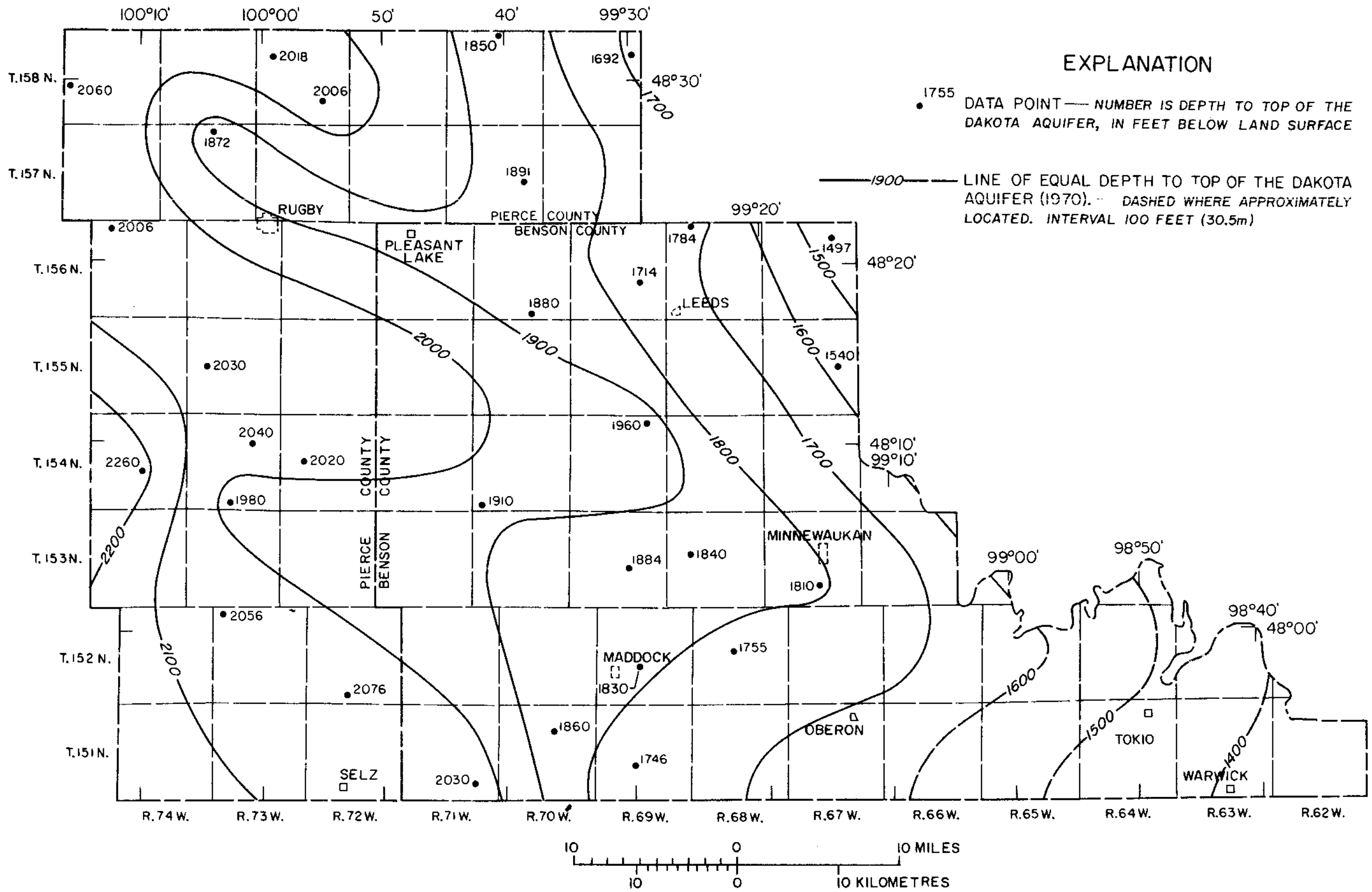


FIGURE 6.—Depth to the top of the Dakota aquifer.

siltstone interbedded with shale and claystone, which are too fine grained to be of importance as an aquifer.

Recharge to the Fox Hills aquifer is mainly in the central part of the study area,and is by direct infiltration of precipitation and water from streams and lakes and by seepage through overlying glacial deposits. Ground-water movement through the Fox Hills aquifer generally is from the topographically high recharge areas toward the lower plains and valleys. Hydrographs of water-level fluctuations in observation wells indicate that maximum ground-water storage generally occurs during June and July (figs. 7 and 8). These hydrographs show a continuous increase in ground-water storage for the period of record. They also show that the Fox Hills aquifer responds rapidly to seasonal and annual precipitation.

Results of chemical analyses of water from 16 wells developed in the Fox Hills indicate that the water is a mixed sodium bicarbonate-sulfate type. The analyses showed a range in dissolved-solids concentration of 380 to 1,410 mg/l. The water is relatively soft, and the main constituents in order of magnitude are bicarbonate, sodium, sulfate, and chloride.

A low calcium-magnesium ratio suggests that clay minerals or organic materials capable of base exchange are present in the Fox Hills aquifer and are responsible for the soft water found in most parts of the aquifer. Water from the Fox Hills aquifer is distinguishable from that in glacial-drift aquifers by its softness and high sodium content. The water is satisfactory for most domestic and livestock uses, but caution may be advisable for people on a sodium-restricted diet (North Dakota State Dept. of Health, 1962). The sodium hazard for irrigation use is high except in shallow recharge areas.

Laboratory analyses of drill cuttings from the aquifer indicate porosities of 43 to 45 percent and hydraulic conductivities of 7 to 16 ft/d (2 to 5 m/d). Based on these and field data, wells developed in the aquifer should yield 4 to 100 gal/min (0.3 to 6 l/s), with the larger yields occurring in areas of greatest hydraulic conductivity and sandstone thickness.

Ground Water in the Glacial Deposits

The principal glacial-drift aquifers in the two-county area occur in buried-valley, buried-outwash, and surficial-outwash deposits. Minor aquifers occur in lacustrine, ice-contact, and till and associated sand and gravel deposits. For convenience of discussion and identification in this report and for future reference, the principal aquifers are named, commonly after nearby prominent geographic features such as lakes or cities. The approximate extent and availability of water from these aquifers are shown on plate 2 (in pocket). The estimated potential yields to properly constructed wells in these aquifers range from 50 to 1,500 gal/min (3.2 to 95 l/s). These well yields are based on saturated thickness, estimated hydraulic conductivities, aquifer-test data, and hydrologic boundaries.

Where sufficient test-drilling and hydrologic data are available, an estimate of ground-water availability from storage is given for each aquifer. The estimates are given in acre-feet and are products of areal extent, saturated thickness, and specific yield (about 0.15). The storage estimates are provided

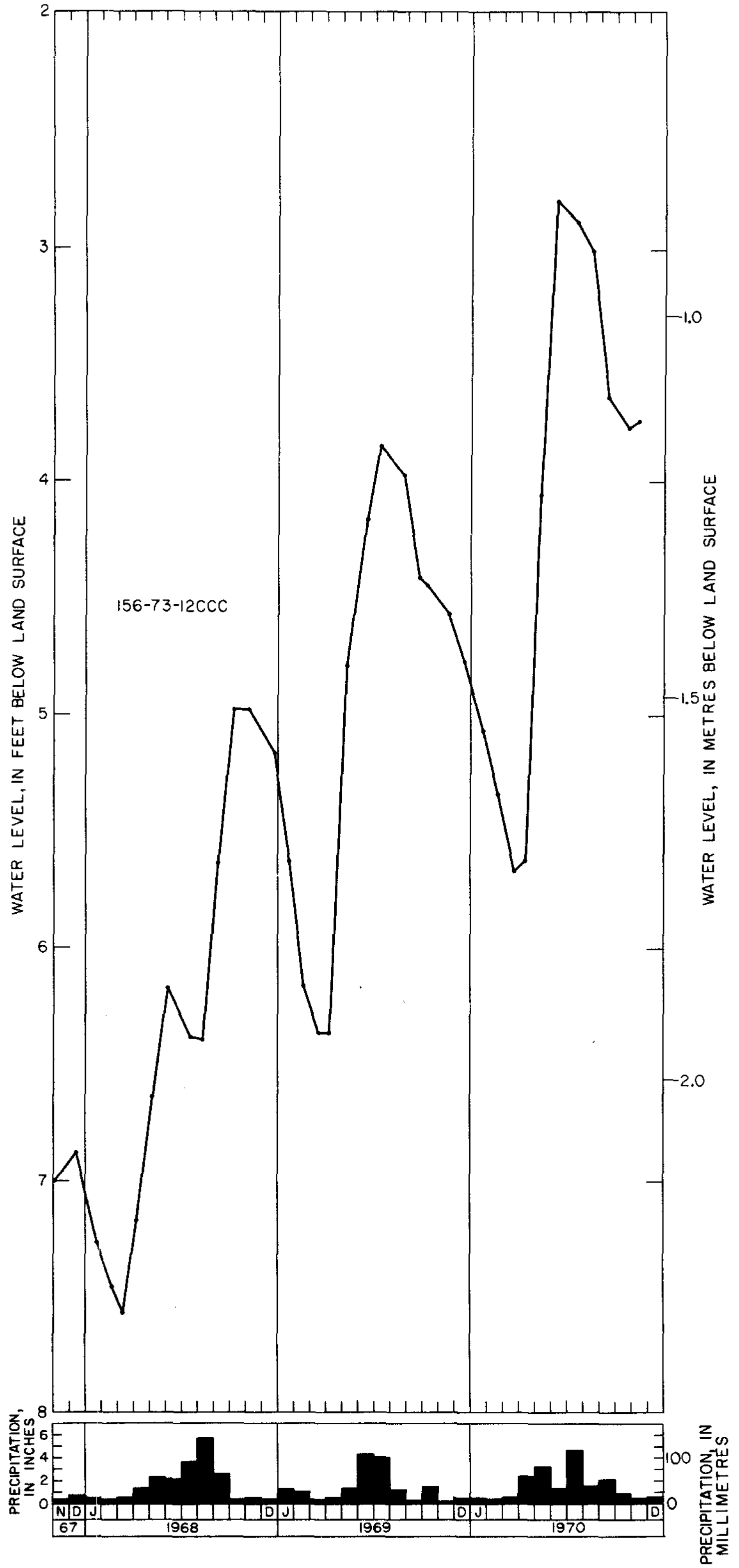


FIGURE 7.— Water-level fluctuations in a shallow well tapping the Fox Hills aquifer, and precipitation at Rugby.

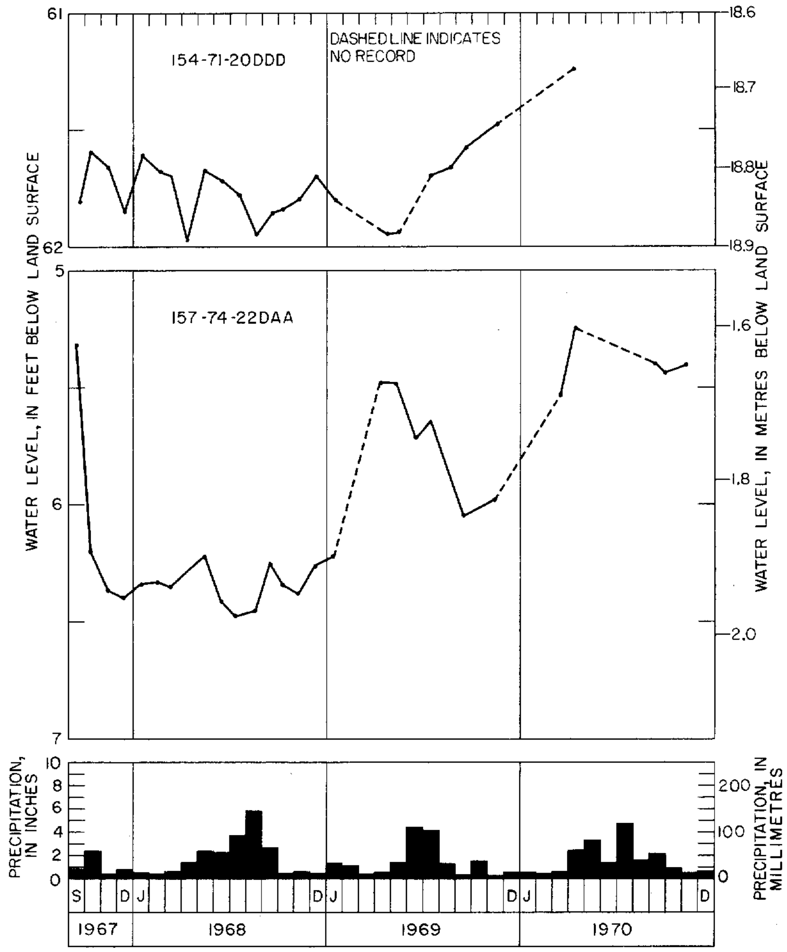


FIGURE 8.— Water-level fluctuations in deep wells tapping the Fox Hills aquifer, and precipitation at Rugby.

for comparison purposes only and are based on static conditions. They do not take into account recharge, natural discharge by evapotranspiration or springs, or ground-water movement between adjacent aquifers. The quantitative evaluation of these factors is beyond the scope of the present reconnaissance-type study.

Buried-Valley Aquifers

There are four major aquifers in the buried valleys of Benson and Pierce Counties. They are identified on plate 2 as the New Rockford aquifer, Spiritwood aquifer system near Warwick and near Minnewaukan, and Kilgore aquifer. All extend beyond the study area, but are herein discussed as they exist in Benson and Pierce Counties.

New Rockford aquifer

The New Rockford aquifer, in southwestern Benson County and southern Pierce County, extends westward into McHenry County and southeastward into Wells County (pl. 2). Trapp (1968, p. 41) applied the name New Rockford for the city in Eddy County. The aquifer was traced through Wells County to southwestern Benson County by Buturla (1970, pl. 2).

The New Rockford aquifer was penetrated by 28 test holes in Benson and Pierce Counties. It is about 21 miles (34 km) long, generally 2 to 4 miles (3 to 6 km) wide, and underlies approximately 80 mi^2 (207 km^2) of the study area. The aquifer occupies a buried valley (fig. 4 and pl. 1) incised into the Fox Hills and Pierre Formations and is widest near Selz where drainage from glacial Lake Souris entered the valley.

The top of the aquifer generally is about 150 feet (46 m) below land surface and the bottom extends to a depth of 383 feet (116 m) in places. The aquifer has an average thickness of 147 feet (45 m). A large block of till partly obstructs the upper part of the aquifer between 2 and 5 miles (3 and 8 km) west of North Dakota State Highway 3 in southern Pierce County (pl. 2). This obstruction consists of gravelly till, which is probably older in origin than the surficial Martin end moraine (pl. 3, sec. A-A′, in pocket) at this location.

Particle-size analyses[2] of 36 samples indicate a westward gradation of aquifer materials from medium and coarse sand (fig. 9) to a very fine and medium gravel (fig. 10). The gradation suggests that the source area for the aquifer material was west of Pierce County. The sand and gravel generally occur as separate, although somewhat interfingered, deposits (pl. 3, sec. B-B′). The materials are well sorted and have a mean porosity of 33 percent. Thin lenses of silty clay are interfingered throughout the aquifer.

In order to determine the hydraulic properties of the New Rockford aquifer, an aquifer test was made in July and August 1969 by the North Dakota State Water Commission and the U.S. Geological Survey using well 151-72-25BCB4. The well had 250 feet (76 m) of 16-inch (0.41-m) casing and 45 feet (13.7 m) of 10-inch (0.25-m) nominal 50-slot screen exposed to the aquifer 250-295 feet (76-90 m) below land surface. The well pump consisted of a four-stage 12-inch (0.30-m) bowl assembly with 140 feet (42.7 m) of 8-inch (0.20-m) pump column and was powered by a propane engine. Observation wells were installed at 20 sites. These wells were located at distances ranging from 270 feet (82 m) to about 6 miles (10 km) from the pumped well. The well was pumped at a constant rate of 1,420 gal/min (90 l/s) for

[2] Samples from the major glacial-drift aquifers in Benson and Pierce Counties were analyzed for particle-size distribution (Randich, 1971, table 5). Particle-size distribution curves were then prepared to graphically determine the mean particle size, uniformity coefficient (Cu), and sorting coefficient (Co). Hydraulic conductivity and porosity of the samples were estimated from the particle-size analyses using the relationships described by Johnson (1963, p. 26-29). This correlation is reasonably close to results obtained from aquifer test sites. Transmissivity is calculated as the product of the average hydraulic conductivity and the saturated thickness of the aquifer.

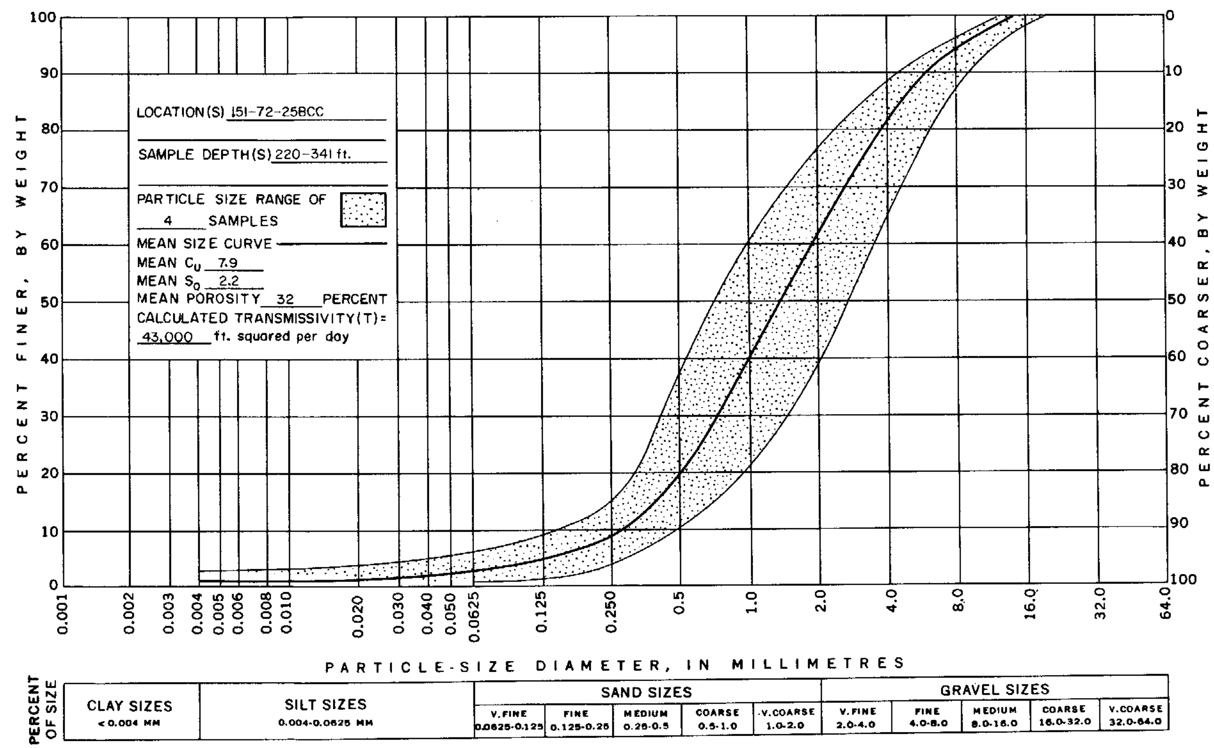


FIGURE 9.—Particle-size distribution curves for samples from the eastern part of the New Rockford aquifer.

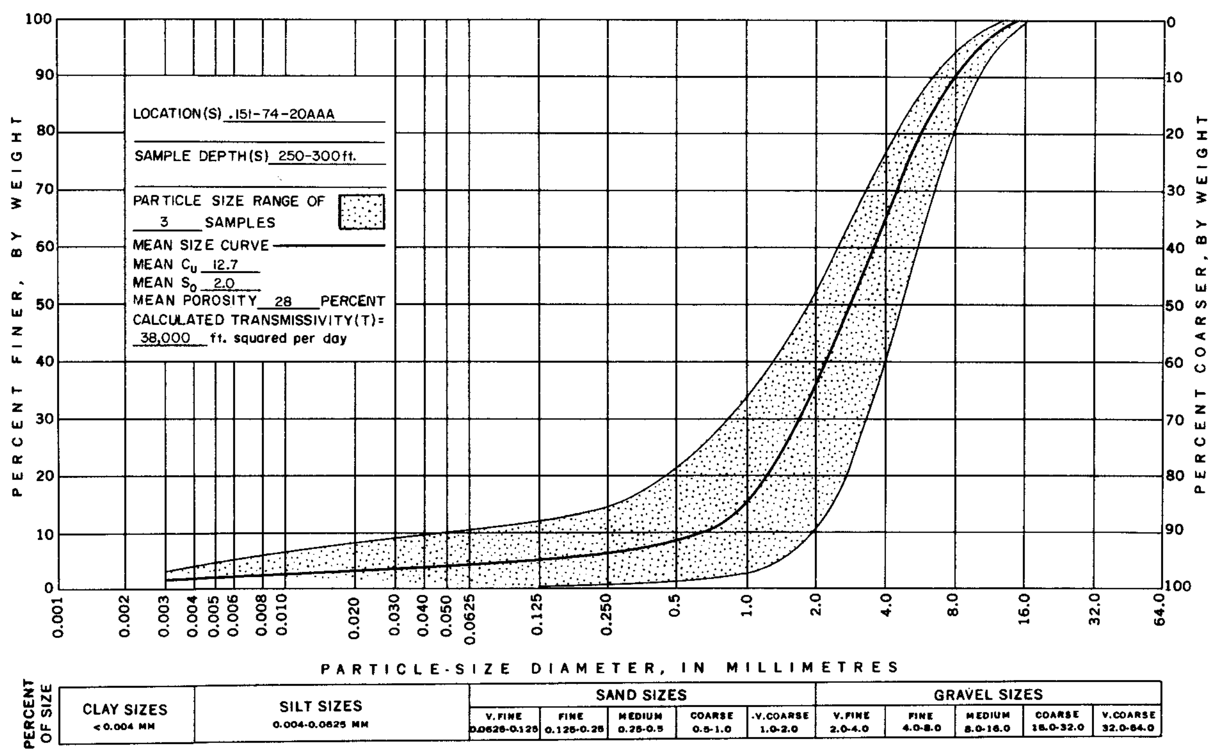


FIGURE 10.—Particle-size distribution curves for samples from the western part of the New Rockford aquifer.

7,200 minutes (5 days). The water was discharged into an existing pothole near the site. The water level in the pothole rose about 1 foot (0.3 m) during the test. Drawdown and recovery measurements were made on all wells. No other wells in the area were known to be pumping from the aquifer during the test.

Drawdown of the potentiometric surface as a result of the pumping is shown in figure 11. Wells in the shallow unconfined aquifer were not influenced — either because there is no direct hydraulic connection or the period of pumping was not long enough. Figure 12 shows long-term water-level trends and the effects of this test in well 151-72-36AAA1, 6,000 feet (1,800 m) from the pumping well.

The aquifer-test data were analyzed according to methods devised by Theis (1935, p. 519-524) and Cooper and Jacob (1946). The analyses show a transmissivity range of 40,000 to 56,000 ft^2/d (3,700 to 5,300 m^2/d) and a storage coefficient of about 0.0007. The analysis of the data from observation well 151-72-25BBC (fig. 13), which is 600 feet (180 m) from the pumped well, shows confined aquifer conditions, and influences of impermeable boundary effects by departures from the type curve. A straight-line solution, using the drawdown obtained in six observation wells after 5 days of pumping (fig. 14), generally represents the mean transmissivity of the aquifer in the test area.

The specific capacity of the pumped well after 5 days of pumping was 79 (gal/min)/ft [16 (l/s)/m] of drawdown. This indicates that the aquifer at this site may yield as much as 1,500 gal/min (95 l/s) with about 20 feet (6 m) of drawdown after 5 days of pumping. Analysis of the test results indicates, however, that due to boundary conditions in the test area, varying lithologies, and slow recharge, sustained yields to wells would generally be restricted to the 750 to 1,000 gal/min (48 to 63 l/s) range.

Recharge to the New Rockford aquifer in Benson and Pierce Counties is by percolation of water through shallow overlying aquifers and by underflow from adjacent and underlying bedrock deposits (p. 1). These shallow aquifers, which contain unconfined water, are recharged by precipitation (fig. 15) and have water levels 10 to 50 feet (3 to 15 m) higher than the New Rockford aquifer. They are potentially large sources of recharge to the New Rockford aquifer. In the western part of the area, where the New Rockford aquifer underlies the Martin end moraine (pls. 2 and 3), substantial recharge also occurs from prairie potholes. Clear Lake appears to by hydraulically connected to the aquifer.

Water levels, in the New Rockford aquifer show only small annual fluctuations, indicating that recharge is nearly balanced by natural discharge (figs. 12 and 16). A long-term increase of ground water in storage shown in figure 16 is the result of above-average precipitation. Water levels in the western part of the aquifer (fig. 16) are generally 40 to 50 feet (12 to 15 m) higher than in the eastern part (fig. 12). Ground-water movement through the aquifer system is generally east to southeast. The difference in head is due to recharge occuring in the western part of the aquifer and the mass of till partially blocking the buried valley in T. 151 N., R. 73 W. A ground-water

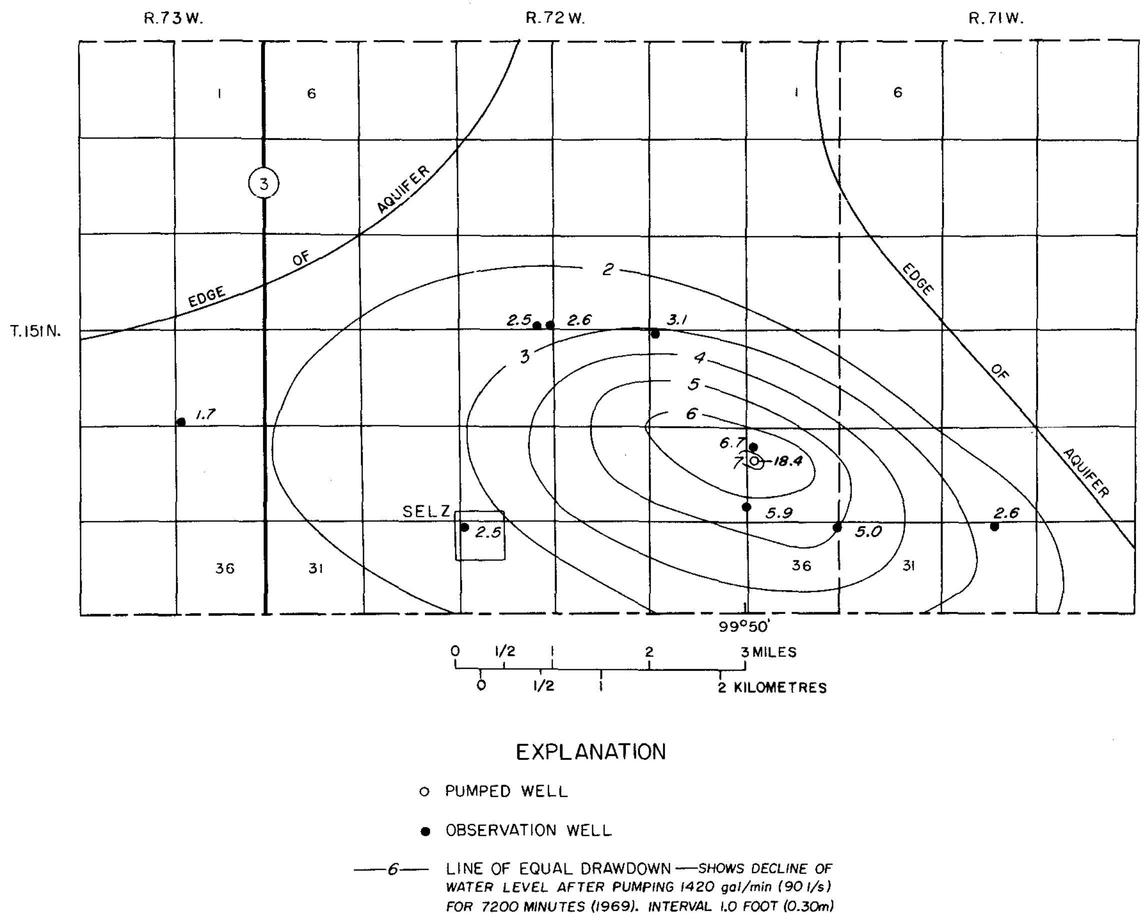


FIGURE 11.—Locations of wells in the New Rockford aquifer, and drawdown caused by aquifer test near Selz.

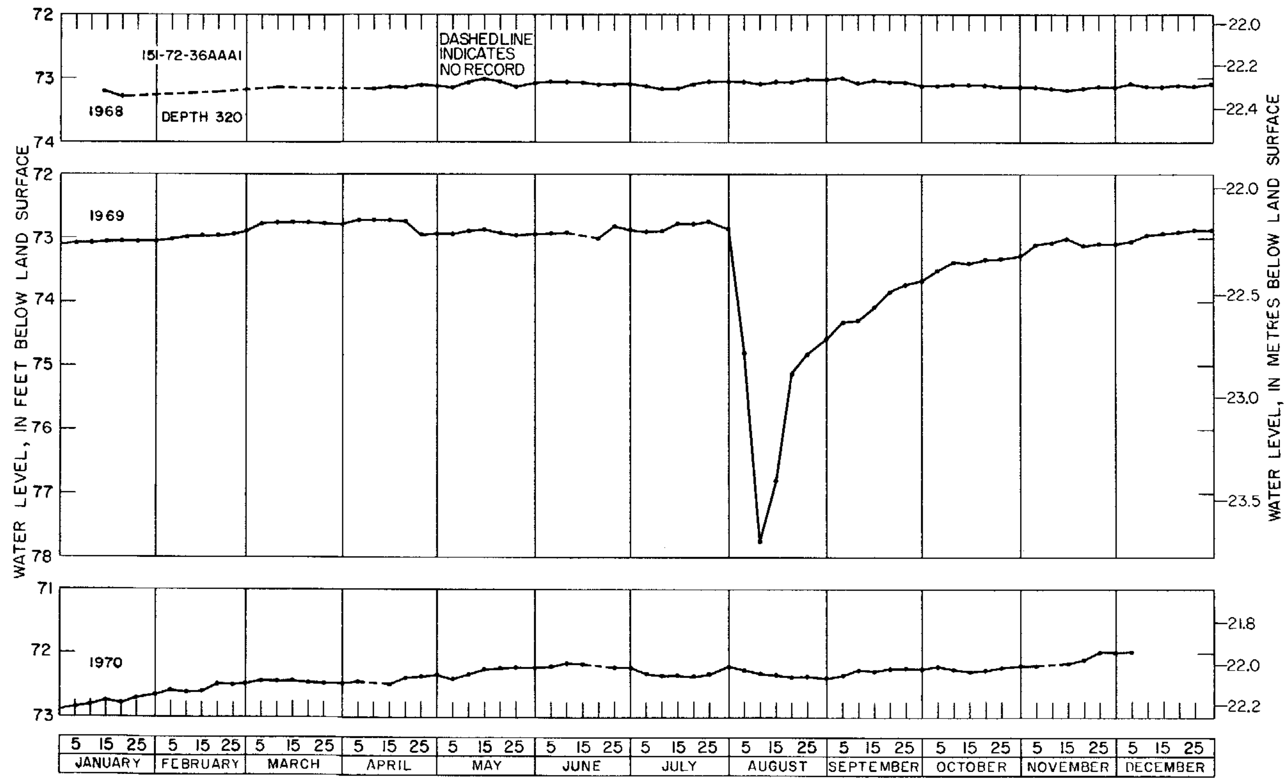


FIGURE 12.—Water-level trends in the New Rockford aquifer.

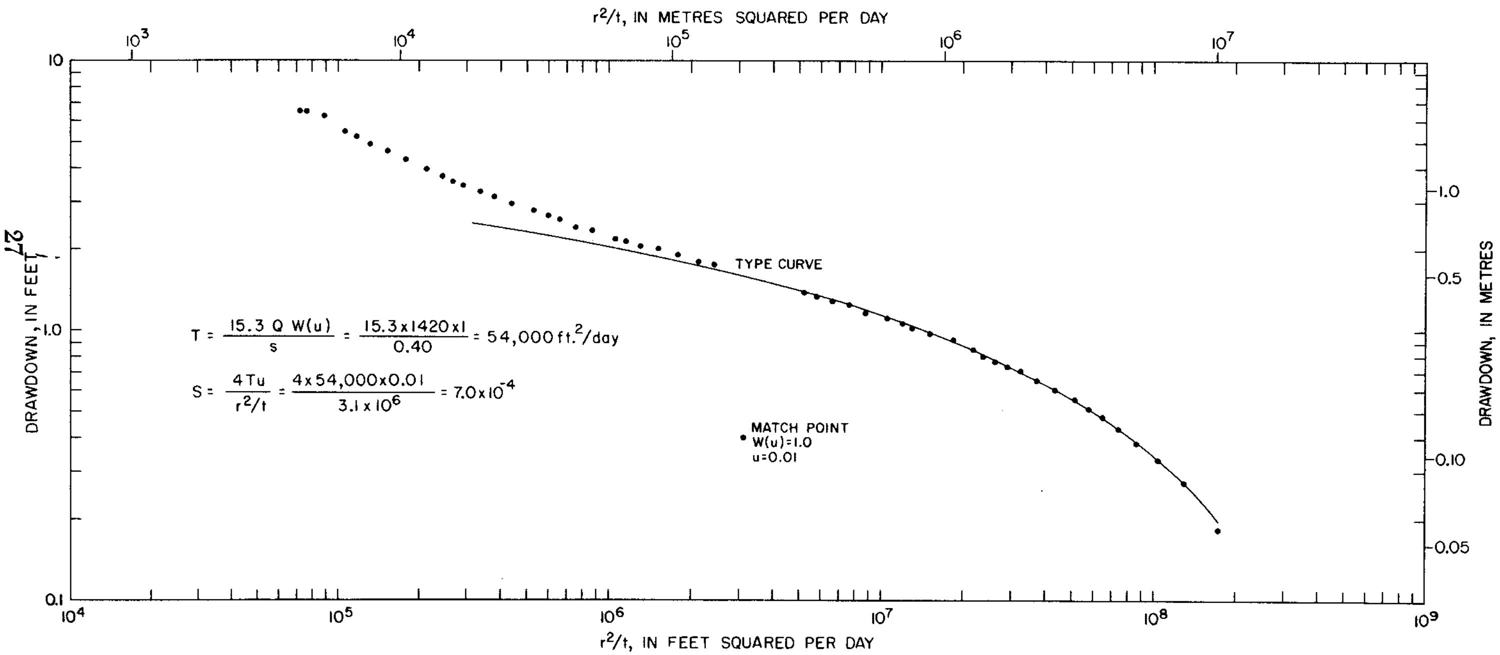


FIGURE 13.— Type-curve calculation of transmissivity (T) and storage coefficient (S), well 151-72-25BBC, New Rockford aquifer test (1969).

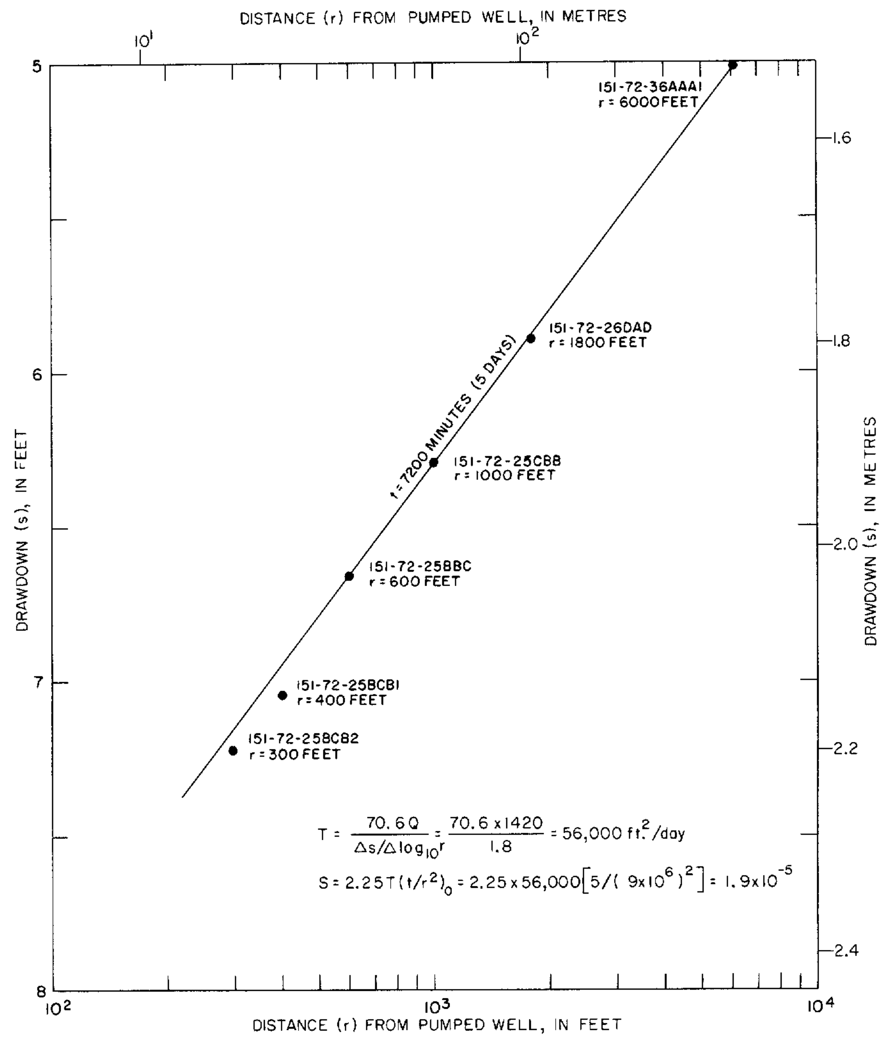


FIGURE 14.— Straight-line solution of transmissivity (T) and storage coefficient (S), New Rockford aquifer test (1969).

divide, where recharge is occurring, appears to be located near the Pierce-McHenry County border. Water levels in these areas indicate that ground-water movement is southeast in Pierce County and northwest in McHenry County.

About one-half million acre-feet (0.6 km^3) of water is available from storage within the Benson and Pierce Counties segment of the New Rockford aquifer.

Water from the New Rockford aquifer is generally a sodium bicarbonate

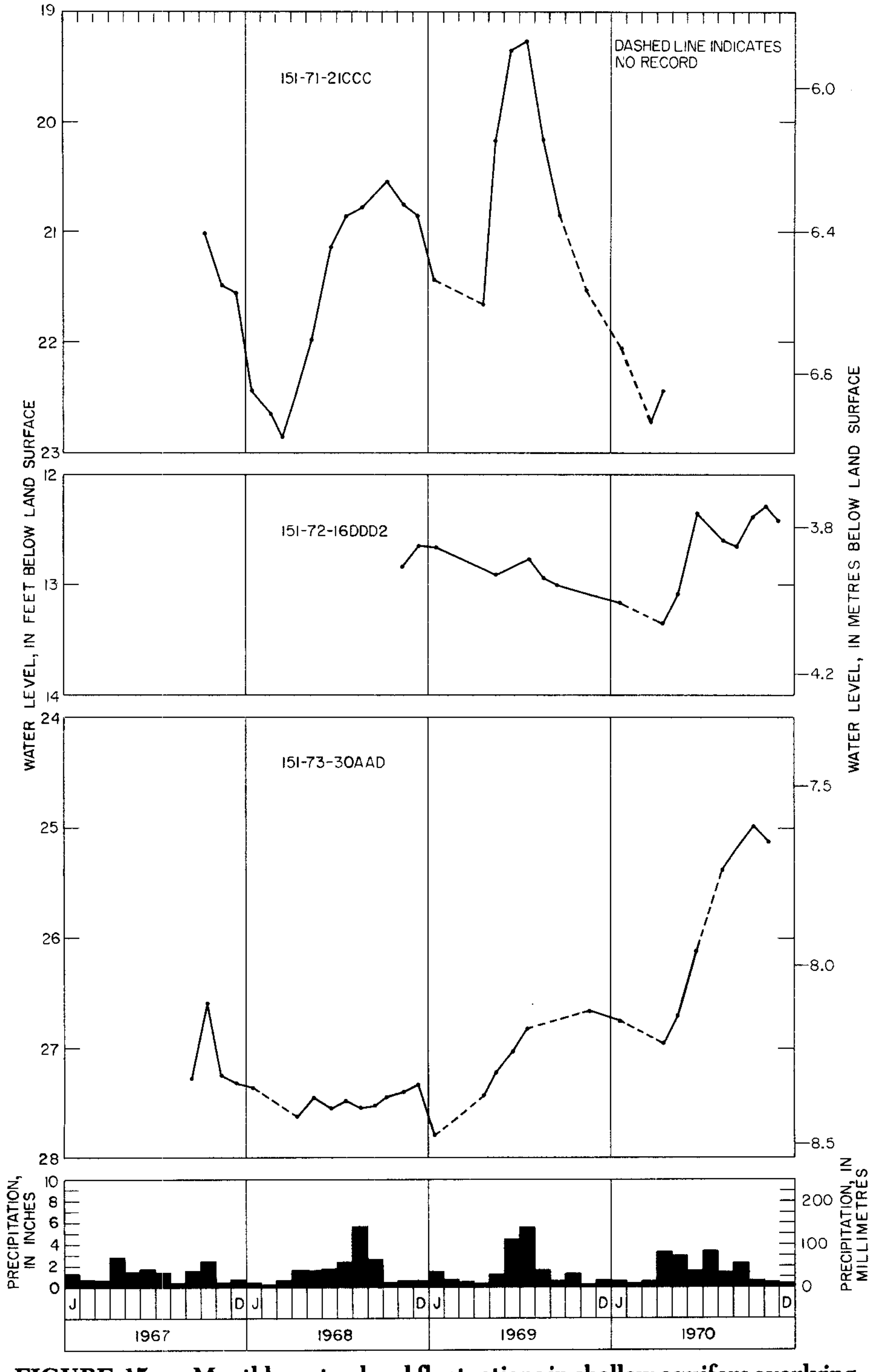


FIGURE 15.— Monthly water-level fluctuations in shallow aquifers overlying the New Rockford aquifer, and precipitation at Balta.

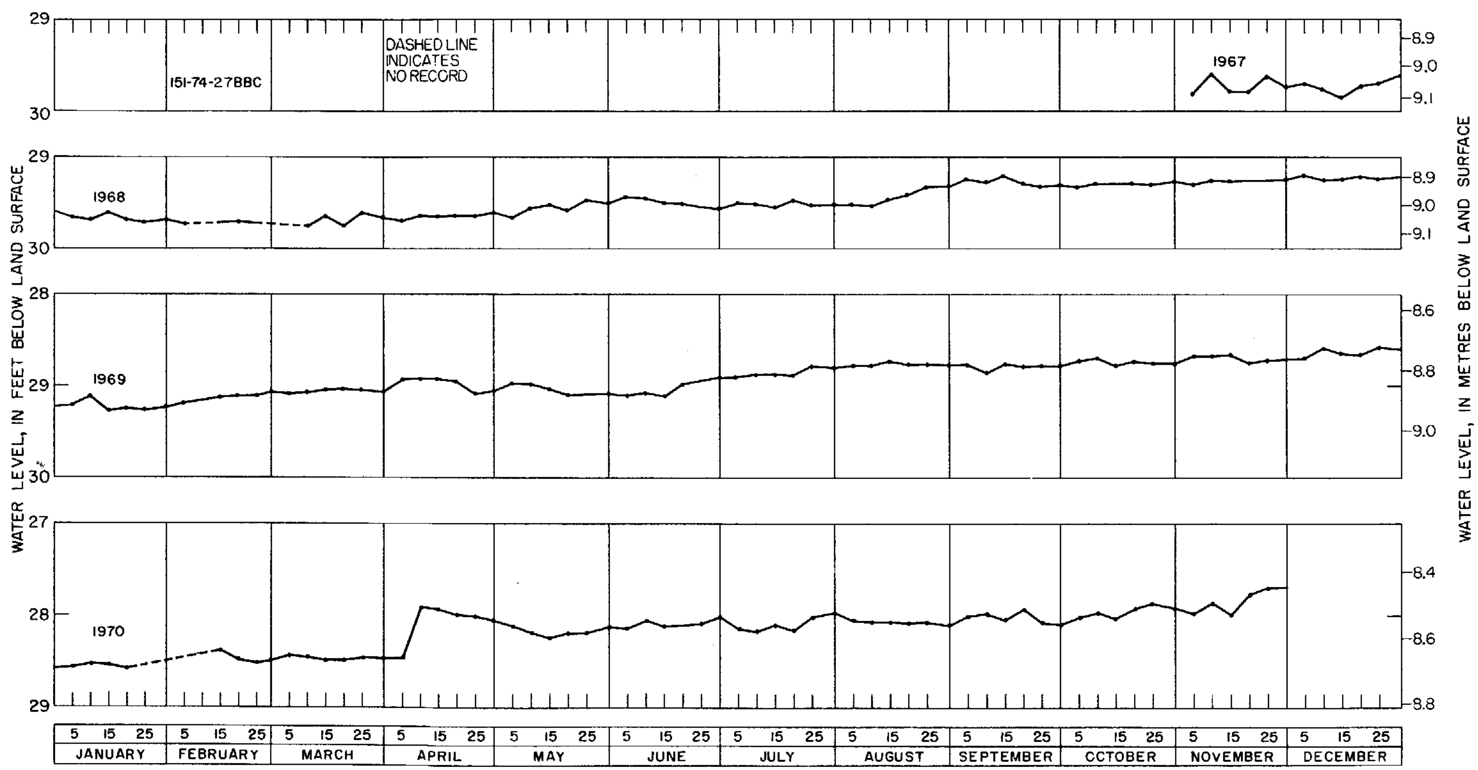


FIGURE 16.—Water-level fluctuations in the New Rockford aquifer showing long-term increase in storage.

type, but locally it is a mixed sodium bicarbonate-sulfate type. The dissolved-solids concentration of 18 water samples ranged from 450 to 1,250 mg/l, and averaged less than 700 mg/l. Most of the samples were in the C3 (high salinity) classification for irrigation (fig. 5). The sodium-hazard classification ranged from S1 (low sodium) to S2 (medium sodium). The highest concentrations of sodium and sulfate were found along the flanks and near the base of the aquifer where recharge from the underlying bedrock may be significant.

Analyses of samples taken during the 5-day aquifer test at 151-72-25BCB4 showed that calcium increased 22 percent, bicarbonate 5 percent, and disolved solids about 4 percent. The increase in calcium and bicarbonate suggests vertical leakage from overlying materials.

The New Rockford aquifer is potentially the most productive aquifer in Pierce County. Little water was withdrawn from wells in the aquifer in 1971, while the recharge-discharge relationship was in a state of near equilibrium. Yields to properly constructed wells range from 250 to 500 gal/min (16 to 32 l/s) in most parts of the aquifer and from 500 to 1,500 gal/min (32 to 95 l/s) in the central part (pl. 2).

Spiritwood aquifer system

The aquifer system was first named by Huxel (1961, p. 179-181) in Stutsman County. It was traced northward through Barnes County by Kelly (1964, p. 161-165). In Eddy County, Trapp (1968, p. 68-69) identified a buried-valley aquifer that he believed to be part of the Spiritwood aquifer system. Downey (1973, p. 27) traced an aquifer, which is part of the Spiritwood system, from Eddy County through the southwestern corner of Nelson County to the Benson County line.

There are two segments of the Spiritwood aquifer system in Benson County. These segments are separated geographically and have some differing hydraulic and chemical characteristics. Thus, the buried-valley aquifers in southeastern and eastern Benson County are herein considered as two parts, the Spiritwood aquifer system near Warwick and the Spiritwood aquifer system near Minnewaukan.

Spiritwood aquifer system near Warwick. – This segment of the Spiritwood aquifer system occurs in a buried valley that underlies about 12 mi^2 (31 km^2) of southeastern Benson County. It underlies part of the Warwick aquifer (pl. 2) and extends north beneath an east-trending end moraine and Devils Lake.

Results from drilling nine test holes indicate that the top of the aquifer lies from 79 to 180 feet (24 to 55 m) below land surface. The Spiritwood aquifer has an average thickness of about 94 feet (29 m) in this area. Large thicknesses of lake-deposited clay and silty clay interfingered with sand overlie the aquifer, indicating a period of glacial stagnation during which a lake occupied the overlying area (pl. 3, sec. C-C′).

Particle-size analyses were made on 19 samples of aquifer material taken from the test holes. Particle-size graphs for these samples indicate a range in aquifer materials from medium and very coarse sand in the upper parts to very fine and medium gravel in the lower parts. Distribution curves for four samples from test hole 151-62-27AAA2 are shown in figure 17. The porosity ranges from 25 to 45 percent and averages about 34 percent. The calculated transmissivity averages about 22,400 ft^2/d (2,080 m^2/d) and the hydraulic conductivity for selected intervals ranges from 29 to 402 ft/d (9 to 123 m/d).

Recharge to the aquifer is primarily from overlying glacial-drift deposits and underflow from connecting tributary buried valleys. Some recharge is from adjacent bedrock formations.

Water levels in the aquifer are generally 14 to 20 feet (4 to 6 m) below land surface, except in the northern part of T. 151 N., where the aquifer underlies an end moraine. Here the water levels range from 40 to 61 feet (12 to 19 m) below land surface. Hydrographs indicate a delayed response to precipitation (fig. 18) due to low permeability of overlying deposits. The gradual rise of water levels during the period of record indicates an increase in storage, which can be attributed to seepage from East Devils Lake. East Devils Lake was dry in 1968. Overflow from Devils Lake and high runoff during 1969 partly filled East Devils Lake, and lake levels continued to rise during the period 1969-74.

About 125,000 acre-feet (0.15 km^3) of water is available from storage within the Benson County segment of the Spiritwood aquifer system near Warwick.

The water in the Spiritwood aquifer system near Warwick is generally a calcium bicarbonate type in the central part of the aquifer and a sodium bicarbonate type near the flanks. The sulfate concentration decreases along the axis of the aquifer from north to south. The water is generally high in calcium and magnesium and is very hard. Dissolved solids in six samples ranged from 319 to 1,000 mg/l and averaged 464 mg/l. All the samples were in the irrigation classification C2, medium-salinity hazard, and S1, low-sodium hazard (fig. 5).

Based on present data (1970), potential yields to wells (pl. 2) should range from 250 to 1,500 gal/min (16 to 95 l/s).

Spiritwood aquifer system near Minnewaukan. – This segment of the Spiritwood aquifer system extends from near Leeds in northwestern Benson County, southeast to near the city of Minnewaukan, and eastward beneath Devils Lake (pl. 2). The aquifer materials were deposited in an ice-marginal channel during an early age of glaciation in the area. The aquifer was previously called the Grahams Island aquifer (Paulson and Akin, 1964, p. 38) when part of it was first identified east of Minnewaukan.

The Spiritwood aquifer system near Minnewaukan underlies about 60 mi^2 (155 km^2); it was penetrated by 48 test holes in Benson County. The top of the aquifer is generally less than 100 feet (30 m) below the land surface, and the overlying materials are mostly till and lacustrine deposits. The saturated thickness of the aquifer ranges from 7 to 159 feet (2 to 48 m) and averages 50 feet (15 m).

Particle-size analyses were determined for 21 samples of aquifer materials taken from test holes. Particle-size distribution graphs for these samples show that the most productive aquifer materials generally range from medium sand to medium gravel. However, these materials are randomly interbedded throughout the aquifer (pl. 3, sec. D-D′). Figures 19 and 20 illustrate

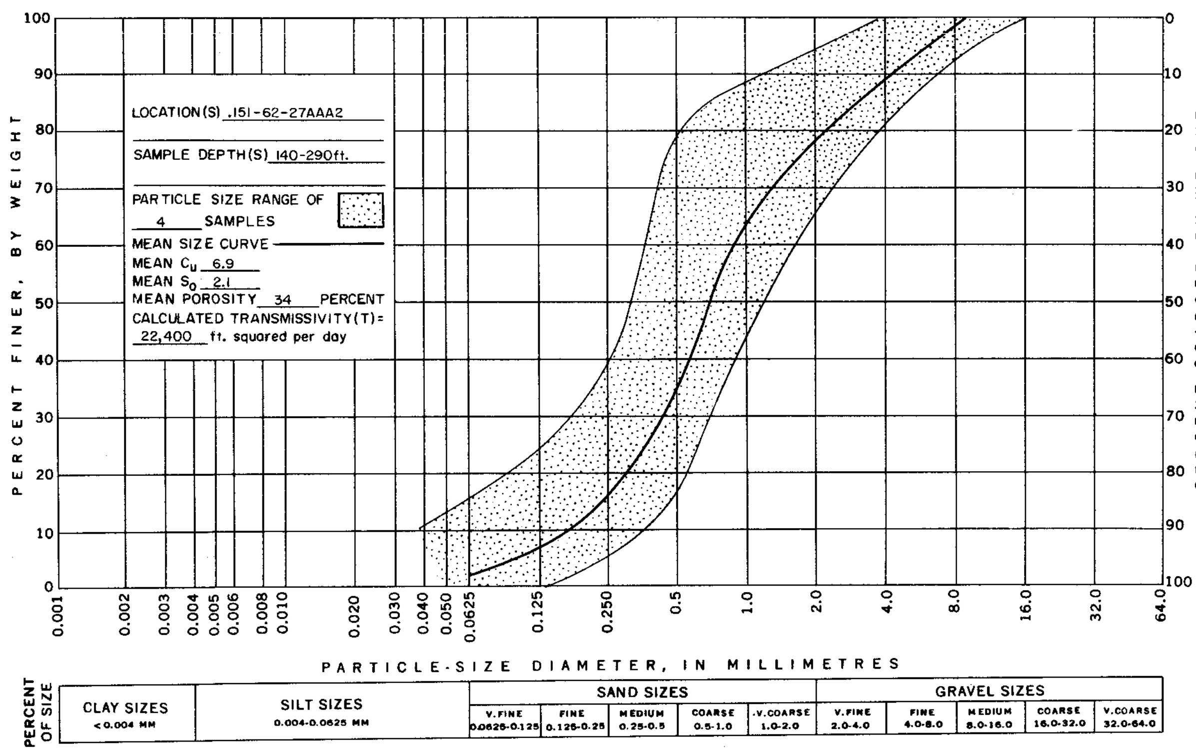


FIGURE 17.—Particle-size distribution curves for samples from the Spiritwood aquifer system near Warwick.

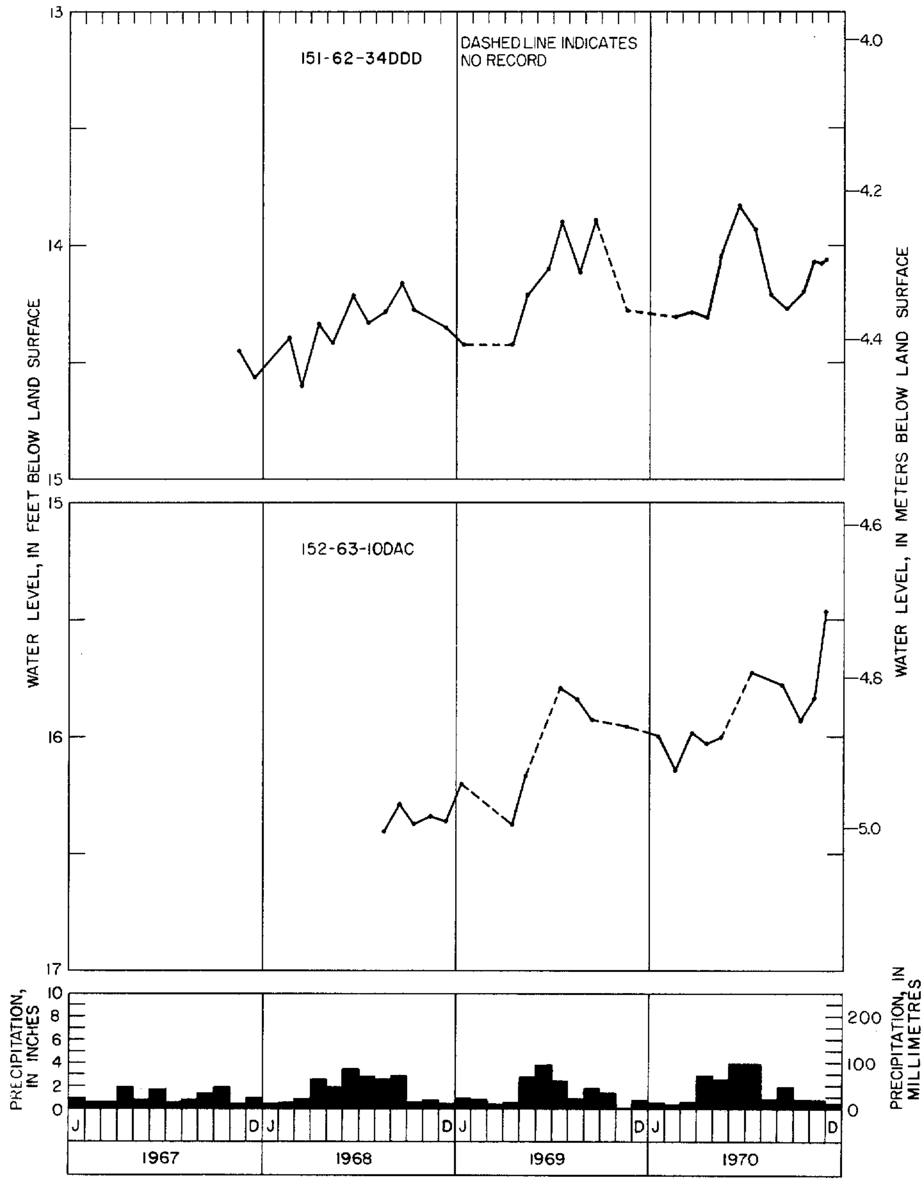


FIGURE 18.— Water-level fluctuations in the Spiritwood aquifer system near Warwick, and precipitation at Warwick.

the generally poor sorting and wide range of particle sizes, respectively, in the aquifer materials.

An aquifer test was conducted using a 4-inch (100-mm) partially penetrating well (154-67-11DDD1). The well was pumped at a rate of 30 gal/min

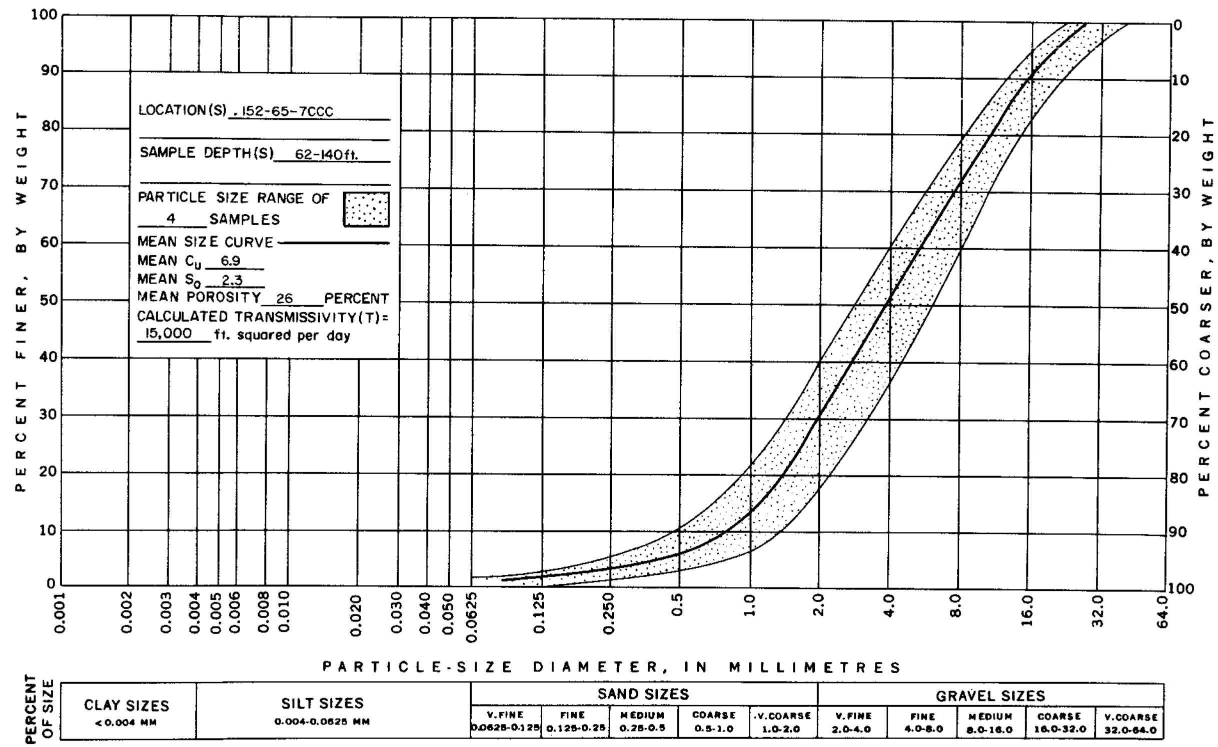


FIGURE 19.— Particle-size distribution curves for samples from the upper sediments of the Spiritwood aquifer system near Minnewaukan.

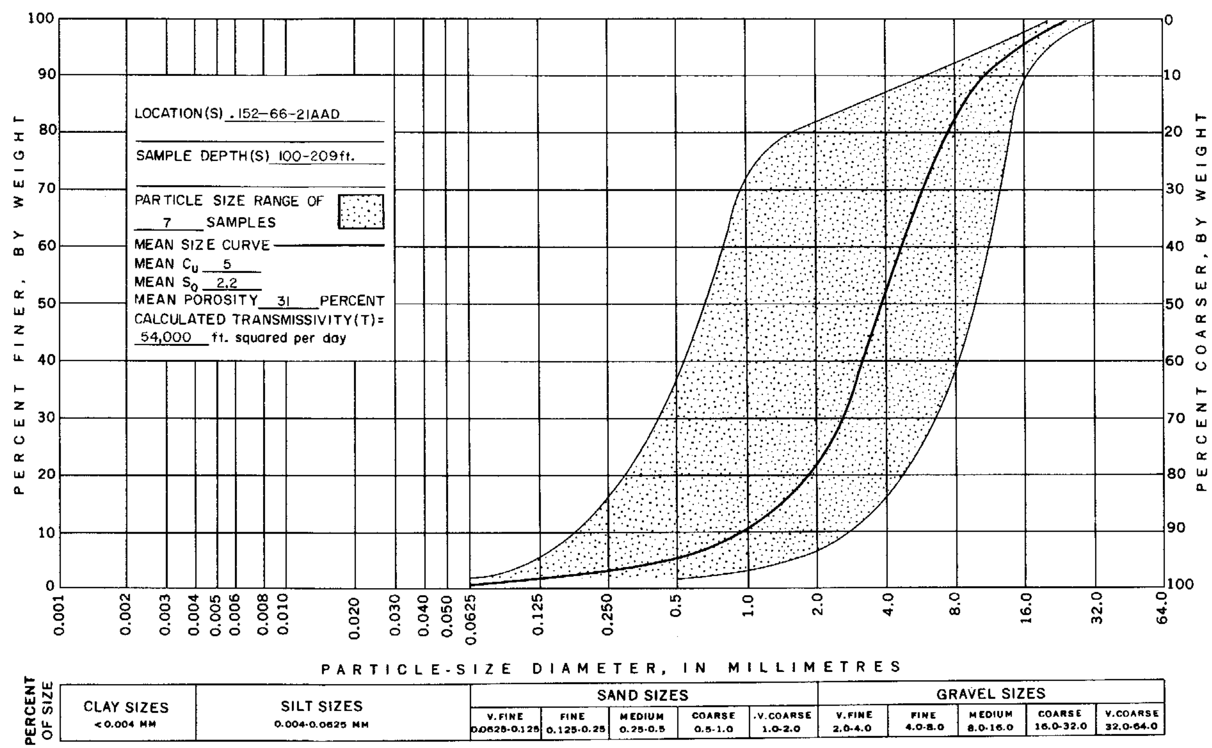


FIGURE 20.— Particle-size distribution curves for samples from the lower sediments of the Spiritwood aquifer system near Minnewaukan.

(1.9 l/s) for 600 minutes. One observation well 100 feet (30 m) north of the pumped well was used to monitor effects of pumping. Results show that the transmissivity of the aquifer at this site is about 4,000 ft²/d (370 m²/d) and the specific capacity of the well is 14 (gal/min)/ft [2.9 (l/s)/m] of drawdown.

Recharge to the aquifer is from overlying glacial-drift deposits and adjacent bedrock formations. Figure 21 shows hydrographs of wells developed in the aquifer in an area of shallow water levels with rapid recharge from precipitation. Figure 22 shows a hydrograph of well 154-67-11DDD1, which is in an area where recharge is relatively slow and where there has been a slow but gradual increase of water in storage. Water levels in the aquifer are deeper than 100 feet (30 m) near Brinsmade, owing, in part, to very little recharge through thick overlying till due to draining of most prairie potholes in this area that formerly were sources of recharge.

About 290,000 acre-feet (0.36 km³) of water is available from storage in the Spiritwood aquifer system near Minnewaukan. The calculated hydraulic conductivity for selected intervals ranges from 13 to 938 ft/d (4 to 286 m/d). The calculated transmissivity for the aquifer is highly variable, but averages about 20,000 ft²/d (1,900 m²/d).

Water in the Spiritwood aquifer system near Minnewaukan is generally a mixed sodium sulfate-bicarbonate type, but it is also high in calcium and chloride content. However, the quality varies considerably from place to place and with depth. The section of the aquifer extending from Brinsmade to Minnewaukan contained water with about 2,000 mg/l dissolved solids. This water is high in iron, boron, and sodium content. In other parts of the aquifer, the water quality was considerably better, with the dissolved solids generally being less than 1,200 mg/l. The classification for irrigation use ranged from C2 to C4, medium to very high salinity hazard, and S1 to S4, low to very high sodium hazard (fig. 5).

There are several small-yield domestic and livestock wells in this part of the aquifer, but properly constructed high-capacity wells may yield as much as 500 to 1,500 gal/min (32 to 95 l/s) in places. Persons planning to drill wells in the aquifer should consider areal differences in chemical quality of the water in addition to differences in availability.

Kilgore aquifer

The Kilgore aquifer is located in a buried valley underlying the Kilgore and Girard Lake areas in southwest-central Pierce County (pl. 2). The aquifer materials were deposited by water discharging from glacial Lake Souris.

The aquifer underlies about 25 mi² (65 km²) and was penetrated by 15 test holes. The thickness ranges from 0 to 241 feet (73 m) and averages about 60 feet (18 m). Geologic sections of the aquifer deposits are shown in section E-E′ on plate 3.

Recharge to the Kilgore aquifer is from direct infiltration and from water accumulated in surface depressions overlying the aquifer. Water levels are generally 10 feet (3 m) or less below land surface. Water in the aquifer is unconfined and hydraulically connected with Kilgore and Girard Lakes.

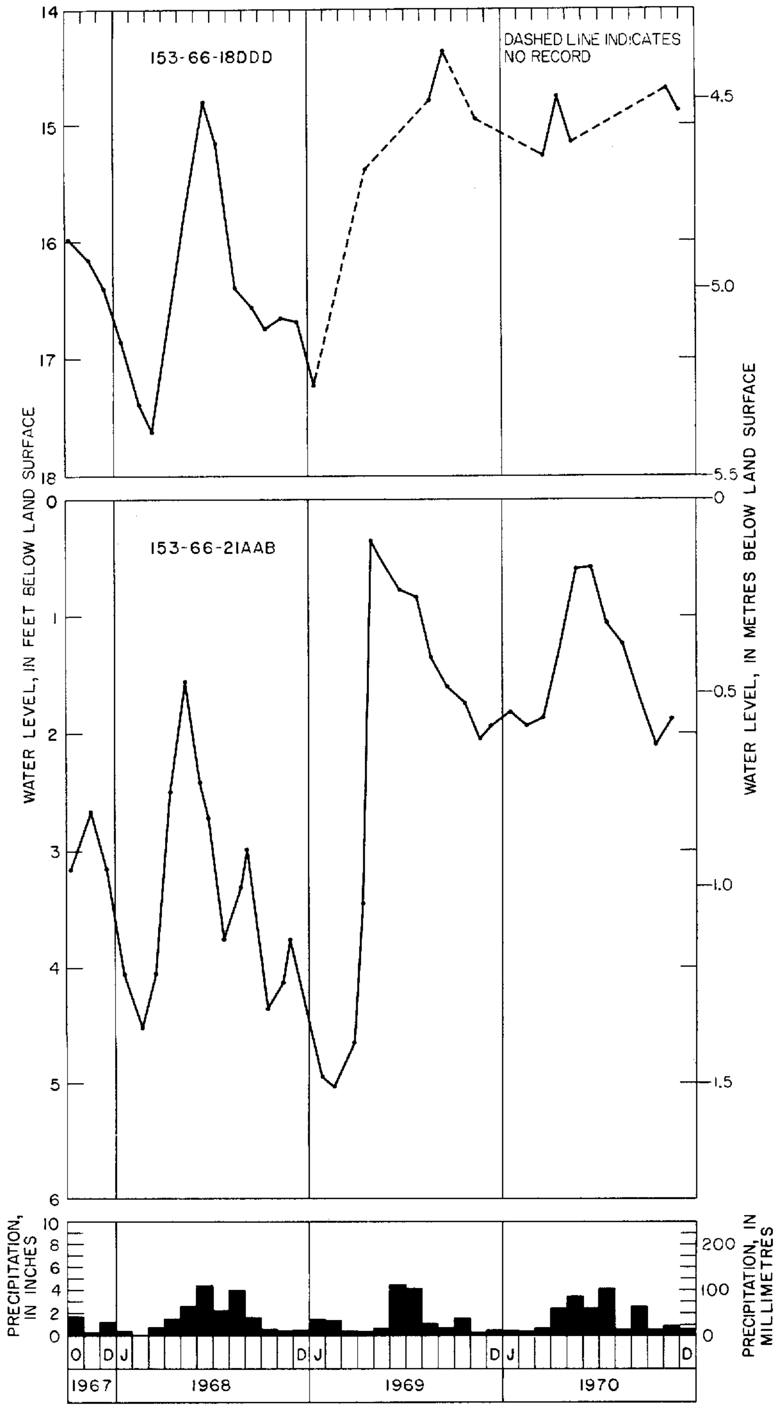


FIGURE 21.— Water-level fluctuations in the Spiritwood aquifer system near Minnewaukan, and precipitation at Maddock.

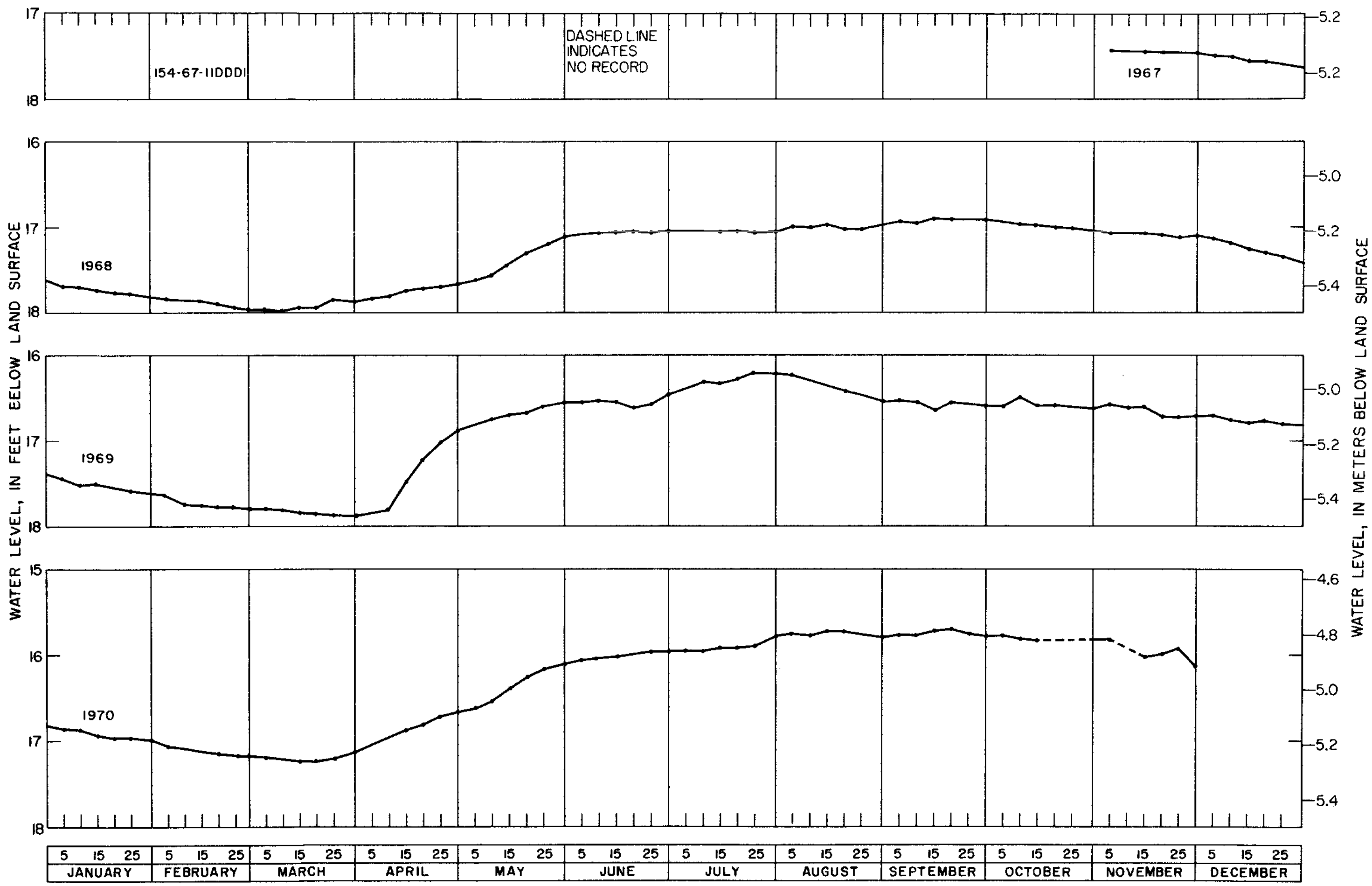


FIGURE 22.— Water-level fluctuations in the Spiritwood aquifer system near Minnewaukan showing a gradual increase in storage.

About 150,000 acre-feet (0.18 km^3) of water is available from storage in the Kilgore aquifer.

The water is generally a sodium bicarbonate type; dissolved solids of five samples ranged from 348 to 1,210 mg/l. The best quality water is a calcium bicarbonate type that is found near areas of rapid recharge. The classification for irrigation use ranged from C2 to C3, medium- to high-salinity hazard, and S1 to S2, low- to medium-sodium hazard (fig. 5).

Based on present data, potential yields to properly constructed wells may be from 50 to 500 gal/min (3.2 to 32 l/s). The largest yields can be obtained along the central axis of the aquifer (pl. 2).

Buried-Outwash Aquifers

Two small aquifers associated with buried-outwash deposits in Benson County are shown on plate 2 as the Maddock and Leeds aquifers. The two aquifers consist of localized deposits of sand and gravel buried beneath till.

Maddock aquifer

The Maddock aquifer, which underlies about 8 mi^2 (21 km^2) in south-central Benson County near the city of Maddock (pl. 2), was penetrated by three test holes. The aquifer directly overlies the Pierre Formation, and is overlain by till (pl. 3, sec. F-F′). It ranges from 0 to 83 feet (25 m) in thickness and averages about 70 feet (21 m). Generally the upper part of the aquifer is sand and the lower part is fine to medium gravel. Calculations, using data from particle-size graphs, show that hydraulic conductivity of the aquifer ranges from 115 to 261 ft/d (35 to 80 m/d) and that porosity is about 30 percent.

Water-level fluctuations in the Maddock aquifer (151-69-15AAA) and in overlying glacial-drift deposits (151-69-10DAA) are shown in figure 23; they indicate a gradual increase of water in storage. Water in the Maddock aquifer generally is under confined conditions, whereas in the overlying drift the water is unconfined. The water table in the overlying drift and water levels in the Maddock aquifer respond quickly to spring snowmelt and precipitation (fig. 23). Ground water in the eastern part of the Maddock aquifer is believed to be semiconfined because a stream has cut through most of the confining bed. Water levels in the aquifer range from about 10 to 30 feet (3 to 9 m) below land surface. Water movement through the Maddock aquifer is generally south toward the Sheyenne River.

Recharge to the aquifer is derived from percolation of precipitation through the overlying glacial deposits and by inflow from adjacent deposits.

About 55,000 acre-feet (0.07 km^3) of water is available from storage in the Maddock aquifer.

Water in the Maddock aquifer ranges from a mixed calcium bicarbonate-sulfate type in areas of recharge to a sodium bicarbonate-sulfate type in areas of discharge. Dissolved-solids concentration ranged from 598 to 1,510 mg/l. The classification for irrigation use was C3, high-salinity hazard, and S1 to S3, low- to high-sodium hazard (fig. 5).

Potential yields to wells in the Maddock aquifer range from 10 to 250 gal/min (0.6 to 16 l/s; pl. 2).

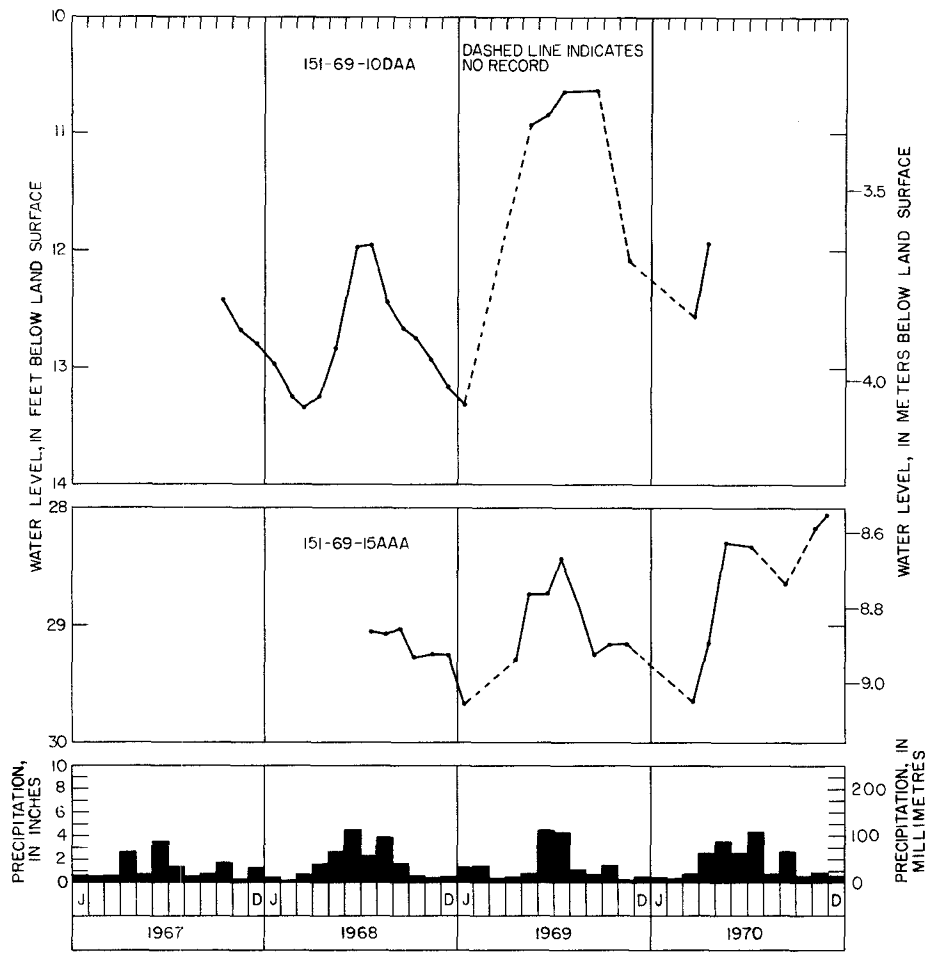


FIGURE 23.— Water-level fluctuations in the Maddock aquifer (151-69-15AAA) and in overlying glacial-drift deposits (151-69-10DAA), and precipitation at Maddock.

Leeds aquifer

The Leeds aquifer is located in north-central Benson County 3 miles (5 km) west of the city of Leeds (pl. 2). The aquifer is underlain and overlain by separate till deposits (pl. 3, sec. G-G′). It underlies about 7 mi^2 (18 km^2) and was penetrated by 13 test holes. The aquifer thickness ranges from 3 to 51 feet (1 to 16 m) and averages 23 feet (7 m).

Aquifer materials, as shown by figure 24, are mostly coarse sand to medium gravel. Based on particle-size analyses, the mean porosity is about 34 percent, and the estimated transmissivity is about 400 ft^2/d (37 m^2/d).

Aquifer test results show that transmissivity of the Leeds aquifer ranges from 300 to 600 ft^2/d (28 to 56 m^2/d). While pumping 100 gal/min (6 l/s)

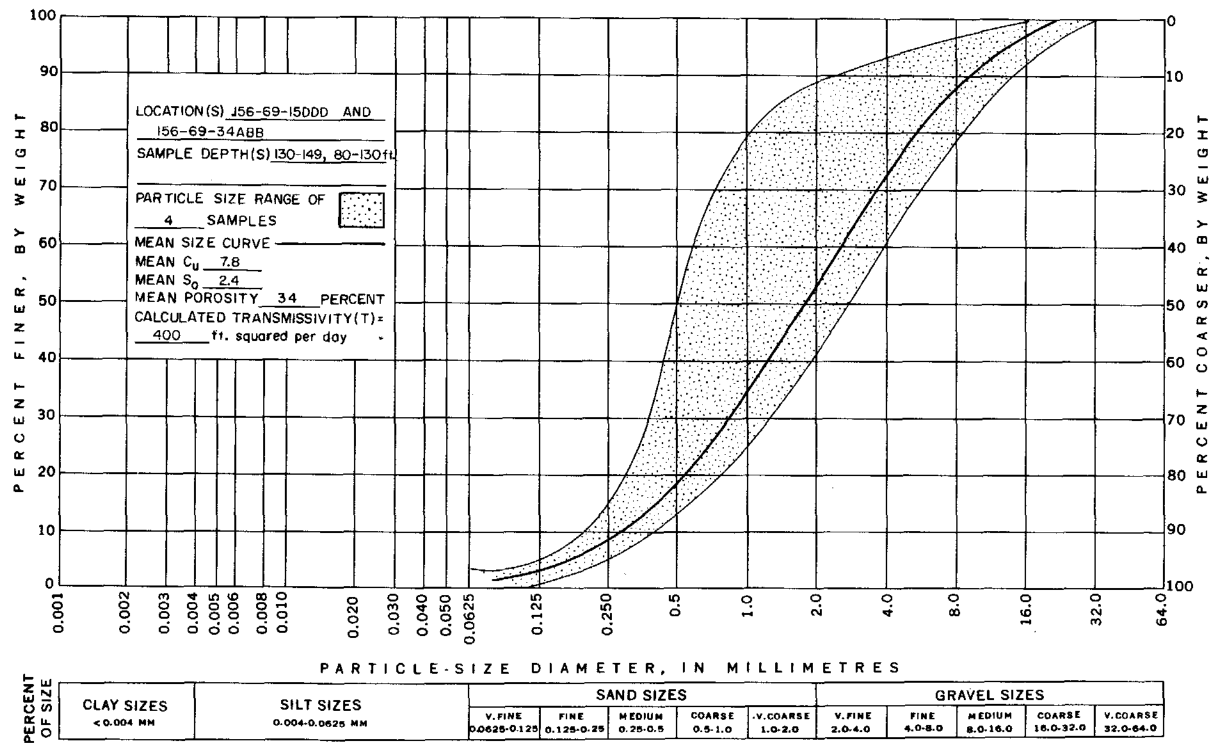


FIGURE 24.—Particle-size distribution curves for samples from the Leeds aquifer.

for 100 hours, the water level in well 156-69-15DDD declined about 12 feet (4 m) and did not return to levels measured before the test for 6 months. The slow recovery is attributed to dewatering of the aquifer during the test, and the presence of confining beds in the vicinity of the test site that restricted recharge. The high clay content mixed with the sand and gravel is the major factor limiting potential well yields in the Leeds aquifer.

Recharge to the Leeds aquifer is from overlying glacial-drift deposits and from intermittent streams that flow across the northern part of the aquifer. Water-level fluctuations responding to seasonal precipitation in two parts of the aquifer are shown in figures 25 and 26. Seasonal water-level fluctuations in the southwestern part of the aquifer are shown in figure 25. Annual changes in storage in the central part of the aquifer are indicated in figure 26; a substantial increase shown in 1970 is due to above-normal precipitation. Water levels generally range from 10 to 15 feet (3 to 5 m) below land surface.

About 17,500 acre-feet (0.02 km^3) of water is available from storage in the Leeds aquifer.

The water in the Leeds aquifer is a mixed sodium sulfate-bicarbonate type. Dissolved solids in 12 samples ranged from 1,340 to 2,670 mg/l and averaged 1,710 mg/l. The water is generally very hard and is high in boron concentration. The classification for irrigation was C4, high-salinity hazard, and S2 to S3, medium- to high-sodium hazard (fig. 5).

In 1971, three wells that produced less than 10 gal/min (0.6 l/s) for domestic and livestock use were developed in the aquifer. The potential yield to wells (pl. 2) is probably less than 75 gal/min (4.7 l/s).

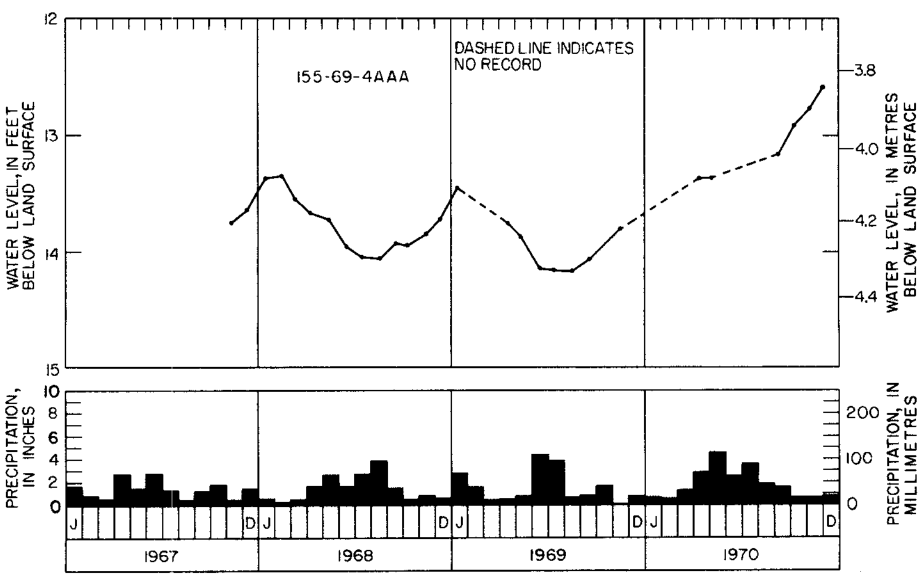


FIGURE 25.— Water-level fluctuations in the southwestern part of the Leeds aquifer, and precipitation at Leeds.

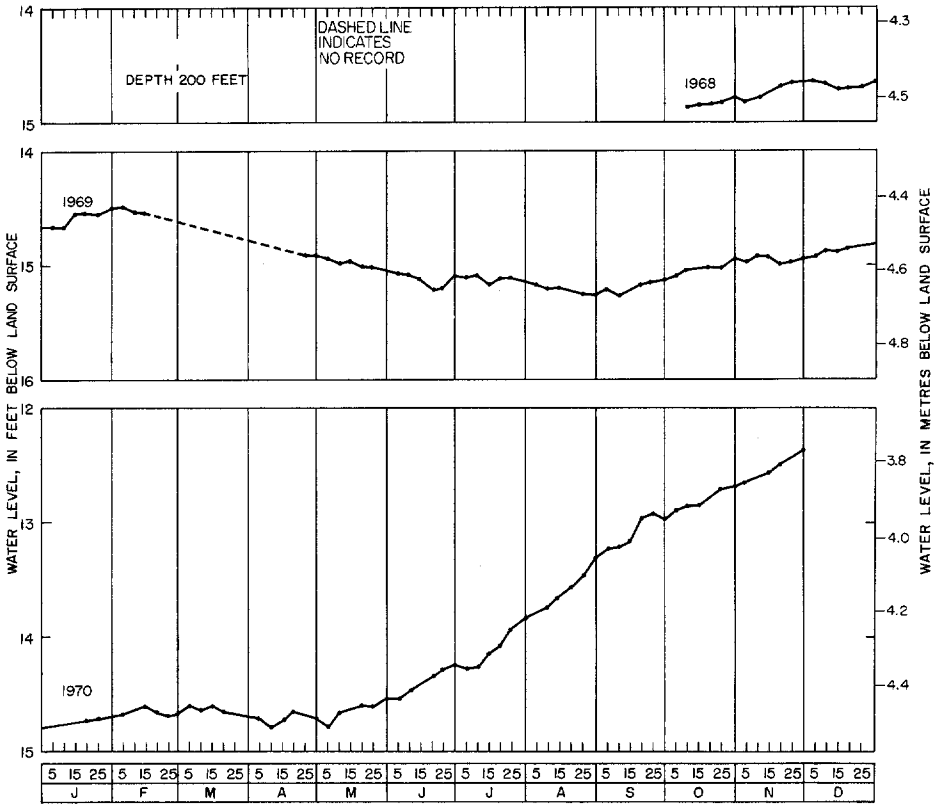


FIGURE 26.— Water-level fluctuations in the central part of the Leeds aquifer.

Surficial-Outwash Aquifers

Surficial glacial-outwash deposits comprise significant aquifers in four areas in Benson and Pierce Counties. The glacial outwash was transported by melt water from the glaciers and for the most part, was deposited beyond the end moraines associated with the glaciers. Aquifers formed in the deposits are the Warwick, Esmond, Pleasant Lake, and Tokio. These aquifers generally contain the best quality ground water available in the two-county area.

Warwick aquifer

The Warwick aquifer underlies about 30 mi^2 (78 km^2) of eastern Benson County (pl. 2). Paulson and Akin (1964, p. 30) described the Warwick outwash deposits as extending from the North Viking moraine in Benson and Ramsey Counties, south to the Sheyenne River valley in Eddy and Nelson Counties.

Based on 40 test holes, the aquifer thickness ranges from 20 to 200 feet (6 to 61 m) and averages about 74 feet (23 m). Geologic section H-H′ (pl. 3) shows the different lithologic units near Warwick. Northeast of Warwick the aquifer overlies a part of the Spiritwood aquifer system, as shown on section C-C′ (pl. 3).

Particle-size distribution curves (fig. 27) indicate that the aquifer materials are rather uniform. The mean porosity is 42 percent and the estimated hydraulic conductivity ranges from 21 to 214 ft/d (6 to 65 m/d).

The results of 10 aquifer tests in the Warwick aquifer are summarized in table 2. Two of the tests were made as part of this investigation at sites 151-63-25ADB1 and 151-62-19ADD1.

Water-level drawdown and recovery in the Warwick aquifer resulting from pumping 242 gal/min (15 l/s) from well 151-63-25ADB1 for 4,500 minutes (3.13 days) are shown in figure 28. The test data indicate the aquifer has a transmissivity of 10,700 ft^2/d (990 m^2/d).

The aquifer at well 151-62-19ADD1 consists primarily of gravel. The transmissivity here is almost twice as large as at well 151-63-25ADB1 where the aquifer consists of a sand and gravel mixture.

Recharge to the Warwick aquifer is derived mainly from direct infiltration of precipitation. Ground-water movement through the aquifer is south toward the Sheyenne River.

Water-level fluctuations in several parts of the aquifer are shown in figures 29-31. Long-term water-level trends in an observation well about 700 feet (213 m) east of the eastern-most well in the city of Devils Lake (Ramsey County) well field are shown in figure 29. The decrease of water in storage during the period 1960-70 is due mainly to increased withdrawals of water from the aquifer. Well 151-62-19ADD1 (fig. 30) records water-level fluctuations in a relatively unused part of the aquifer. Water levels vary less than 1 foot (0.3 m) during the year owing to little water use in this part of the aquifer and the high specific yield of the deposits.

The relationships of water-table fluctuations and corresponding stage changes in Shinbone Lake (pl. 2) are shown in figure 31. The lake, which is hydraulically connected to the aquifer, receives little direct runoff because of the high permeability of the surrounding surface deposits. During most of the year, water discharges from the aquifer into the lake.

The Warwick aquifer in Benson County contains about 300,000 acre-feet (0.37 km^3) of ground water available from storage.

The water in the Warwick aquifer is primarily a calcium bicarbonate type. Dissolved-solids concentrations ranged from 222 to 1,010 mg/l, and averaged less than 300 mg/l. In most areas near bedrock highs (pl. 1), the water was a sodium bicarbonate type and dissolved solids were at least 1,000 mg/l. All samples were in the irrigation classification C2, medium-salinity hazard, and S1, low-sodium hazard (fig. 5). Water in Shinbone Lake was a sodium bicarbonate type with dissolved solids ranging from 1,570 to 1,930 mg/l. Residual sodium carbonate exceeded the recommended limit (U.S. Salinity

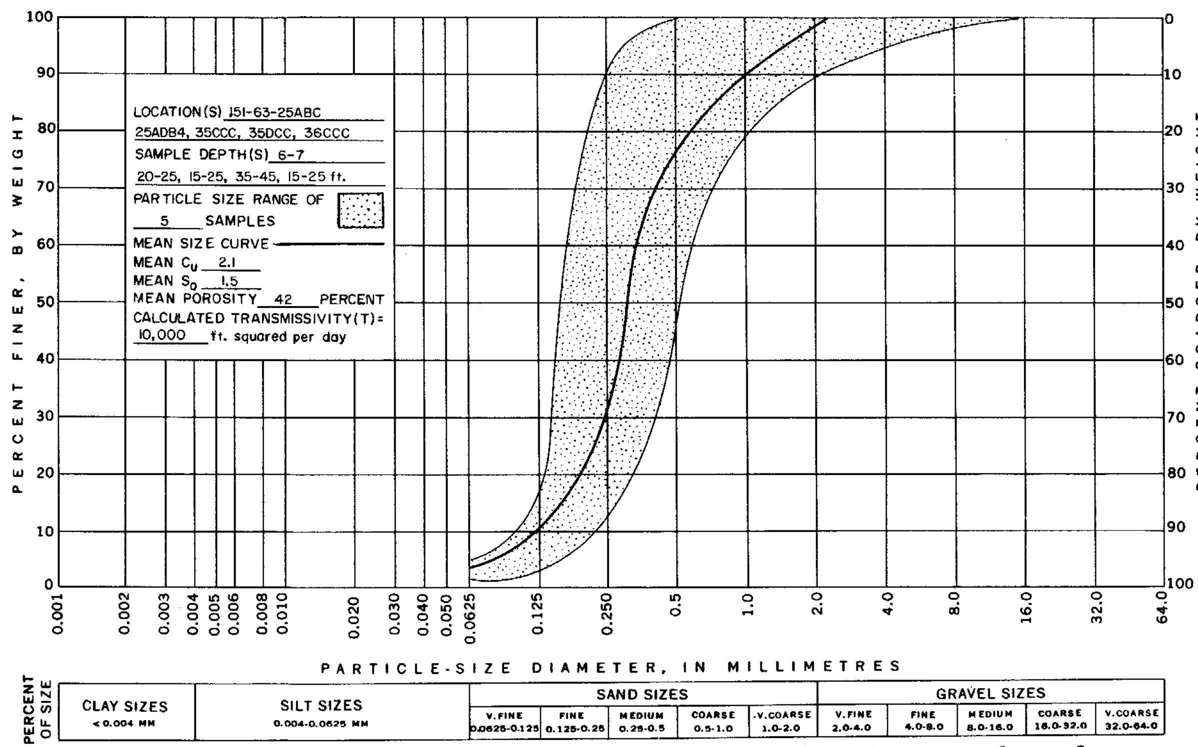


FIGURE 27.—Particle-size distribution curves for samples from the Warwick aquifer.

TABLE 2. — Summary of data obtained from pumping tests in the Warwick aquifer.

Test locations	Date of test	Well depth (ft)	Well diameter (in)	Screened interval (ft)	Discharge (gal/min)	Duration of test (days)	Static water level (ft below lsd)	Draw-down (ft)	Specific capacity [(gal/min)/ft]	Number of observation wells	Transmissivity (ft^2/d)
151-62-19ADD1	5- 1-68 to 5- 2-68	38	4	33-38	90	0.63	17.5	2.5	36	1	20,600
151-63-20CDD11[1]	8- 2-51 to 8- 3-51	135	12	120-133	148	1	18.23	—	—	2	8,700
151-63-20CDD11[1,2] and	8-15-52 to	135	12	120-133	200	30	21.00	28.0	7	4	6,300
151-63-20CDD12	9-16-52	155	12	127-147	300	30	22.04	14.0	21	—	—
151-63-20CDD12[1]	4-22-52	155	12	127-147	150	.17	19.42	4.3	35	3	7,800
151-63-20CDD12[1]	4-29-52 to 4-30-52	155	12	127-147	320	1	19.36	10.2	31	7	7,000
151-63-25ADB1	8- 8-68 to 8-11-68	40	17	20-40	242	3.13	7.68	15.9	15	4	10,700
151-63-29ABB[1]	11-15-61 to 11-16-61	167	12	—	550	1	21.4	13.6	40	1	11,900
151-63-29ABC1[1]	8- 9-61 to 8-10-61	112	12	65.5-70 and 74-112	650	1	16.6	6.5	99	2	10,500
151-63-29ABC2[1]	5-14-62 to 5-15-62	89	12	—	500	1	17.7	14.4	35	—	—
151-63-29ACB[1]	9-12-61 to 9-13-61	110	12	78-85 and 96-110	1,200	1	14.6	13.6	88	2	10,900

[1]Results from Paulson and Akin, 1964, p. 34.
[2]Two wells discharging.

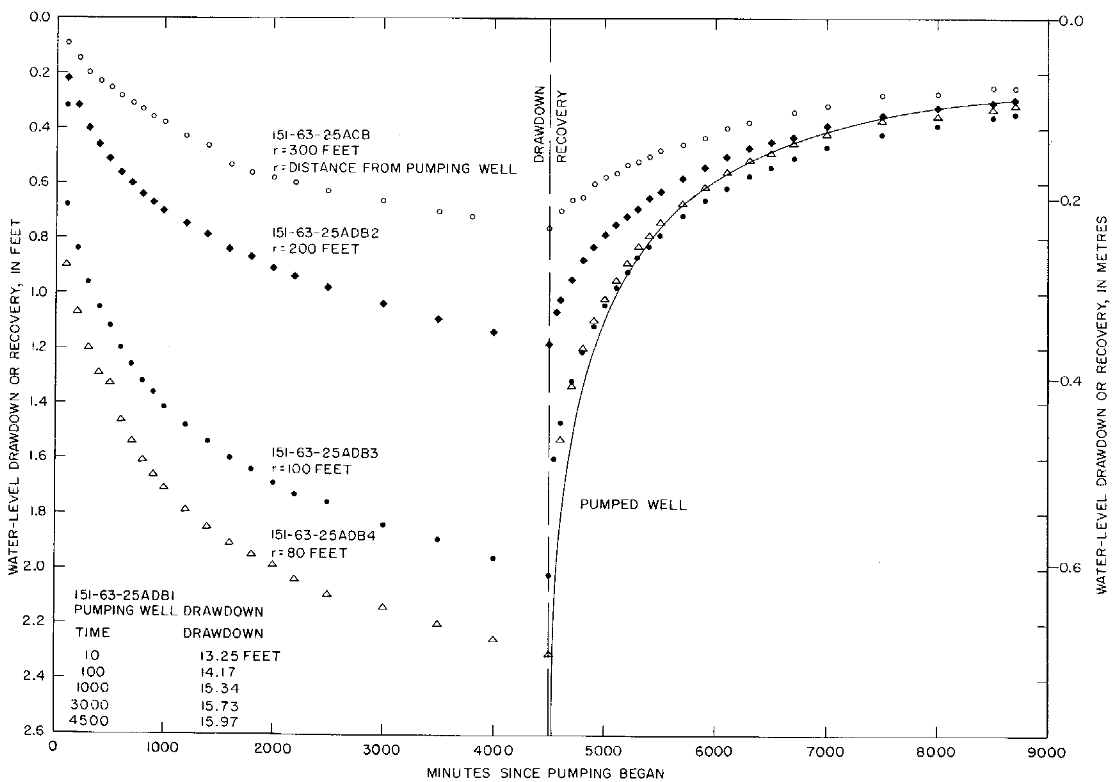


FIGURE 28.— Water-level drawdown and recovery in the Warwick aquifer caused by pumping well 151-63-25ADB1 for 3.13 days (1969).

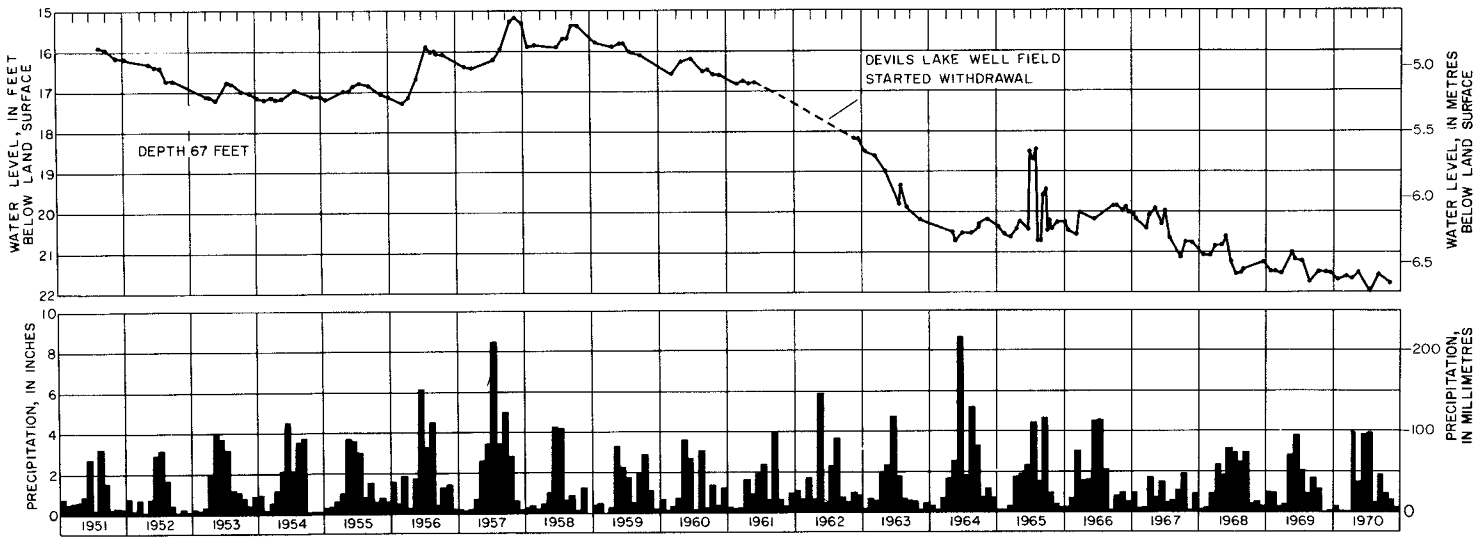


FIGURE 29.— Long-term water-level trends in the Warwick aquifer near the city of Devils Lake (Ramsey County) well field, and precipitation at Warwick.

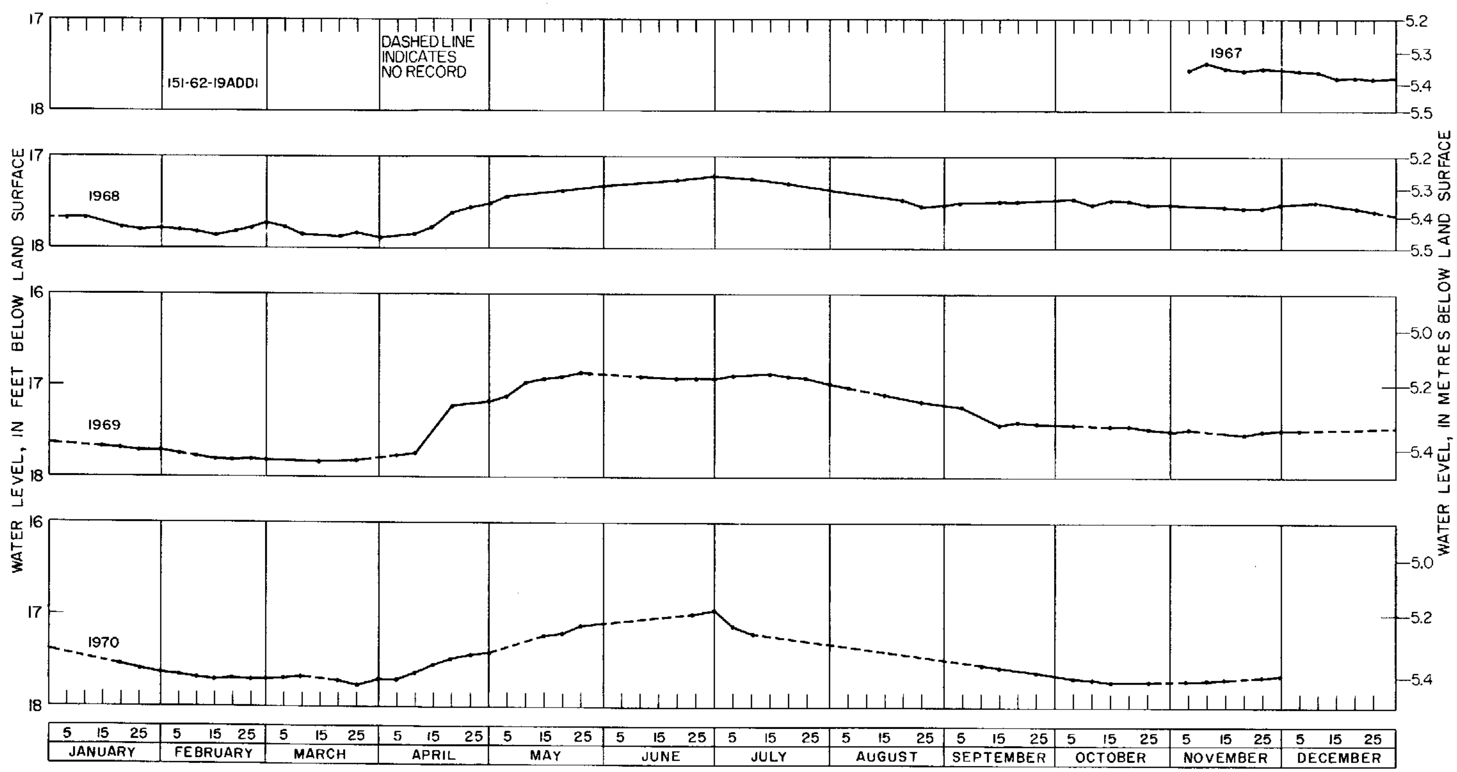


FIGURE 30.— Water-level fluctuations in a relatively unused part of the Warwick aquifer showing seasonal change in storage.

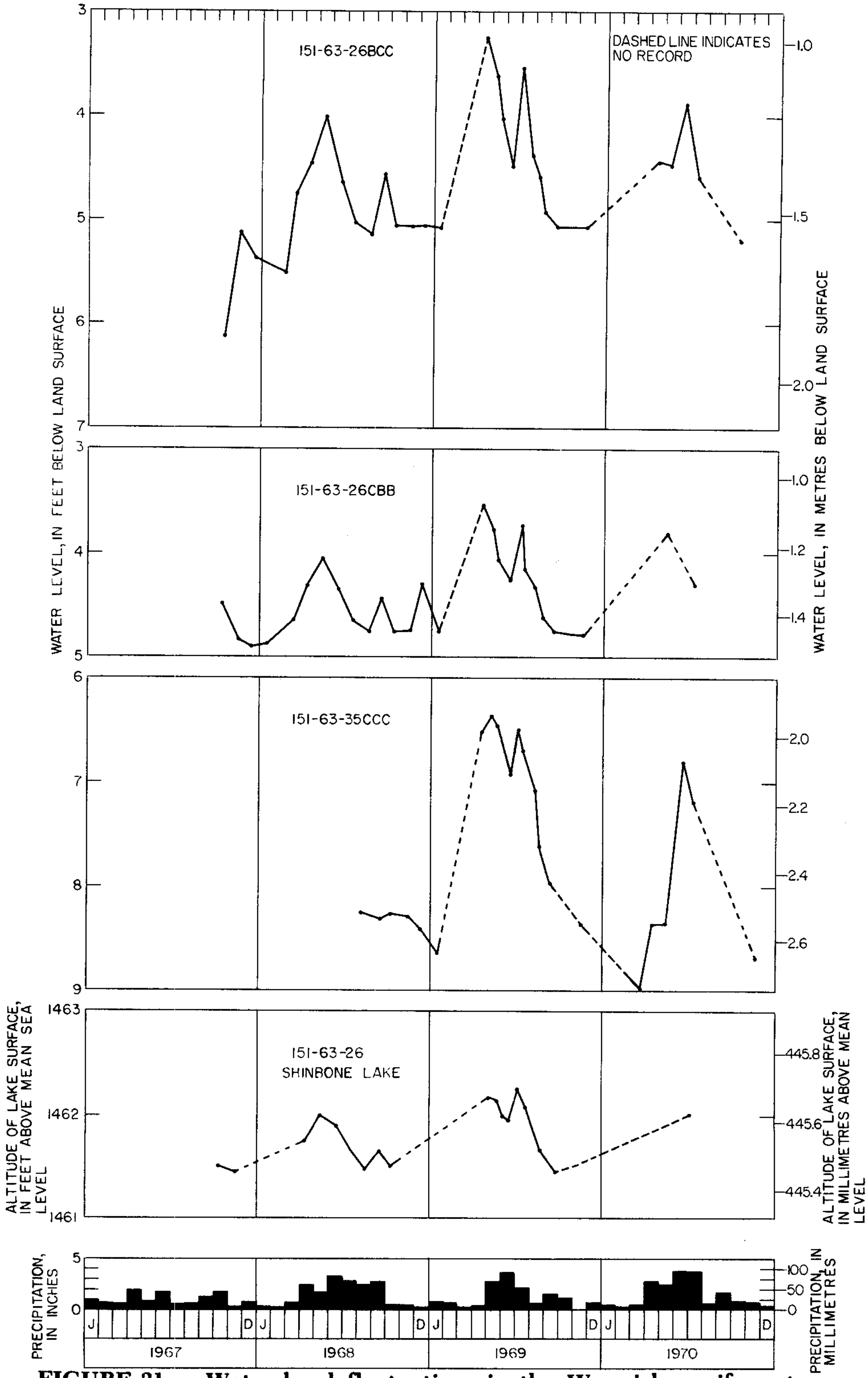


FIGURE 31.— Water-level fluctuations in the Warwick aquifer, stage changes in Shinbone Lake, and precipitation at Warwick.

Laboratory Staff, 1954, p. 81) of 2.5 meq/l for irrigation only in the surface-water lakes in the area. Generally the aquifer contains some of the best quality ground water available in North Dakota. The dissolved-solids concentration is less than in many surface waters.

The Warwick aquifer supplies about 0.84 Mgal/d (3,200 m^3/d) from four wells, via a 20-mile (32-km) pipeline, for the city of Devils Lake. This is only a small part of the potential water-yielding capability of the aquifer. Potential yields ranging from 50 to 500 gal/min (3.2 to 32 l/s) are obtainable from most parts of the aquifer (pl. 2), and yields of about 1,500 gal/min (95 l/s) are obtainable in some parts of the aquifer.

Esmond aquifer

The Esmond aquifer, which is located in southwestern Benson County near Esmond (pl. 2), consists of sand and gravel deposits along the southern side of the Heimdal and Martin end moraines (fig. 4). Part of the materials may have been deposited by outflow from glacial Lake Souris through the Long Lake kettle chain (pl. 2).

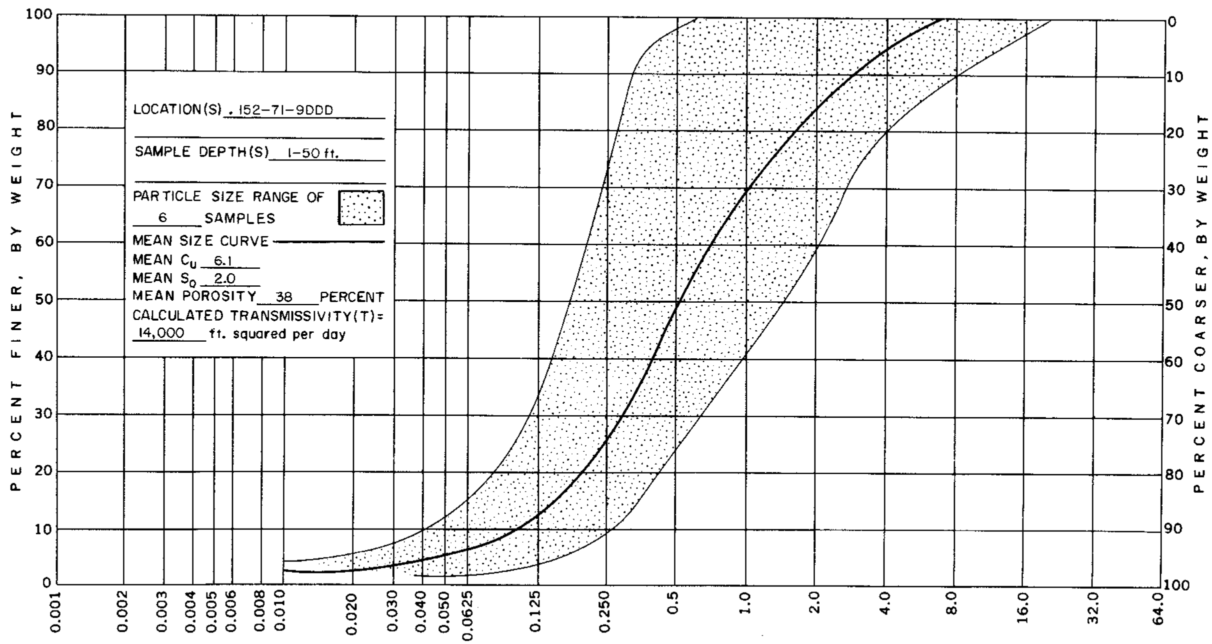
The aquifer, which underlies about 20 mi^2 (52 km^2), was penetrated by 25 test holes. The thickness ranges from 10 to 75 feet (3 to 23 m) and averages 28 feet (9 m). Figures 32 and 33, which show particle-size distributions for samples collected in the southern and northern parts of the aquifer, respectively, indicate that the aquifer material is mostly sand. The porosity is about 38 percent and the estimated hydraulic conductivity ranges from 5 to 220 ft/d (2 to 67 m/d) and averages 72 ft/d (22 m/d).

An aquifer test was conducted using well 153-71-17DDD1. The well was pumped at 102 gal/min (6.4 l/s) for about 23 hours. Two observation wells 50 and 100 feet (15 and 30 m) from the pumped well were monitored. The results of the test indicate an average transmissivity of 15,000 ft^2/d (1,400 m^2/d) at this site.

Recharge to the Esmond aquifer is from direct infiltration of precipitation and from seepage of intermittent streamflow. Also, some underflow moves into the aquifer from the Fox Hills Formation in the northwestern part of the area. Springs discharge water from the aquifer along the east bank of Trappers Coulee and the north bank of the Sheyenne River. Seasonal responses of ground-water levels to precipitation with an overall increase in storage due to above-average precipitation during the period of record (1967-70) are shown in figure 34.

About 70,000 acre-feet (0.08 km^3) of ground water is available from storage in the Esmond aquifer.

Water in the Esmond aquifer is mainly a calcium bicarbonate type. Locally, in the northwestern part of the aquifer, the water is a sodium bicarbonate type — probably as a result of recharge from the Fox Hills Formation. Dissolved solids in five water samples ranged from 348 to 524 mg/l and averaged 444 mg/l. The classification for irrigation (fig. 5) was C2 to C3, medium- to high-salinity hazard, and S1 to S2, low- to medium-sodium



PERCENT OF SIZE	CLAY SIZES	SILT SIZES	SAND SIZES					GRAVEL SIZES				
			V.FINE	FINE	MEDIUM	COARSE	V.COARSE	V.FINE	FINE	MEDIUM	COARSE	V.COARSE
	< 0.004 MM	0.004-0.0625 MM	0.0625-0.125	0.125-0.25	0.25-0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	8.0-16.0	16.0-32.0	32.0-64.0

FIGURE 32.—Particle-size distribution curves for samples from the southern part of the Esmond aquifer.

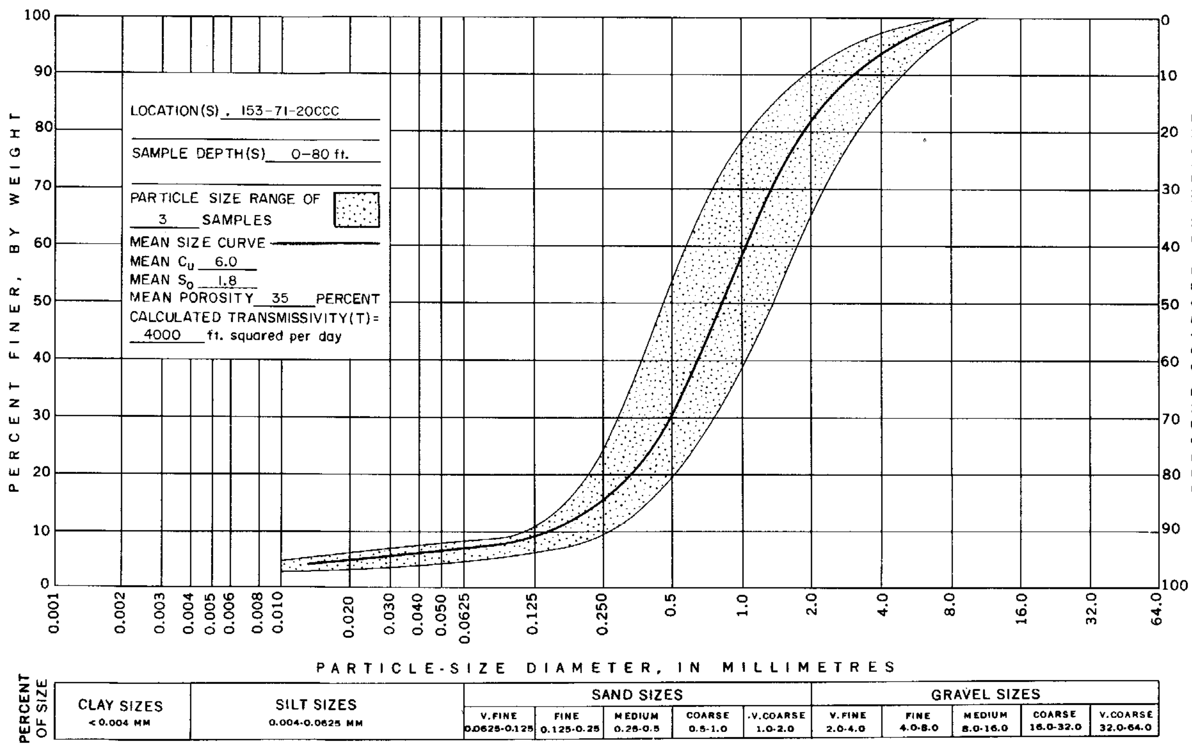


FIGURE 33.—Particle-size distribution curves for samples from the northern part of the Esmond aquifer.

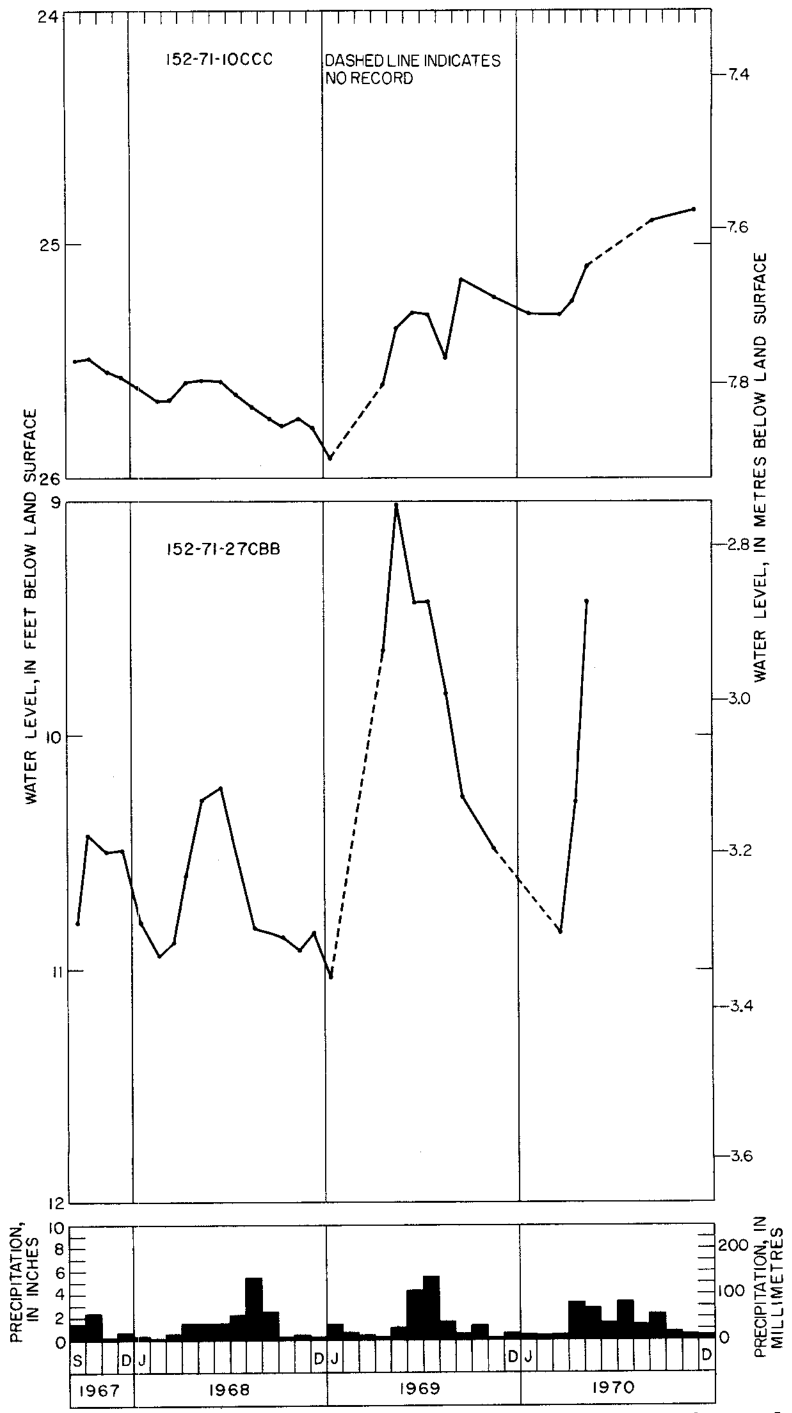


FIGURE 34.— Water-level fluctuations in the Esmond aquifer, and precipitation at Balta.

hazard. The residual sodium carbonate exceeded 2.5 meq/l in the area of sodium bicarbonate type water.

Several wells tap the Esmond aquifer for domestic and livestock supplies. These wells generally yield less than 10 gal/min (0.6 l/s). Potential yields to wells fully developed in the aquifer may range from 50 to 250 gal/min (3.2 to 16 l/s).

Pleasant Lake aquifer

The Pleasant Lake aquifer is located in northeast-central Pierce County, east of Rugby (pl. 2) and west of a large end-moraine complex. The aquifer underlies about 25 mi^2 (65 km^2) and was penetrated by 26 test holes. The aquifer thickness ranges from 4 to 98 feet (1 to 30 m) and averages about 42 feet (13 m). The major part of the aquifer is sand, but lenses of gravel are common in the basal part in some areas. Geologic section J-J′ (pl. 3) shows the irregular distribution of materials that form the aquifer.

Particle-size distribution curves for materials in the eastern part of the aquifer are shown in figure 35. The materials are well sorted, and porosity is about 45 percent. The hydraulic conductivity from nine intervals ranges from 16 to 308 ft/d (5 to 94 m/d) and averages 104 ft/d (32 m/d).

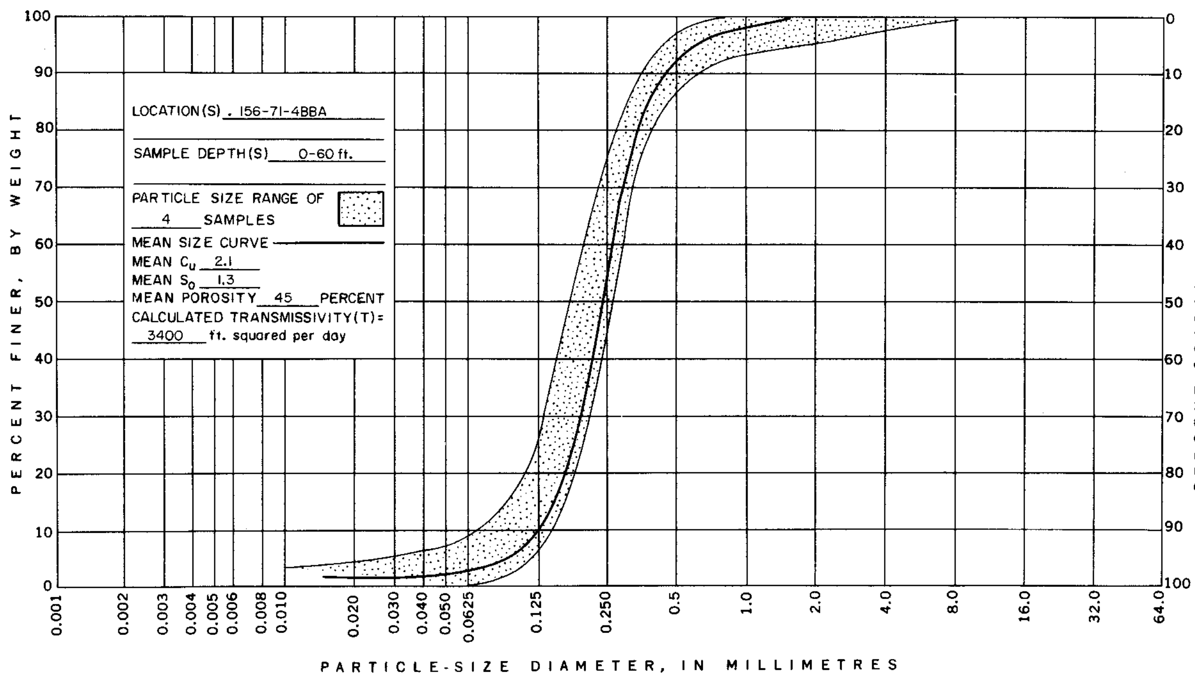
An aquifer test was conducted on well 157-72-36ADD during a municipal water-supply study for the city of Rugby in 1965 (Froelich, 1965, p. 32-36). Test results indicate that the transmissivity of the Pleasant Lake aquifer at this site is about 9,500 ft^2/d (880 m^2/d) and that the water in the aquifer is under leaky confined conditions. Another test made as part of the present study was conducted on well 156-71-4BBA in the eastern part where the aquifer is generally under unconfined conditions. The well was pumped at 21 gal/min (1.3 l/s) for 23 hours. The average transmissivity was 4,800 ft^2/d (450 m^2/d) at this site.

Recharge to the Pleasant Lake aquifer is derived mostly from direct infiltration of precipitation and infiltration of water accumulated in potholes. Also, in some areas recharge is from upward movement of water from the Fox Hills Formation. Springs discharge large quantities of ground water from the aquifer into Northern Broken Bone Lake.

Water-level records from well 157-71-32DAA (fig. 36), which taps the central part of the Pleasant Lake aquifer, show an increase in ground-water storage for the period of record (1967-70) responding to increases in precipitation. The water level in well 157-72-36ADD3 (fig. 37), located near the city of Rugby well field, declined about 22 feet (7 m) from 1966 through 1970 due to pumping. The hydraulic gradient in the eastern part of the aquifer is about 10 ft/mi (2 m/km) westward, generally conformable with the land surface.

There is about 150,000 acre-feet (0.18 km^3) of ground water available from storage in the Pleasant Lake aquifer.

The water in the Pleasant Lake aquifer is a mixed calcium-magnesium bicarbonate-sulfate type. Water in the underlying Fox Hills Formation is a sodium bicarbonate type, and, in places, upward migration of water from the Fox Hills has increased the sodium content in water in the Pleasant Lake



PERCENT OF SIZE	CLAY SIZES	SILT SIZES	SAND SIZES					GRAVEL SIZES				
	<0.004 MM	0.004-0.0625 MM	V.FINE 0.0625-0.125	FINE 0.125-0.25	MEDIUM 0.25-0.5	COARSE 0.5-1.0	V.COARSE 1.0-2.0	V.FINE 2.0-4.0	FINE 4.0-8.0	MEDIUM 8.0-16.0	COARSE 16.0-32.0	V.COARSE 32.0-64.0

FIGURE 35.—Particle-size distribution curves for samples from the Pleasant Lake aquifer.

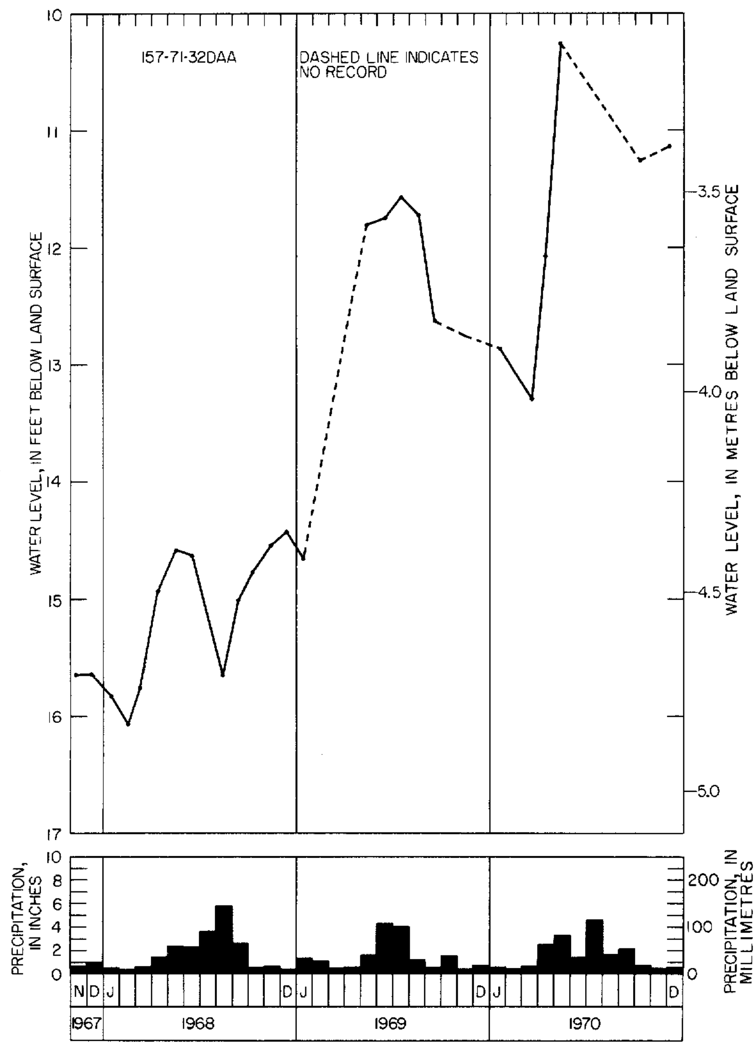


FIGURE 36.— Water-level fluctuations in the central part of the Pleasant Lake aquifer showing an increase in ground-water storage, and precipitation at Rugby.

aquifer. Dissolved solids in six water samples ranged from 225 to 452 mg/l and averaged 310 mg/l. Residual sodium carbonate did not exceed 2.5 meq/l in any of the samples and was less than 1 in most. The classification for irrigation was C2, which is a medium-salinity hazard, and S1, which is a low-sodium hazard (fig. 5).

Several wells withdraw water from the aquifer for domestic and livestock purposes. These generally yield less than 10 gal/min (0.6 l/s). The city of Rugby has two municipal wells yielding an average of 153 gal/min (10 l/s)

FIGURE 37.— Water-level fluctuations in the Pleasant Lake aquifer affected by pumpage for the city of Rugby.

from the aquifer. It is doubtful if this yield can be maintained in future years due to declining water levels (fig. 37).

Potential sustained yields to properly developed wells in the aquifer (pl. 2) probably range from 50 to 150 gal/min (3.2 to 16 l/s).

Tokio aquifer

The Tokio aquifer is located in southeastern Benson County west of Tokio (pl. 2). The aquifer consists of a collapsed outwash deposit along the southern side of the North Viking end moraine.

The Tokio aquifer, which underlies about 30 mi^2 (78 km^2), was penetrated by 15 test holes. It consists of sand and gravel with locally abundant till and clay. The aquifer thickness ranges from 10 to 89 feet (3 to 27 m) and averages about 32 feet (10 m). The hydraulic conductivity for seven intervals ranges from 58 to 308 ft/d (18 to 94 m/d) and averages 151 ft/d (46 m/d). The porosity averages about 35 percent.

Recharge to the Tokio aquifer is derived from infiltration of precipitation through the surface materials, and southward movement of ground water from North Viking end moraine. Big Coulee (pl. 2) is the major drain of ground water from the aquifer. Figure 38 compares discharge of Big Coulee near Fort Totten with fluctuations in ground-water levels and precipitation. These indicate the prompt responses of water levels in the aquifer as related to precipitation and streamflow. During most of the year, streamflow in Big Coulee is sustained by ground water discharged from the Tokio aquifer. The bed of the coulee is about 50 feet (15 m) below the surface of the outwash. The high hydraulic conductivity of the outwash deposits and steep gradient of the water table account for the rapid ground-water discharge from the aquifer. Water levels range from about 2 feet (0.6 m) below land surface near Big Coulee to 45 feet (14 m) in other parts of the aquifer.

About 110,000 acre-feet (0.13 km^3) of water is available from storage in the Tokio aquifer.

Water in the Tokio aquifer is a calcium bicarbonate type. Dissolved solids in four samples averaged 330 mg/l. The irrigation classification was C2, medium-salinity hazard, and S1, low-sodium hazard.

Several wells yielding less than 10 gal/min (0.6 l/s) have been developed in the aquifer for domestic and livestock supplies. Yields to properly constructed wells probably would be less than 100 gal/min (6 l/s; pl.2). The most desirable locations for maximum yields are along Big Coulee and near potholes.

Minor Glacial-Drift Aquifers

Numerous relatively small and localized glacial deposits that yield less than 50 gal/min (3.2 l/s) to wells for domestic and livestock purposes occur throughout the two-county area. These deposits are classified according to glacial origin as (1) Lake Souris deposits, (2) ice-contact deposits, and (3) till and associated sand and gravel deposits.

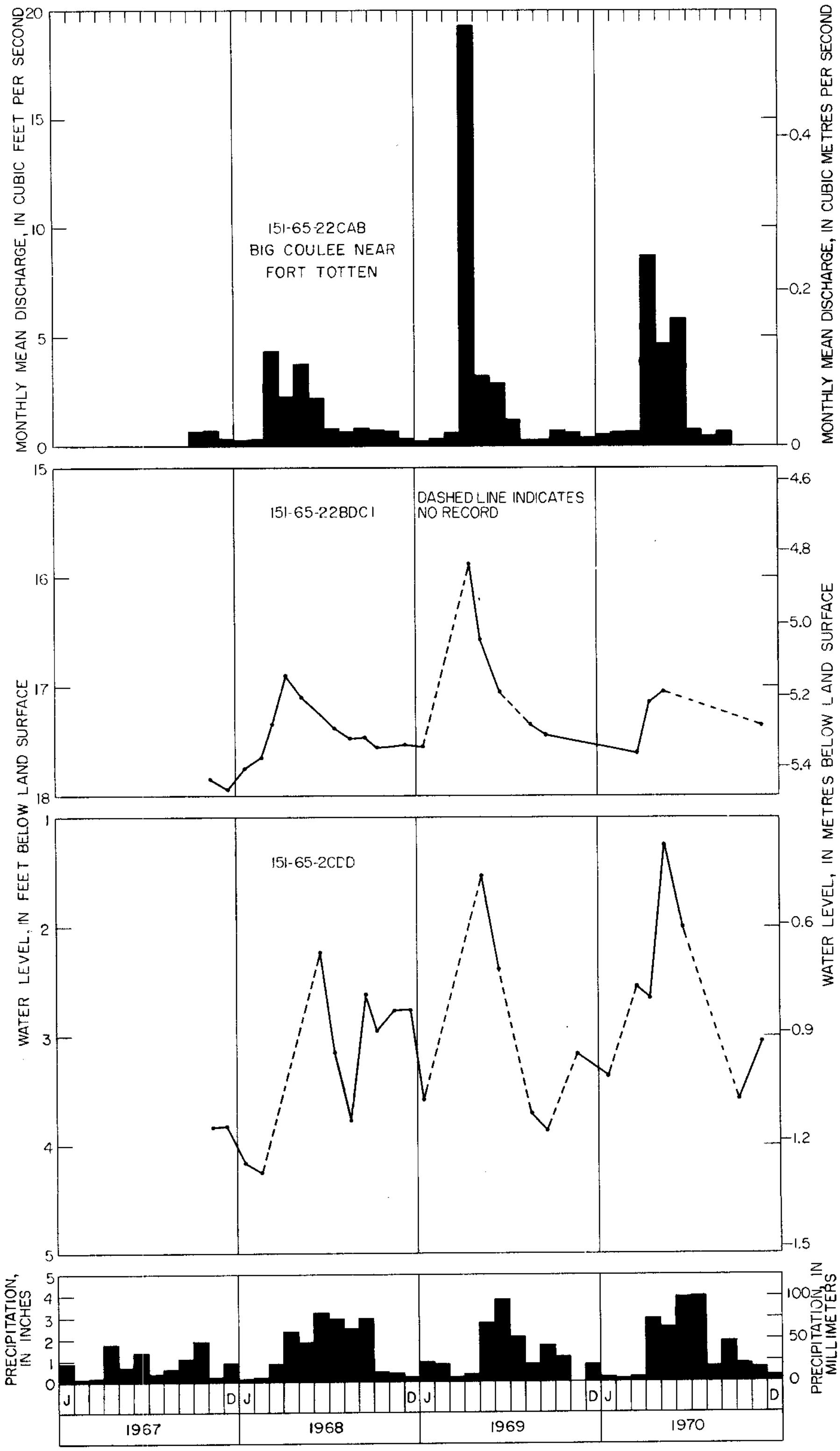


FIGURE 38.— Water-level fluctuations in the Tokio aquifer, discharge of Big Coulee, and precipitation at Warwick.

Lake Souris deposits

Lake Souris glacial deposits cover parts of 12 townships in western Pierce County (fig. 4). The deposits, which were penetrated by 35 test holes, are generally less than 100 feet (30 m) thick. Figure 39 shows particle-size distribution curves for core samples collected near Round Lake, northwestern Pierce County. The median particle size is very fine sand, the average porosity is 32 percent, and the transmissivity is estimated to be 160 ft^2/d (15 m^2/d). The hydraulic conductivity for eight samples of Lake Souris deposits ranges from 2 to 160 ft/d (1 to 49 m/d) and averages about 42 ft/d (13 m/d).

Recharge to the Lake Souris deposits is from infiltration and percolation of precipitation through surficial materials, and lateral movement from topographically higher deposits of end moraine that lie to the east. Figure 40 shows that a general increase in ground-water storage has occurred from 1967 through about June 1970. The large water-level fluctuations are indicative of rapid responses to spring thaws, seasonal precipitation, low specific yields for the deposits, and high evapotranspiration discharges.

About 0.7 million acre feet (0.9 km^3) of ground water is available from storage in the Lake Souris deposits.

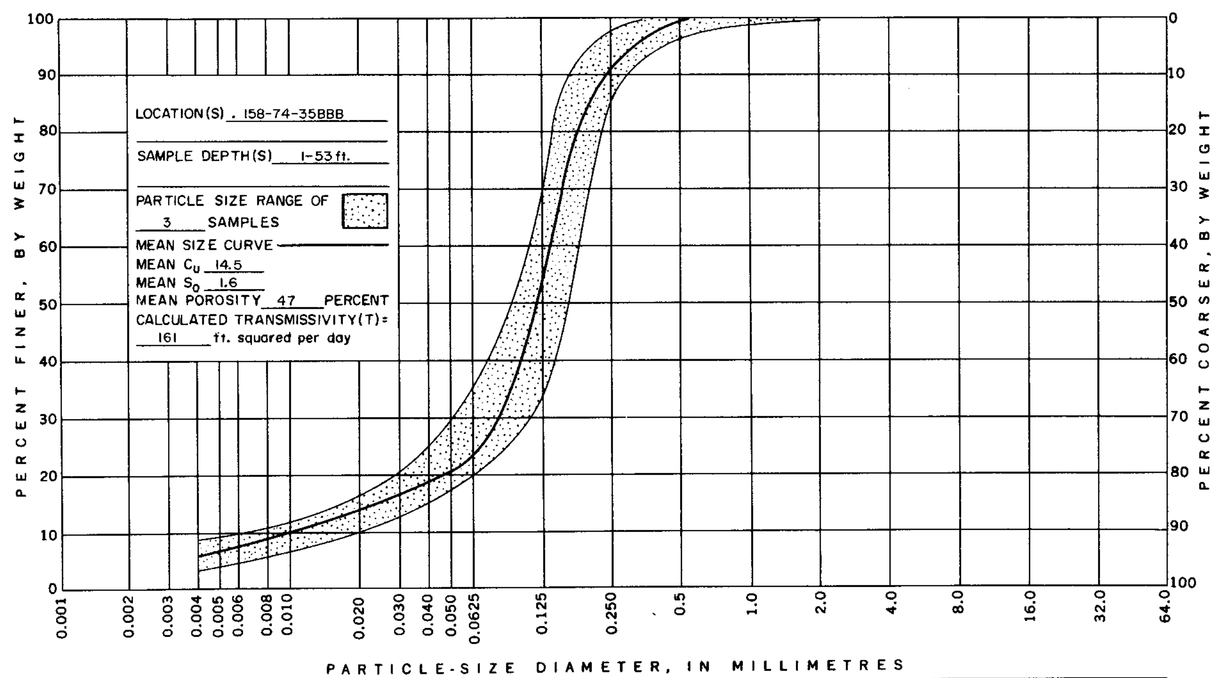
Water in the Lake Souris deposits ranged from a mixed calcium-sodium bicarbonate type in south-central Pierce County to a mixed sodium-calcium sulfate type in the northern part of the county. Generally the sodium-calcium sulfate type water occurs where the lake deposits are relatively thin. All the ground water sampled from the lake deposits was very hard. Therefore, in some areas wells have been drilled through the lake deposits and developed in the underlying Fox Hills Formation in order to obtain relatively soft water for domestic purposes.

Ice-contact deposits

Ice-contact deposits occur in Pierce County and locally in Benson County along the northern sides of end moraines, as shown in figure 4. These deposits occupy hills and ridges (some rather sinuous) that are conspicuously higher than the surrounding terrain and consist of poorly sorted sand, gravel, and silt. One such feature, locally named Devils Heart Butte, forms a prominent hill near Tokio in Benson County.

Recharge from precipitation moves through the deposits rapidly, as shown by small water-level fluctuations (fig. 41), and above-average precipitation (as occurred in 1969-70) is needed to increase the amount of water in storage. Because these deposits generally are located on topographic highs (hills) and are readily discharged, only the lower one-half or less (generally less than 20 feet) of the material remains saturated for any length of time — thus restricting potential yields to wells.

The water in the ice-contact deposits is highly variable in quality and ranges from a calcium bicarbonate to sodium sulfate type. Dissolved solids for 16 samples ranged from 220 to 1,060 mg/l and averaged 548 mg/l. Residual sodium carbonate exceeded 2.5 meq/l in about half of the samples.



PERCENT OF SIZE	CLAY SIZES	SILT SIZES	SAND SIZES					GRAVEL SIZES				
			V.FINE	FINE	MEDIUM	COARSE	V.COARSE	V.FINE	FINE	MEDIUM	COARSE	V.COARSE
	<0.004 MM	0.004-0.0625 MM	0.0625-0.125	0.125-0.25	0.25-0.5	0.5-1.0	1.0-2.0	2.0-4.0	4.0-8.0	8.0-16.0	16.0-32.0	32.0-64.0

FIGURE 39.—Particle-size distribution curves for samples from Lake Souris glacial deposits.

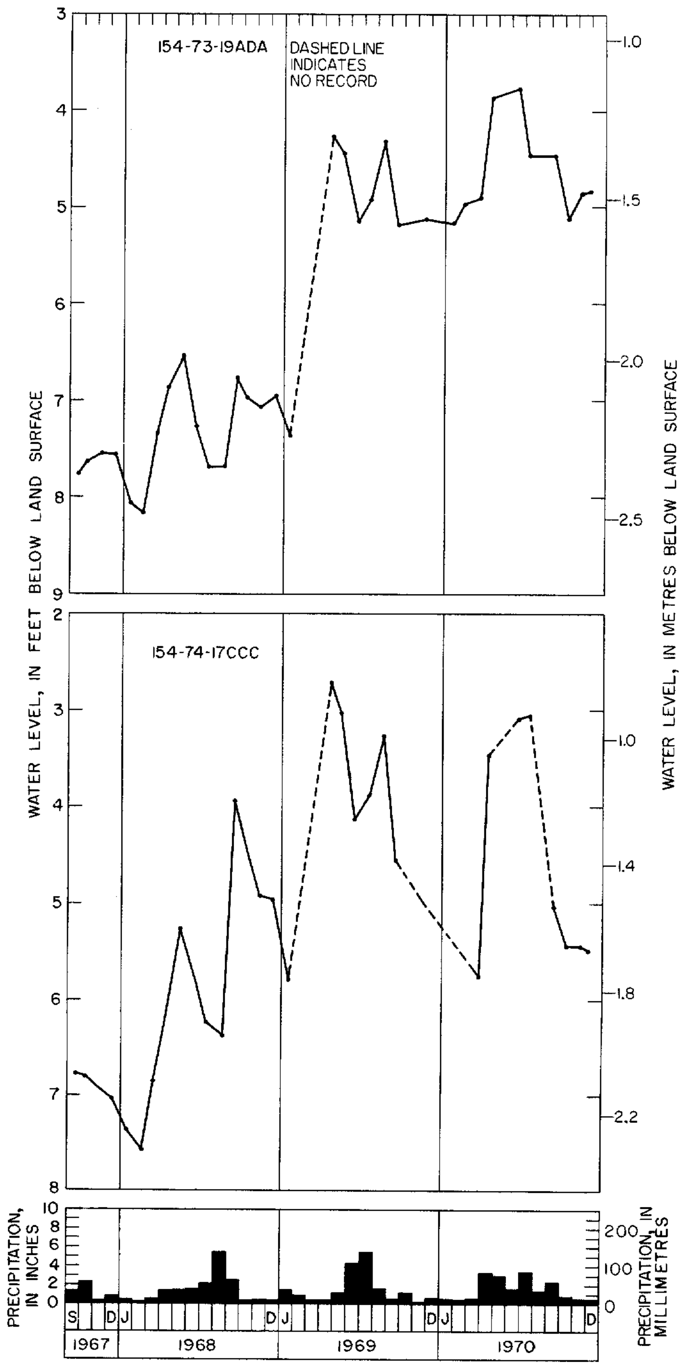


FIGURE 40.— Water-level fluctuations in Lake Souris glacial deposits and precipitation at Balta.

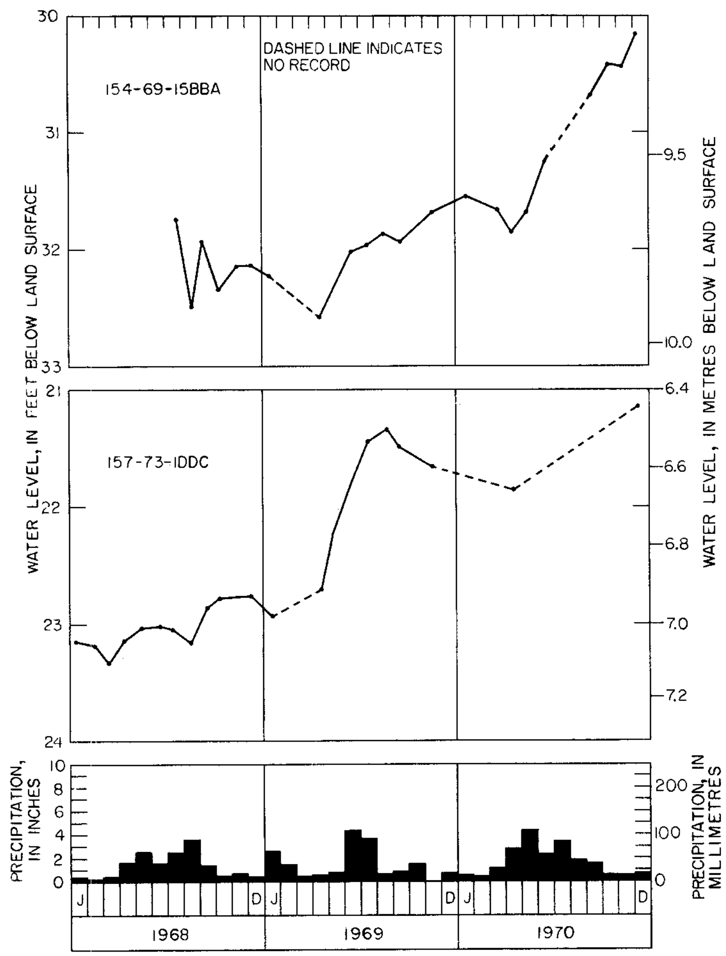


FIGURE 41.— Water-level fluctuations in ice-contact deposits, and precipitation at Leeds.

In 1971, there were several small-yield domestic and livestock wells developed in the ice-contact deposits. Potential yields to wells probably would be about 50 gal/min (3.2 l/s).

Till and associated sand and gravel deposits

Sand and gravel lenses interspersed in till form aquifers of local importance. These aquifers generally are limited to small areas and are isolated from one another by confining layers of till. The areal extent and location of these aquifers are virtually impossible to predict using existing data; however, the sand and gravel lenses seem to be more common in end moraines (fig. 4) than in other forms of till deposits. All test holes drilled in end moraines penetrated one or more lenses of sand or gravel capable of producing small yields to wells.

Ground water found in these deposits ranges from a mixed calcium sulfate-bicarbonate to a mixed sodium bicarbonate-sulfate type. The chemical quality of the water is highly variable, but the concentration of dissolved solids generally increases with depth. Dissolved solids for seven samples ranged from about 400 to 1,700 mg/l and averaged 840 mg/l. The water generally is very hard.

Almost half of all domestic and farm wells in the area are developed in till and associated sand and gravel deposits. The wells commonly range from about 10 to 200 feet (3 to 61 m) in depth, and are either hand dug, bored, or drilled. Yields from these wells range from 1 to about 12 gal/min (0.1 to 0.8 l/s). Sustained yields are dependent upon the size, hydraulic conductivity, storage coefficient, and recharge of the deposits. In some places the water in some of these aquifers is under adequate pressure to flow at land surface.

UTILIZATION OF GROUND-WATER RESOURCES

Most of the water supplies in Benson and Pierce Counties are derived from ground-water sources. There are no large manufacturing industries or irrigation projects in the area (1970). However, the potential exists for development of large supplies in many areas.

Farm Supplies

Most of the domestic and livestock wells in Benson and Pierce Counties are drilled or dug less than 100 feet (30 m) deep; they commonly do not penetrate below the first water-yielding zone. Yields of such wells generally range from 2 to 20 gal/min (0.1 to 6.1 l/s). These supplies are obtained from glacial-drift and shallow bedrock aquifers.

Estimates of the amount of ground water pumped daily for domestic and livestock use are:

Use	Individual requirements (gal/d)	Population or number	Pumpage (gal/d)
Domestic[1]	100		
Benson County		[2] 6,416	600,000
Pierce County		[2] 3,434	300,000
Livestock			
Cattle	15		
Benson County		[3]40,000	600,000
Pierce County		[3]27,000	400,000
Hogs	5		
Benson County		[3] 1,800	9,000
Pierce County		[3] 1,600	8,000
Sheep	1.5		
Benson County		[3] 7,400	11,000
Pierce County		[3] 3,600	5,400
Poultry	.1		
Benson County		[3]25,000	2,500
Pierce County		[3]34,000	3,400
	Total		1,939,300

[1] Does not include communities having municipal supplies.
[2] U.S. Bureau of the Census, 1971.
[3] North Dakota State University, 1968.

Public Supplies

Devils Lake, Fort Totten, Leeds, Maddock, Minnewaukan, and Rugby obtain their municipal supplies from ground-water sources. Total pumpage in 1970 by the six municipalities was estimated to be about 1.2 Mgal/d (4,500 m^3/d). Residents of other communities are dependent upon privately owned wells.

Devils Lake (Ramsey County) obtains its water supply from four wells in the Warwick aquifer. Pumpage by these wells averaged about 0.84 Mgal/d (3,200 m^3/d) in 1970. The water is transported via pipeline 20 miles (32 km) to Devils Lake. Ground water from this source is low in dissolved solids, and of a calcium bicarbonate type. Additional large-yield wells may be installed in this aquifer for expansion of present supplies.

Fort Totten obtains its water supply from a well developed in a gravelly till and fractured shale near the contact between the drift and the Pierre Formation. Fort Totten used about 40,000 gal/d (150 m^3/d) in 1970. The aquifer is recharged readily from local precipitation. If proper well spacing is maintained, these materials should yield sufficient quantities of water for about twice the present population of Fort Totten.

Leeds is using highly mineralized water from wells in the Dakota aquifer for sanitary and fire-protection purposes. The wells pumped about 25,000 gal/d (95 m^3/d) in 1970. Residents haul their drinking water from a shallow well on the west side of the city. The well is developed in a small glacial sand and gravel deposit in an intermittent-stream valley. The deposit is an isolated deposit associated with till and is not part of or connected to any major aquifer in the area. The Leeds aquifer, located about 3 miles (5 km) west of the city, may be capable of yielding up to 50 gal/min (3.2 l/s) to wells.

Maddock obtains water from a minor glacial-drift aquifer 2 miles (3 km) west of the city. Daily use by the city in 1970 was about 100,000 gallons (380 m^3). The Maddock aquifer, located about 3 miles (5 km) southeast of the city could be used if an additional supply is needed.

Minnewaukan pumped about 22,000 gal/d (80 m^3/d) in 1970 from two shallow wells, which are located near the center of the city, developed in a minor glacial-drift aquifer underlying the city. The Spiritwood aquifer, located about 3 miles (5 km) east of the city, is capable of yielding about 1,500 gal/min (95 l/s) to wells if additional water is needed.

Rugby pumped about 220,000 gal/d (830 m^3/d) in 1970 from two wells in the Pleasant Lake aquifer and transported the water 5 miles (8 km) via pipeline to city reservoirs. The aquifer contains a sufficient quantity of ground water to sustain additional development of wells about 4 miles (6 km) east of the present well field.

SUMMARY AND CONCLUSIONS

Ground water is obtainable in Benson and Pierce Counties from aquifers in the preglacial rocks of Cretaceous age and from aquifers in the glacial drift of Pleistocene age. The aquifers in the preglacial rocks are more widely distributed, but the aquifers in the drift will provide higher yields and better quality water.

Aquifers in the preglacial rocks occur in the Dakota Group and the Pierre and Fox Hills Formations. The Dakota aquifer consists of sandstone and lies from about 1,400 to 2,200 feet (430 to 610 m) below land surface in Benson and Pierce Counties. Wells tapping the aquifer will generally flow at land surface altitudes between 1,500 and 1,600 feet (460 and 490 m). The water contains about 4,000 mg/l dissolved solids and is a sodium sulfate to a mixed sodium sulfate-chloride type. Because of its depth, mineralization, and the general availability of water from shallower aquifers, the Dakota aquifer has not been extensively used.

The Pierre aquifer consists of shale, which is highly fractured in many localities. Small quantities of soft sodium bicarbonate, sodium sulfate, or sodium chloride water are available from fracture zones and are sufficient for most domestic and stock purposes.

The Fox Hills aquifer consists of semiconsolidated sandstone in the upper part. The lower part is mostly siltstone interbedded with shale and claystone. Wells developed in the aquifer will yield 4 to 100 gal/min (0.3 to 6 l/s) of soft, high-sodium water. The water is satisfactory for most domestic and livestock uses.

The principal glacial-drift aquifers are composed of sand and gravel; they occur in buried-valley, buried-outwash, and surficial-outwash deposits. The New Rockford aquifer, Spiritwood aquifer system, and Kilgore aquifer are buried-valley aquifers and are the largest potential sources of water in Benson and Pierce Counties. Wells developed in these aquifers are capable of yielding 50 to 1,500 gal/min (3.2 to 95 l/s) of sodium bicarbonate to calcium bicarbonate type water. Sulfate concentrations may be high in some localities.

Buried-outwash deposits are relatively small in areal extent when compared with other glacial deposits. The Maddock and Leeds aquifers occur in buried-outwash deposits in Benson and Pierce Counties. Wells in these aquifers have potential yields of 10 to 250 gal/min (0.6 to 16 l/s). The water generally is a mixed calcium-sodium bicarbonate-sulfate or a mixed sodium sulfate-bicarbonate type.

The Warwick, Esmond, Pleasant Lake, and Tokio aquifers occur in surficial-outwash deposits. The Warwick aquifer is the most extensive and is capable of yielding about 1,500 gal/min (95 l/s). The Esmond, Pleasant Lake, and Tokio aquifers are generally thin and yield less than 250 gal/min (16 l/s) to wells. The surficial-outwash aquifers yield the best water in the report area.

The major glacial-drift aquifers underlie nearly 300 mi^2 (780 km^2) in Benson and Pierce Counties and contain about 1.8 million acre-feet (2.2 km^3) of water in available storage. Hydrologic data for the major glacial-drift aquifers are presented in the summary table.

Minor glacial-drift aquifers occur in ice-contact, lacustrine, and till and associated sand and gravel deposits. These deposits contain numerous localized aquifers that yield adequate water supplies for domestic and livestock use. Wells in these deposits rarely yield as much as 50 gal/min (3.2 l/s) and generally yield less than 10 gal/min (0.6 l/s). The water is highly variable in quality but generally is very hard.

Practically all water used in Benson and Pierce Counties is from ground-water sources. About 2 Mgal/d (7,600 m^3/d) was pumped for domestic and livestock uses in 1970. Devils Lake, Fort Totten, Leeds, Maddock, Minnewaukan, and Rugby have municipal water systems. The amount pumped by the six communities was estimated to be about 1.2 Mgal/d (4,500 m^3/d) in 1970. Therefore, the total pumpage of ground water in the two-county area in 1970 was about 3.2 Mgal/d (12,100 m^3/d).

Summary of data for major glacial-drift aquifers

Aquifers	Aquifer extent (mi²)	Average saturated thickness (ft)	Estimated water available from storage (acre-feet)	General type of water	General irrigation class	Potential yield to wells (gal/min)
New Rockford	80	147	500,000	Sodium bicarbonate	C3-S1 to C3-S2	250 to 1,500
Spiritwood system near Warwick	12	94	125,000	Calcium bicarbonate	C2-S1	250 to 1,500
Spiritwood system near Minnewaukan	60	42	290,000	Sodium sulfate-bicarbonate	C2-S1 to C4-S4	50 to 1,500
Kilgore	25	60	150,000	Sodium bicarbonate	C2-S1 to C3-S2	50 to 250
Maddock	8	70	55,000	Calcium or sodium bicarbonate-sulfate	C3-S1 to C3-S3	50 to 250
Leeds	7	23	17,500	Sodium sulfate-bicarbonate	C4-S2 to C4-S3	10 to 75
Warwick	30	74	300,000	Calcium bicarbonate	C2-S1	50 to 1,500
Esmond	20	28	70,000	Calcium bicarbonate	C2-S1 to C3-S2	50 to 250
Pleasant Lake	25	42	150,000	Calcium-magnesium bicarbonate-sulfate	C2-S1	50 to 150
Tokio	30	32	110,000	Calcium bicarbonate	C2-S1	10 to 250

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GLOSSARY OF SELECTED TERMS

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 and springs.

Area of influence – the area encompassed by the periphery of the "cone of depression" commonly caused by a discharging well.

Bedrock – the consolidated rock underlying the glacial and alluvial deposits.

Capture – water withdrawn artificially from an aquifer is derived from a decrease in storage in the aquifer, a reduction in the previous discharge from the aquifer, an increase in recharge, or a combination of these changes. (See Theis, 1940, p. 277.) The decrease in discharge plus the increase in recharge is termed capture.

Cone of depression – the depression roughly conical in shape produced in a water table or potentiometric surface by a discharging well.

Drawdown – decline of the water level in a well or in nearby wells during pumping.

Evapotranspiration – a term embracing that part of the precipitation returned to the air through direct evaporation from water or land surfaces and through transpiration by vegetation, no attempt being made to distinguish between the two.

Flowing well – well having sufficient head to discharge water above the land surface.

Gaging station – site where stream-discharge measurements are made and records of stage are kept to calculate the flow.

Ground water – water in the saturated zone.

Ground-water divide – boundary of aquifer region contributing to well or spring discharge.

Hydraulic conductivity – if a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient – the change in head per unit of distance in a given direction.

Hydrograph – a graph showing stage, flow, water level, or other property of water with respect to time.

Inflow – movement of ground water into an area in response to a hydraulic gradient.

Irrigation – the controlled application of water to arable lands to supply water for crop demands not satisfied by rainfall.

Kettle – a depression in drift, made by the wasting away of a detached mass of glacier ice that had been either wholly or partly buried in the drift.

Lacustrine – formed by or deposited in a lake environment.

Losing stream – a stream that contributes water to the ground-water reservoir.

Observation well – a well in which water-level data are measured.

Percolation – the movement under hydrostatic pressure, of water through the interstices of a rock or soil.

Perennial stream – a stream that flows continuously.

Permeable rock – a rock that has a texture permitting water to move through it under ordinary pressure differentials.

Porosity – the ratio of the total volume of openings to the total volume of a rock or soil. Generally expressed as a percentage or a decimal fraction.

Potentiometric surface –an imaginary surface defined by the levels to which water will rise in tightly cased wells.

Radius of influence – the distance from a discharging well to a point on the periphery of the cone of depression.

Recharge – addition of water to the zone of saturation.

Runoff – that part of the precipitation that appears in surface streams.

Specific capacity – the rate of discharge of water from a well divided by the drawdown of water level within the well.

Specific yield (dimensionless) – the ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil.

Stage – the height of a water surface above an established datum plane. Stage is often used interchangeably with the term "gage height."

Static water level – the level at which water will stand in a tightly cased well at a time when the water level is not affected by pumping from other wells in the aquifer. The static water level coincides with the potentiometric surface at a given well.

Storage, ground water – water stored in openings in the saturated zone.

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.

Till – serves both as a genetic and descriptive term, and indicates an unsorted and unstratified mixture of material ranging from clay to boulder in size.

Transmissivity – the rate at which water, at the prevailing field conditions, is transmitted through a unit width of the aquifer under a unit hydraulic gradient.

Water table – that surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water.

Zone, saturated – in the saturated zone all voids, large and small, are ideally filled with water under pressure greater than atmospheric.