GROUND-WATER RESOURCES
of
CAVALIER and PEMBINA COUNTIES, NORTH DAKOTA

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SELECTED FACTORS FOR CONVERTING ENGLISH UNITS TO THE 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 of 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)
	.004047	square kilometres (km^2)
Acre-feet	.001233	cubic hectometres (hm^3)
	.000001233	cubic kilometres (km^3)
Feet	.3048	metres (m)
Feet per day (ft/d)	.3048	metres per day (m/d)
Feet squared per day (ft^2/d)	.0929	metres squared per day (m^2/d)
Gallons	.003785	cubic metres (m^3)
Gallons per day (gal/d)	.003785	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]	.207	litres per second per metre [(l/s)/m]
Inches	25.4	millimetres (mm)
Miles	1.609	kilometres (km)
Million gallons per day (Mgal/d)	3,785	cubic metres per day (m^3/d)
Pounds per square inch gage (lb/in^2g)	.07031	kilograms per square centimetre (kg/cm^2)
Square miles (mi^2)	2.590	square kilometres (km^2)

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By R. D. Hutchinson

ABSTRACT

Cavalier and Pembina Counties are underlain by bedrock of Precambrian, Ordovician, Silurian, Devonian, Mississippian, Triassic and Jurassic, and Cretaceous ages. The principal bedrock aquifers are the Cretaceous Dakota Group and the Pierre Formation. The Dakota aquifer consists of sandstone with interlayered shale and may yield as much as 500 gallons per minute (32 litres per second) locally to individual wells. The Pierre aquifer, which consists of fractured shale, generally does not yield more than 10 gallons per minute (0.63 litres per second). Water from both aquifers is of poor quality, but is extensively utilized. The pre-Dakota bedrock aquifers yield a highly mineralized sodium chloride type water. Yields greater than 500 gallons per minute (32 litres per second) may be available locally from the Ordovician carbonate-rock aquifers.

The Munich aquifer, located in southwestern Cavalier County, is the most productive glacial-drift aquifer. It is capable of yielding a slightly saline sodium sulfate type water at rates up to 500 gallons per minute (32 litres per second).

Pembina County contains four major glacial-drift aquifers. The Pembina River aquifer yields calcium magnesium bicarbonate water at rates up to 250 gallons per minute (16 litres per second). The Icelandic, Pembina Delta, and Hamilton aquifers are each capable of yields up to 50 gallons per minute (3.2 litres per second). Water from the Icelandic and Pembina Delta aquifers is a calcium magnesium bicarbonate type, but the Hamilton aquifer yields sodium chloride water. Several smaller aquifers will supply relatively small quantities of good to poor quality water.

A regional ground-water flow system that apparently originates in the topographically higher Drift Prairie to the west discharges in Pembina County. Water moving in this flow system becomes more saline and develops into a sodium chloride type as it moves to the discharge area. A large, saline soil area and small saline lakes are located in eastern Pembina County as the result of natural discharge from the deep ground-water flow system.

About 60 percent of the people in the counties rely on ground water for their supplies. Of these people, 83 percent have self-supplied systems. Only the cities of Mountain, Osnabrock, and Walhalla have public ground-water supplies. The total ground-water pumpage in 1970 averaged an estimated 1.3 million gallons per day (4,900 cubic metres per day).

INTRODUCTION

The study of Cavalier and Pembina Counties (fig. 1) was requested and supported by the Cavalier County Water Management District and the Pembina County Board of Commissioners and was made under the statewide cooperative program of the U.S. Geological Survey, the North Dakota State Water Commission, and the North Dakota Geological Survey. The investigation was begun in July 1968 and was completed in June 1972.

Purpose and Need for the Investigation

The purpose of the investigation was to determine the quantity and quality of ground water available for municipal, domestic, livestock, industrial, and irrigation uses. Specifically the objectives were: (1) to describe the location, extent, and nature of the ground-water reservoirs in Cavalier and Pembina Counties; (2) to evaluate the occurrence and movement of ground water, including the sources of recharge and discharge; (3) to estimate the quantities of ground water in storage; (4) to estimate the potential yields of wells; and (5) to evaluate the chemical quality of the ground water.

Knowledge of the ground-water resources of the counties is needed in order to promote the economic growth and enhance the health and welfare of the people. Many wells in Cavalier and Pembina Counties yield only small quantities of rather highly mineralized water. In September 1936, W. W. Felson, former Pembina County auditor, conducted a mail survey of farm water supplies in Pembina County (written commun., 1936). From the replies that were received, 48 percent of the farmers reported a shortage of water for livestock use and nearly 45 percent reported a shortage of water for domestic use.

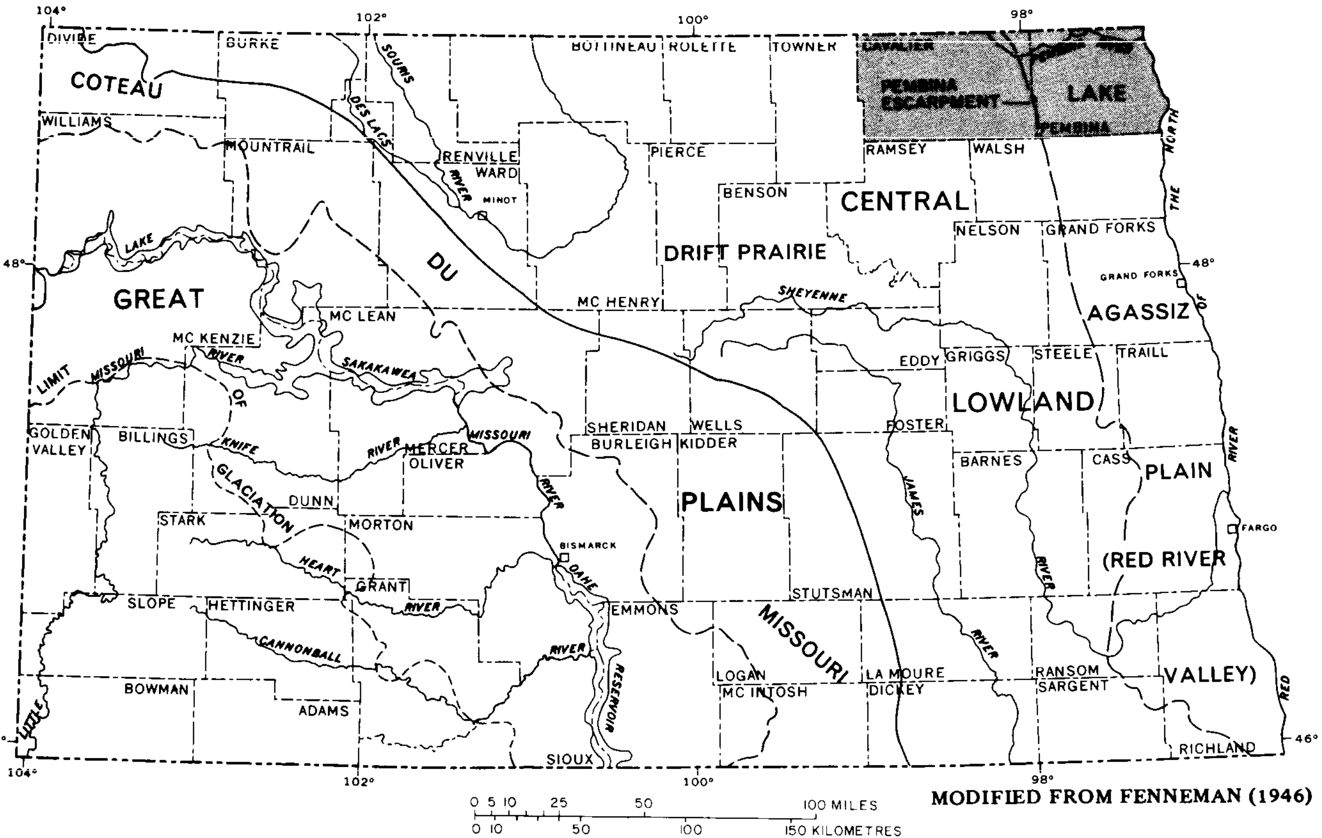
The results of this investigation should provide sufficient information to aid water managers and water users in locating adequate ground-water supplies and in selecting effective plans for the future development of these resources in the counties.

Location and Extent of the Area

Cavalier County, an area of 1,513 mi^2 (3,919 km^2), and Pembina County, an area of 1,124 mi^2 (2,911 km^2), are located in the northeastern part of North Dakota (fig. 1). Cavalier County is bordered on the east by Pembina County and on the west by Towner County. Pembina County is bordered on the east by the Red River of the North. Both counties are bordered on the north by the Province of Manitoba, Canada, and on the south by Walsh County. In addition, Cavalier County is bordered on the south by Ramsey County.

Previous Investigations

The earliest known report of ground-water data was by Underhill (1890), who described a deep well at Hamilton and several shallow wells in the Red



MODIFIED FROM FENNEMAN (1946)

FIGURE 1. —Physiographic divisions in North Dakota and location of study area.

River Valley in a report to Congress. Upham (1895, p. 548-549 and 575-576) reported on ground water in Cavalier and Pembina Counties as a part of a study of glacial Lake Agassiz. Simpson (1929) described the general ground-water conditions in Cavalier County (p. 109-112) and Pembina County (p. 182-187) as part of a statewide survey. Reports have been prepared on the occurrence of ground water near the Pembina County cities of Mountain (Akin, 1946), Neche (Paulson, 1951), and Walhalla (Adolphson, 1960). Data were also gathered in Pembina County for a study made near the Walsh County city of Hoople (Jensen and Bradley, 1962).

Chemical-quality data from wells in Cavalier and Pembina Counties have been included in reports by Abbott and Voedisch (1938), Robinove and others (1958), Scott and Barker (1962), North Dakota State Department of Health (1962 and 1964), and White and others (1963).

Hutchinson (1973) compiled a large amount of ground-water basic data in Cavalier and Pembina Counties — including well records, ground-water levels, logs of test holes, chemical analyses, particle-size analyses, and hydraulic conductivities. Data used in this report are from Hutchinson (1973) unless otherwise referenced.

Arndt (1975) has studied and mapped the surface geology of the two-county area.

Methods of Investigation

The initial phase of the study involved an inventory of existing ground-water supplies. Information was collected on well depths, water levels, well-field pumpage, and related data from drillers, well owners, tenants, and others. Concurrently, information about the geology and hydrology of the area was assembled from previous reports and unpublished information from several Federal, State, and local government offices. A total of 2,286 records of wells, test holes, and springs in the counties was collected, these data provided the basis for selecting sites for more concentrated ground-water exploration.

The North Dakota State Water Commission did most of the test-hole drilling, either with their own hydraulic-rotary equipment or by contract with a private drilling company. The drilling was done mostly for the purpose of locating and delimiting aquifers in the glacial deposits, but some drilling was done to obtain information about the bedrock aquifers. During the field seasons of 1969, 1970, and 1971, the State Water Commission completed 370 test holes in the two counties for a total of 49,030 feet (14,944 m) of drilling. The test holes ranged from 20 to 620 feet (6 to 189 m) in depth. Geologist's and driller's logs were routinely prepared for each test hole. On completion of drilling, geophysical logs were made on most of the holes and usually consisted of either one or a combination of electric, gamma-ray, and caliper logs. Nearly 10,000 rock samples were collected during the test drilling. These samples are available for examination by contacting the North Dakota Geological Survey, Grand Forks, N. Dak.

The North Dakota Geological Survey augered 116 test holes during the 1969 and 1970 field seasons for a total of 2,970 feet (905 m) of drilling. The purpose of the drilling was to obtain information about the character and distribution of near-surface glacial deposits. A geologist's log was prepared for each of these test holes.

Where the data indicated that a significant aquifer had been reached, the test holes were converted to observation wells for water-level measurements and water-quality sampling. The wells were usually constructed of 1¼-inch (32-mm) plastic casing with a 3- or 6-foot (0.9- or 1.8-m) well screen attached at the bottom. In some wells, 4-inch (100-mm) casings were used in order to accommodate floats attached to automatic water-level recorders. Water-level measurements began in the fall of 1968 and continued through 1971. Measurements will continue to be made in many of these wells as part of the statewide observation-well network.

The specific conductances of water samples from selected wells were measured in the field, when possible, during the well inventory. In addition, 209 water samples were collected during the study from observation wells, private wells, municipal wells, springs, and surface-water sources and were analyzed by the North Dakota State Water Commission laboratory in Bismarck. A total of 26 different chemical constituents and physical characteristics were either measured or computed for each water sample. These data are given in detail in the basic-data report (Hutchinson, 1973) and are given in summary in this report.

Five aquifer tests were conducted during the investigation to determine the property of selected aquifers to yield and transmit water. The tests were made at Walhalla (northwestern Pembina County, pl. 2) in July 1968, at a site 6 miles (10 km) southwest of Cavalier (central Pembina County, pl. 2) in July 1971, at a site 3 miles (5 km) west of Munich (southwestern Cavalier County, pl. 1) in August 1971, at a site 7 miles (11 km) southeast of Nekoma (south-central Cavalier County, pl. 1) in October 1968, and at a site 6 miles (10 km) northwest of Langdon (central Cavalier County, pl. 1) in November 1969.

The North Dakota Geological Survey prepared a map of the surficial geologic deposits in Cavalier and Pembina Counties. This work was begun in late 1968 and was completed during the summer of 1970. Information about the deposits was primarily obtained by hand augering along county roads, examination of exposures at roadcuts and other places, and by the use of a truck-mounted power auger. The detailed characteristics, origin, and distribution of these deposits are described in a separate report (Arndt, 1975). The information on surficial geologic conditions was valuable in locating and delineating potentially important sources for shallow ground-water supplies and in understanding the general hydrologic setting.

Most of the ground-water information collected during the study was processed by digital computer. Having the data in this form facilitated the handling of the large number of records, and aided in statistical analysis.

Well-Numbering System

The wells, test holes, and springs are numbered according to a system of land survey in use by the U.S. Bureau of Land Management. The system is illustrated in figure 2. The first numeral denotes the township north of the 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

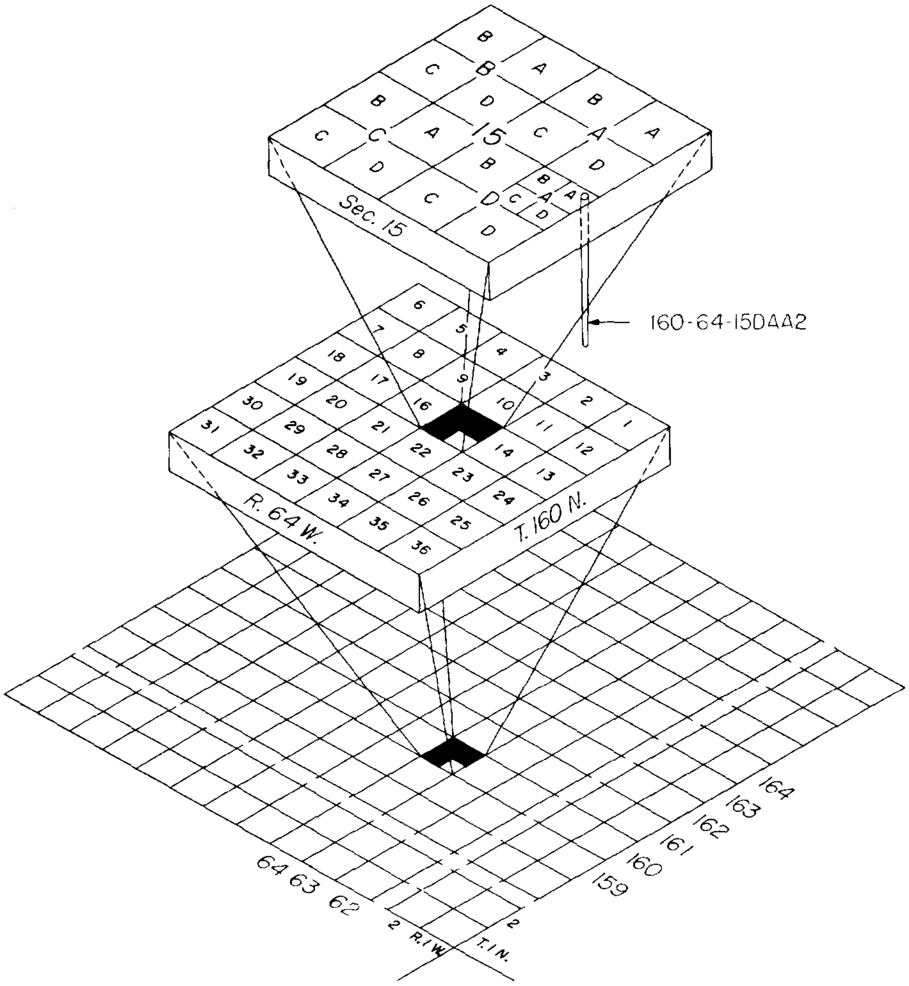


FIGURE 2. —System of numbering wells, test holes, and springs.

quarter-quarter-quarter section (10-acre or 4-ha tract). For example, well 160-64-15DAA2 is in the NE¼NE¼SE¼ sec. 15, T. 160 N., R. 64 W. Consecutive terminal numerals are added if more than one well is recorded within a 10-acre tract.

Acknowledgments

The author expresses his appreciation to members of the Cavalier County Water Management District, the Pembina County Board of Commissioners, city officials, well drillers, and the many residents of both counties who contributed time and effort towards the completion of this study. Particular recognition is due Messrs. L. L. Froelich, M. O. Lindvig, C. E. Naplin, and R. W. Schmid of the North Dakota State Water Commission, who were largely responsible for the test drilling and aquifer-test data. G. O. Muri, chemist for the North Dakota State Water Commission, gave valuable assistance by analyzing water samples collected during the investigation. B. Michael Arndt, of the North Dakota Geological Survey, provided valuable comment and maps of the glacial geology of the area. The U.S. Army Corps of Engineers provided information from an aquifer test they made at a site 6 miles (10 km) northwest of Langdon in Cavalier County.

GEOGRAPHY

Topography and Drainage

Nearly all of Cavalier County lies in the Drift Prairie district of the Central Lowland physiographic province (fig. 1). The Drift Prairie is a gently rolling to undulating upland area underlain by sediments deposited by glaciers. Altitudes range from about 950 feet (290 m) above mean sea level in the northeast corner to about 1,680 feet (510 m) in the south-central part of the county east of Nekoma. The eastern edge of the Drift Prairie generally coincides with the eastern edge of Cavalier County and is marked by the conspicuous Pembina escarpment. To the east of this escarpment is the Lake Agassiz plain.

Pembina County lies almost entirely within the glacial Lake Agassiz plain (Red River valley). Topographically, most of the county is a flat plain that slopes towards the northeast at less than 5 feet per mile (0.9 m/km). The western third of the county is characterized by undulating to steeply sloped areas, due to the presence of numerous beach ridges and the delta of the Pembina River. The beaches are marked by long narrow ridges that rise a few feet above the surrounding lake plain. The Pembina delta, which is mostly south of Walhalla, underlies an area of nearly 80 mi^2 (210 km^2). The northeastern face of this feature rises abruptly above the lake plain. West of Walhalla, the Pembina River flows through a gorge about 400 feet (120 m) deep and more than a mile (1.6 km) wide through the delta deposit. Altitudes in Pembina County range from about 750 feet (230 m) above mean sea level at the northeast corner of the county to about 1,450 feet (440 m) on the Pembina escarpment.

Both counties are located within the drainage system of the Red River of the North, which is part of the large Hudson Bay system. The major tributaries of the Red River that cross the area are the Pembina River, Tongue River, Little South Pembina River, and branches of the Park River. Much of the Drift Prairie is characterized by numerous sloughs and prairie potholes that do not directly drain to any of the major streams.

Climate

The cold weather period, generally beginning in November and lasting through March, tends to be cloudy and snowy. There is sometimes, however, a short-lived midwinter thaw. Streams and lakes begin to freeze in November. Frost usually begins to accumulate in the ground in late October or early November. Early spring is marked by a moderation of the low temperatures of winter, and by early April rainfall replaces snow as the predominant form of precipitation. Stream ice breakup occurs in late March or early April. Lake and reservoir ice may be present until early May and some soil frost may be present until early June. Summers are relatively warm, but are marked by occasional hot, humid periods. Typical fall weather may extend from September to November and is characterized by mild sunny days and cool nights.

Air temperatures within the counties are subject to large seasonal and yearly variations. Air temperature extremes lag about 3 weeks behind the solstices, resulting in July being the warmest month and January the coldest. According to climatological data collected by the National Weather Service, the annual number of days with temperatures of 0°F (-18°C) or less at Langdon has averaged 59 since 1913. The number of days with temperatures of 90°F (32.0°C) or more has averaged 10 per year. The mean annual temperature at Langdon for the period 1913-71 is 36.5°F (2.5°C).

The length of freeze-free period, which is defined as the number of days between the last freeze in the spring and the first freeze in the fall, has averaged 104 days at Langdon and 120 days at Cavalier.

Rainfall ranges from gentle showers of trace quantities to thunderstorms of up to 4 inches (100 mm). The 1931-71 mean annual precipitation at Langdon is 18.68 inches (474 mm), but has ranged from 10.86 inches (276 mm) to 28.05 inches (712 mm). The mean annual precipitation at Cavalier is 19.20 inches (488 mm), but has ranged from 8.34 inches (212 mm) to 28.19 inches (716 mm). The annual precipitation at Cavalier and Langdon and the cumulative departure from the 1931-71 means are shown in figures 3 and 4. Years of above average precipitation cause the cumulative departure curves to rise whereas below average precipitation cause the curves to fall.

Approximately 55 percent of the precipitation occurs as rainfall. Snow is common from early November through early April. Maximum and minimum seasonal snowfall at Langdon since 1913 are 86.7 inches (2,202 mm; winter of 1949-50) and 13.0 inches (330 mm; winter of 1957-58), respectively. The mean seasonal snowfall is 39.5 inches (1,003 mm).

For the period when most of the hydrologic data were being collected for this investigation, (1968-71), precipitation at Cavalier averaged 18.90 inches

(480 mm), or 0.30 inches (7.6 mm) below the 1931-71 mean. Precipitation at Langdon, however, averaged 19.25 inches (489 mm), or 0.57 inches (14.5 mm) above the 1931-71 mean.

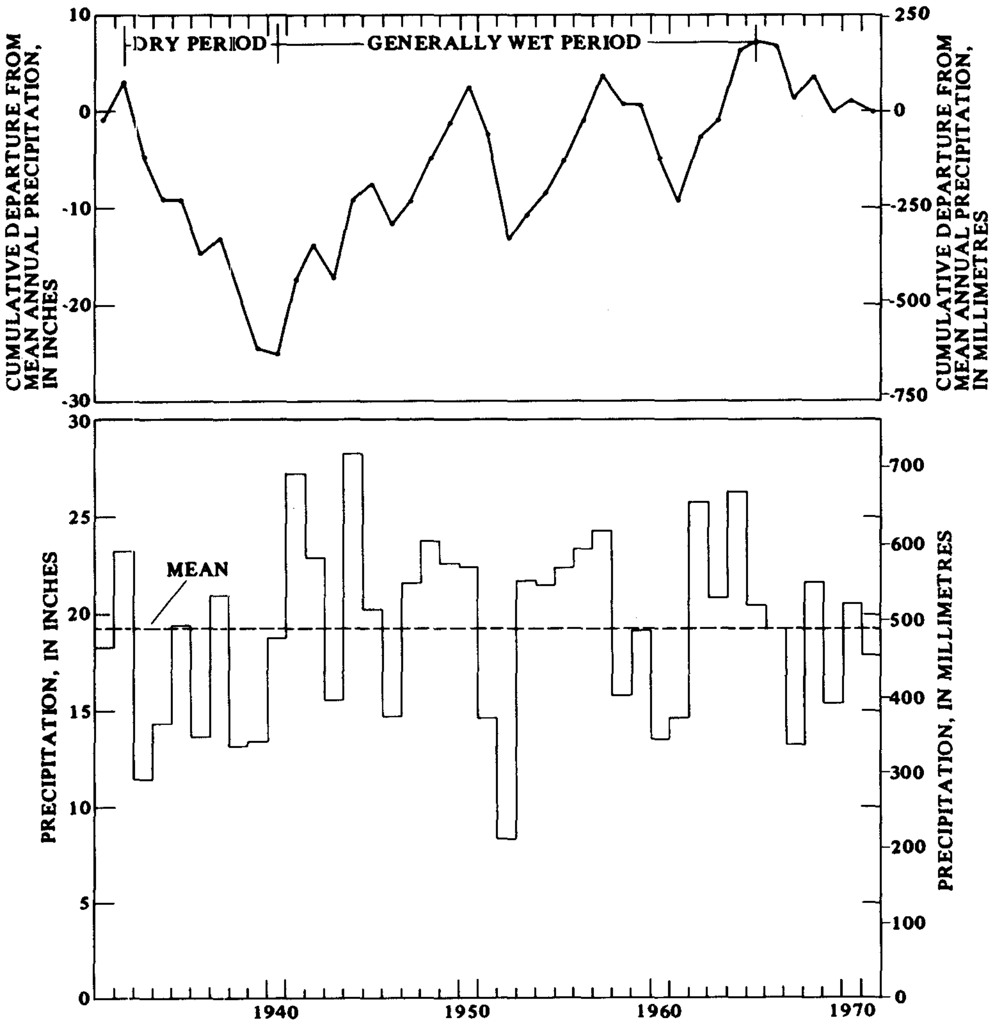


FIGURE 3. —Annual preciptation at Cavalier and cumulative departure from 1931-71 mean. (Precipitation data from the National Weather Service.)

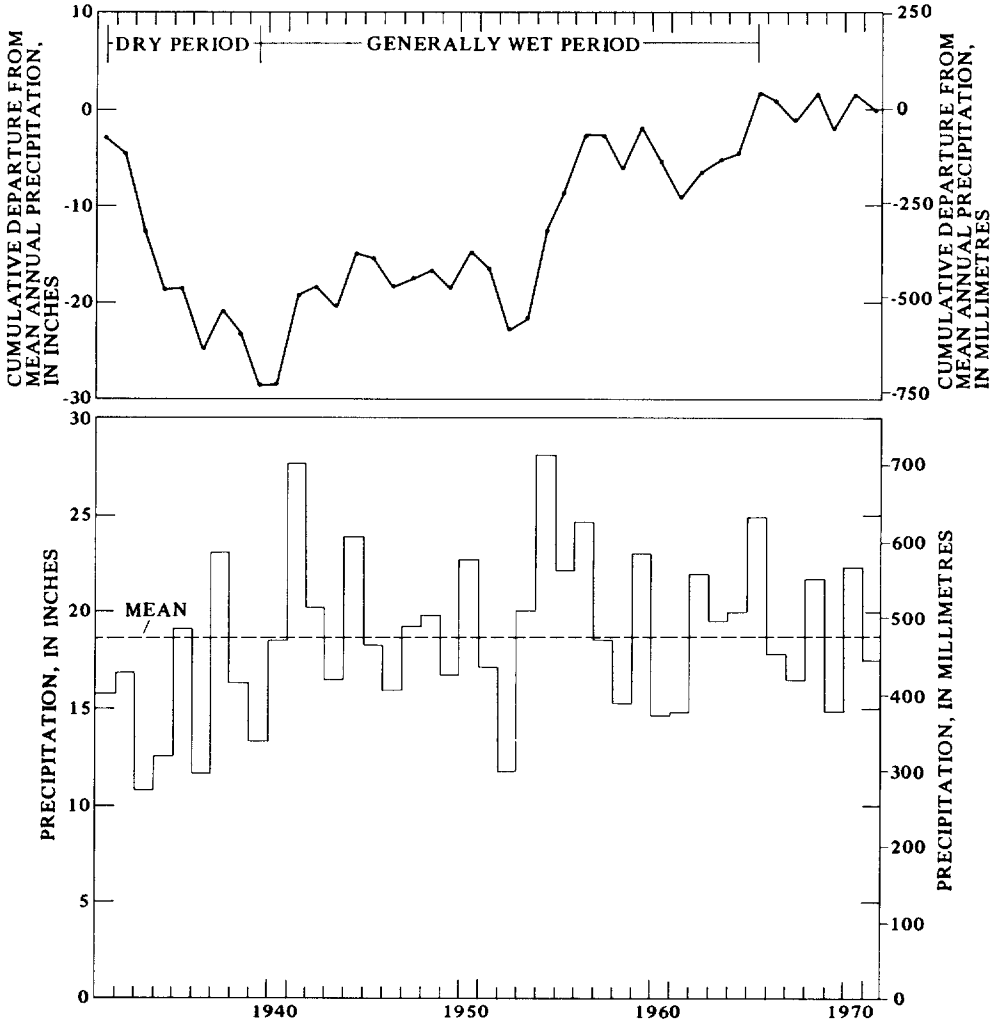


FIGURE 4. —Annual precipitation at Langdon and cumulative departure from 1931-71 mean. (Precipitation data from the National Weather Service.)

AVAILABILITY AND QUALITY OF GROUND WATER

General Concepts

Nearly all of the ground water in Cavalier and Pembina Counties is derived from precipitation. After precipitation falls to the earth's surface, part is returned to the atmosphere by evaporation, part runs off into streams, and the remainder infiltrates into the soil (fig. 5). Some of the water that enters the soil

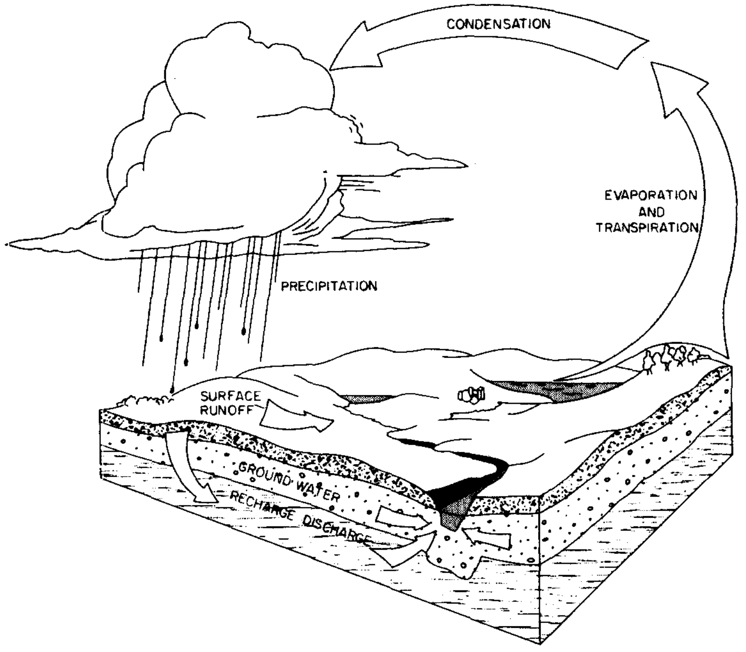


FIGURE 5. —Water cycle.

is held by capillarity, to make up for the water that has evaporated or transpired by plants during the preceding dry period. After the soil and plant requirements have been satisfied, the excess water, if any, will infiltrate downward until it reaches the zone of saturation. After the excess water enters the zone of saturation 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; it may be only a few feet per year. The rate of movement is governed by the hydraulic conductivity of the material through which the water moves and by the hydraulic gradient. Gravel and well-sorted medium or coarse sand generally are highly conductive, and deposits of these materials commonly form aquifers. Fine-grained materials such as silt, clay, and shale usually have low conductivity.

The water level in an aquifer fluctuates in response to recharge to and discharge from the aquifer. Aquifers exposed at land surface are recharged each spring and early summer by direct infiltration of precipitation. Recharge is normally sufficient to replace losses caused by natural processes and by pumping of wells. Long-term trends of several years may develop, however, during which there are net gains or losses in storage. Aquifers that are confined by thick deposits of fine-grained materials such as clay or silt are recharged very slowly by seepage from the fine-grained materials. The rate of recharge may increase as heads in the aquifers are reduced by pumping. However, head declines may continue for several years before sufficient recharge is induced to balance the rate of withdrawal. In some situations this balance may never be achieved without a curtailment of withdrawals.

In parts of Cavalier and Pembina Counties, surface-water sources are in hydraulic connection with the aquifers. The aquifers either may receive recharge from these sources or may discharge into them, depending on head relationships, which generally vary both in time and space.

The ground water in Cavalier and Pembina Counties contains dissolved minerals. The amount and kind of dissolved mineral matter in the water depends upon the reactivity of the water, solubility and types of rocks encountered, the length of time the water is in contact with the rocks, and the amount of carbon dioxide and soil acids in the water. Water that has been underground a long time, or has traveled a long distance from the recharge area, generally is more highly mineralized than water that has been in transit for only a short time.

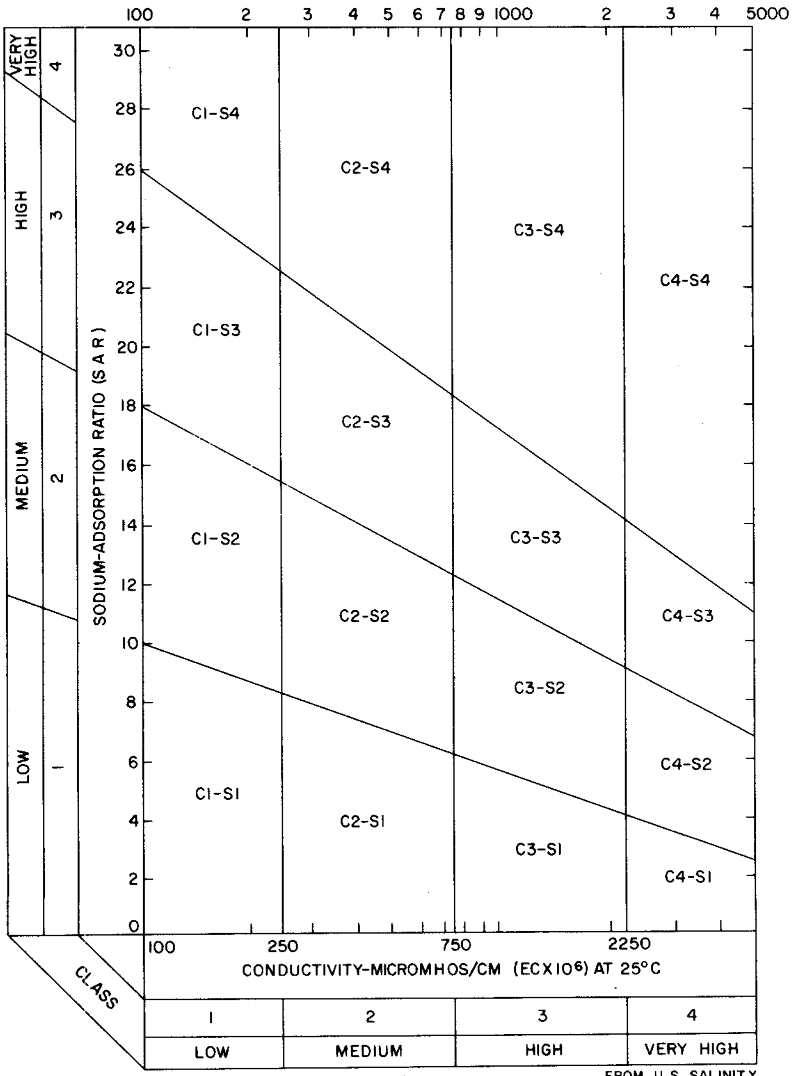
The dissolved mineral constituents in water are reported in milligrams per litre (mg/l) or micrograms per litre (ug/l). Micrograms per litre may be converted to milligrams per litre by dividing micrograms per litre by 1,000. Milliequivalents per litre (meq/l), or less precisely equivalents per million, is the unit chemical combining weight of a constituent in 1 litre of water. These units are not usually reported in tables of analyses but are used to calculate various ratios, such as the sodium-adsorption ratio, and to check the accuracy of a chemical analysis.

Further in this report numerous references are made to ground-water types, such as sodium bicarbonate type, calcium bicarbonate type, etc. These classifications are derived from inspection of the analyses and represent the predominant cation (sodium, calcium, or magnesium) and anion (bicarbonate, sulfate, or chloride), expressed in milliequivalents per litre.

The dissolved solids and conductivity of water can be described in terms of salinity. For this report, the following classification of the relative freshness and salinity has been adopted from Robinove and others (1958).

Class	Dissolved solids (mg/l)	Specific conductance (micromhos per cm at 25°C)
Fresh	Less than 1,000	Less than 1,400
Slightly saline	1,000 to 3,000	1,400 to 4,000
Moderately saline	3,000 to 10,000	4,000 to 14,000
Very saline	10,000 to 35,000	14,000 to 50,000
Brine	More than 35,000	More than 50,000

The suitability of water for various uses is determined largely by the kind and amount of dissolved matter. The chemical constituents, physical properties, and indices most likely to be of concern are: iron, sulfate, nitrate, fluoride, dissolved solids, hardness, temperature, odor, taste, specific conductance, sodium-adsorption ratio, and percent sodium. The source of the major chemical constituents, their effects on usability, and the limits recommended by the U.S. Public Health Service for drinking water are given in table 1. Additional information regarding drinking water standards may be found in "Drinking Water Standards" published by the U.S. Public Health Service (1962a). Irrigation classifications in this report were derived by the use of figure 6.



FROM U.S SALINITY LABORATORY STAFF, 1954

FIGURE 6. —Salinity and sodium hazard classifications.

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 recommended limits for drinking water (1962)
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 iron is present, it will precipitate when exposed to air; causes turbidity, stains plumbing fixtures, laundry and cooking utensils, amd imparts tastes and colors to food and drinks. More than 200 ug/l is objectionable for most industrial uses.	300 ug/l
Manganese (Mn)	Similar to iron in its occurrence and chemical behavior in natural water, but is generally less abundant than iron.	More than 200 ug/l precipitates upon oxidation. Causes undesirable tastes and dark-brown or black stains on fabrics and porcelain fixtures. Most industrial users object to water containing more than 200 ug/l.	50 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 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 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 disress. Concentrations greatly 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

Ground Water in the Consolidated Rocks

The consolidated sediments in Cavalier and Pembina Counties contain thick sequences of water-bearing rocks (table 2), but only those at relatively shallow depths are of present economic importance as aquifers (fig. 7). Information relating to the thickness and lithology of rocks older than the Dakota Group[1] is based mainly on oil-test logs. Ground-water information for the Dakota and younger consolidated rocks is available from both oil and water test holes and wells.

Rocks Below the Dakota Aquifer

Crystalline rocks of Precambrian age form the foundation, or basement, underlying the younger and more conductive rock units of the two-county area. The top of the Precambrian is about 800 feet (244 m) below land surface in eastern Pembina County and about 4,000 feet (1,200 m) in western Cavalier County. The depth to the top of the Precambrian is generally considered the greatest possible depth of available ground water.

Overlying the Precambrian basement are rocks of Ordovician age, including the Winnipeg, Red River, Stony Mountain, and Stonewall Formations (fig. 8[2]). No well in the study area is known to have produced water from the Winnipeg Formation, although the description of the formation suggests that it is an aquifer. The water from this formation probably would be a sodium chloride brine. The water level probably would range from several tens of feet above land surface in eastern Pembina County to several hundred feet below land surface in western Cavalier County.

The Red River Formation overlies the Winnipeg Formation. The Red River Formation can yield moderate to large quantities of water, depending upon the number and size of joints, fractures, and solution cavities open to a well.

Three wells and one test hole are known to penetrate the Red River Formation in Pembina County. An industrial well (159-51-23CDC) drilled at Drayton in 1959 penetrated about 250 feet (76 m) of the Red River Formation. The well reportedly flowed at a rate of about 500 gal/min (32 l/s) and had a 20 psi (1.4 kg/cm^2) pressure, which is equivalent to 46 feet (14 m) of head. In 1968 the flow from this well had reportedly increased to about 700 gal/min (44 l/s). A sample collected in July 1971 showed the water to be a brine with a dissolved-solids concentration of 42,200 mg/l, sodium of 13,100 mg/l, chloride of 22,100 mg/l, and iron of 14,000 ug/l.

Test hole 164-51-28DBD1, which was drilled to a depth of 505 feet (154 m) near Pembina for the North Dakota Geological Survey, produced a substantial flow after penetrating nearly 200 feet (61 m) of the Red River Formation. An

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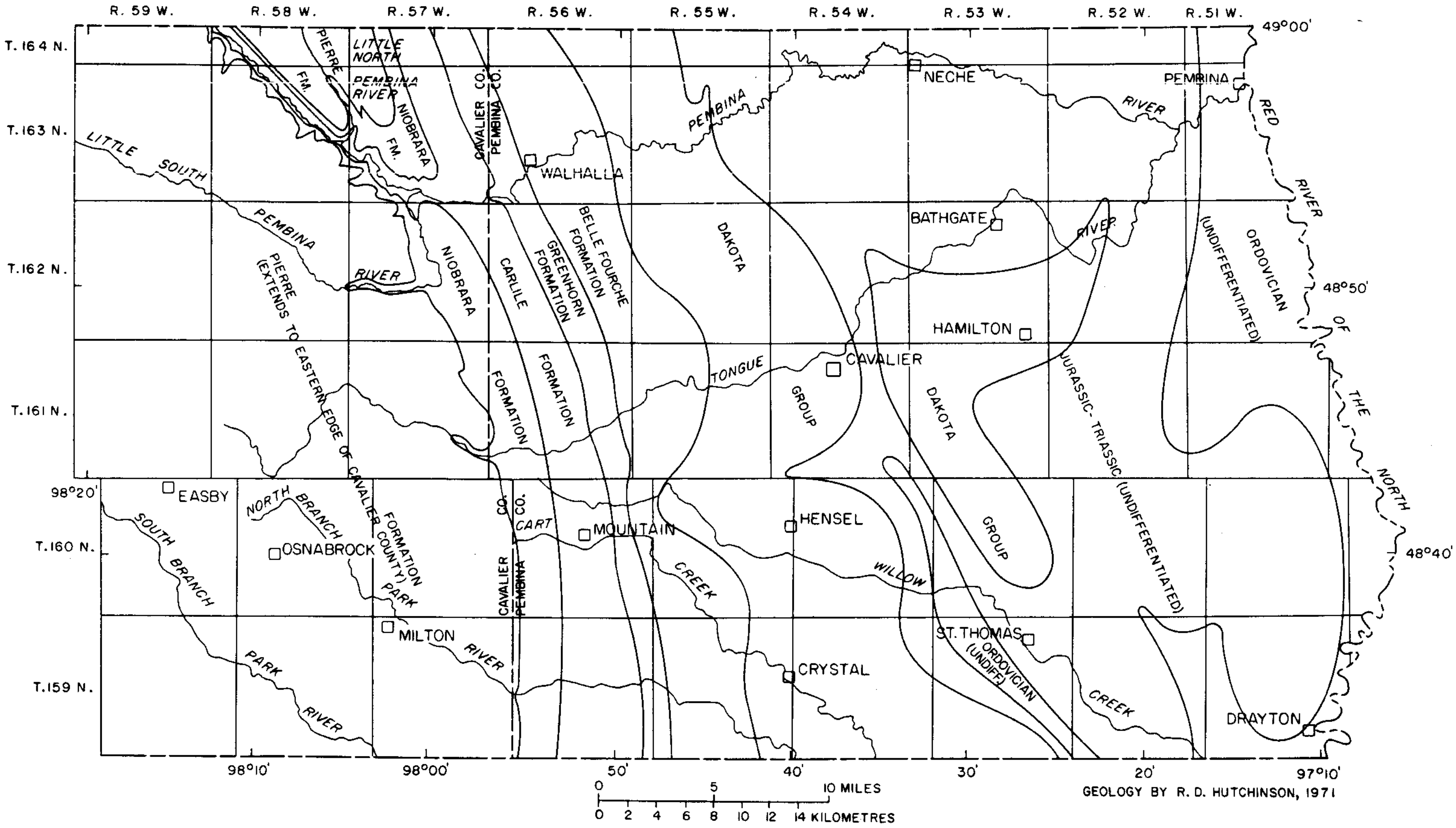
[1] The stratigraphic nomenclature used in this report is that of the North Dakota Geological Survey and does not necessarily follow the usage of the U.S. Geological Survey.

[2] Locations of geologic and hydrologic sections are shown on plates 1 and 2.

TABLE 2.—*Principal rock units and their general water-yielding properties*

Rock units and age		Lithology	Thickness (ft)	Water-yielding properties
Quaternary	Holocene and Pleistocene deposits (glacial drift)	Unsorted mixture of clay, silt, sand, gravel, and boulders; stratified sand and gravel; lake silt and clay.	0-450	Yields of as much as 500 gal/min (32 l/s) can be obtained from major sand and gravel aquifers provided (1) a sufficient thickness of water-bearing materials is present or (2) the deposits are pervious and are in continuity with present streams to allow infiltration of water from streams.
Cretaceous	Pierre Formation	Shale, light-gray to black, partly fractured, bentonitic.	0-300	Rarely yields more than 10 gal/min (0.63 l/s) to wells.
	Niobrara Formation	Shale and marlstone, light-gray to yellowish-brown, speckled.	0-200	Yields small to moderately large quantities of water to wells from joints and fractures.
	Carlile, Greenhorn, and Belle Fourche Formations, undifferentiated	Shale, siltstone, and marlstone; medium-gray to black, noncalcareous to calcareous, partly speckled.	0-600	Yields little or no water to wells.
	Dakota Group	Sandstone, fine- to coarse-grained, white to buff; gray to black shale.	0-200	Yields as much as 500 gal/min (32 l/s) of water to wells. Water is moderately to very saline.
Jurassic and Triassic	Unnamed rocks	Shale and siltstone, red, gray, black; minor amounts of limestone, sandstone, gypsum, and anyhdrite.	0-350	Yields little or no water to wells.
Mississippian	Madison Group	Limestone, varicolored, dolomitic; shale, chert, some anhydrite.	0-123	No wells are known to produce water from these rocks in the study area. Probably contain highly mineralized water.
Devonian	Birdbear, Duperow, Souris River, Dawson Bay, Prairie, Winnipegosis, and Ashern Formations, undifferentiated	Limestone, dolomite, shale, and some anyhdrite.	0-900	
Silurian	Interlake Formation	Dolomite, fine crystalline, pale-orange to white.	0-240	
	Stonewall Formation	Dolomite and limestone, fine crystalline, white to pale-orange, dense, jointed and fractured.	0-75	May locally yield several hundred gallons per minute of brine to wells from joints and fractures. Rarely used.
Ordovician	Stony Mountain Formation	Shale, reddish-brown to light-greenish-gray; minor amounts of limestone and dolomite.	0-140	Yields unknown quantities of brine to wells. Rarely used.
	Red River Formation	Limestone and dolomite, fine crystalline, gray to buff, dense, jointed and fractured.	350-550	Yields moderate to large quantities of brine to wells. Rarely used. Wells in eastern Pembina County will flow.
	Winnipeg Formation	Limestone, greenish-gray waxy shale, and sandstone.	50-180	No wells are known to produce water from this formation. Water probably brine.
	Precambrian rocks	Crystalline, igneous, and metamorphic rocks.	Unknown	Probably not water bearing.



GEOLOGY BY R. D. HUTCHINSON, 1971

FIGURE 7. —Bedrock geologic map of Cavalier and Pembina Counties.

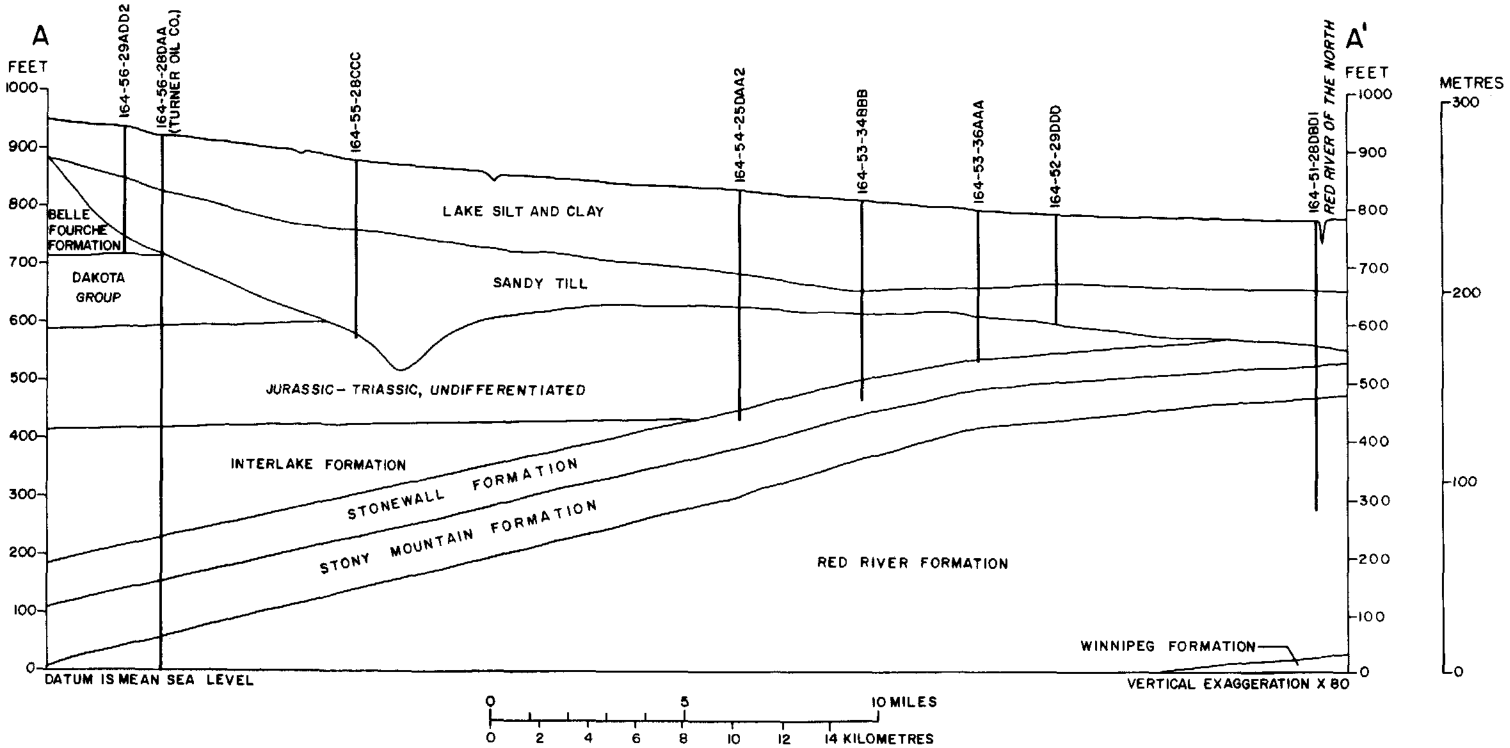


FIGURE 8. —Geologic section through northern Pembina County.

analysis of the water flowing from the open hole showed it to be very saline with 21,300 mg/l dissolved solids, 6,690 mg/l sodium, 11,300 mg/l chloride, and 3,600 ug/l iron.

The average of three analyses of water from a 450-foot (137-m) flowing well (159-53-2CBC2) tapping the Red River Formation at St. Thomas shows the water to be a brine with 43,600 mg/l dissolved solids, 13,500 mg/l sodium, 23,200 mg/l chloride, and 8,500 ug/l iron.

The most highly mineralized brine from the Red River Formation in the two-county area is from an uncontrolled flowing well (162-51-31AAA) in east-central Pembina County. The average of two analyses shows the water to have a concentration of 52,600 mg/l dissolved solids, 16,500 mg/l sodium, 28,600 mg/l chloride, and 4,400 ug/l iron. In November 1969 the well flowed at about 10 gal/min (0.63 l/s) and a 15-foot (5-m) crater had developed around the well.

The Stony Mountain Formation conformably overlies the Red River Formation, except in southeastern Pembina County where it has been removed by erosion. In test hole 164-51-28DBD1, northeastern Pembina County, the unit consists of 44 feet (13 m) of reddish-brown noncalcareous shale overlain by 12 feet (4 m) of dense dolomite. The formation thickens westward and probably reaches a maximum thickness of about 140 feet (43 m) in southwestern Cavalier County.

Only one water sample has been collected from the Stony Mountain Formation in the study area. This sample, from test hole 161-52-24DAD in east-central Pembina County, was collected from the flow at the top of the open hole. The flow was measured at about one-half gal/min (0.03 l/s) with a head 1 foot (0.3 m) above land surface. The analysis of the water shows it to be very similar to the brine from the Red River Formation with a dissolved-solids concentration of 52,800 mg/l, sodium of 15,300 mg/l, chloride of 26,900 mg/l, and iron of 20,000 ug/l. Further study of the bedrock geology in eastern Pembina County may indicate that the test hole terminated in the underlying Red River Formation rather than the Stony Mountain Formation.

The Stonewall Formation conformably overlies the Stony Mountain Formation in the two-county area. The formation increases in thickness from its erosional edge in eastern Pembina County to about 75 feet (23 m) in Cavalier County.

A sample of water was collected from an uncased flowing test hole (164-53-34BBB) that penetrated 32 feet (10 m) of the Stonewall Formation between the depths of 314 and 346 feet (96 and 105 m). The analysis of the water shows it to have a concentration of 53,800 mg/l dissolved solids, 16,600 mg/l sodium plus potassium, and 28,700 mg/l chloride. No quantitative information is available on the potential yield of water from the Stonewall Formation, but yields of several hundred gallons per minute may be available locally.

The Interlake Formation crops out in Manitoba, but is only known from records of oil-test holes in the study area. The Interlake increases in thickness from its erosional edge in Pembina County to about 240 feet (73 m) in northwestern Cavalier County. No well or test hole has been known to produce water from this formation in the two-county area, but the water is likely to be a brine.

Rocks of Devonian age in the study area consist mostly of limestone and dolomite and have been subdivided by the North Dakota Geological Survey into seven formations (table 2). These rocks probably are not present in Pembina County but may reach a combined thickness of nearly 900 feet (270 m) in western Cavalier County. Based on oil-test data, the top of the Devonian sequence ranges from about 1,000 feet (300 m) below land surface in eastern Cavalier County to about 1,700 feet (520 m) in the western part of the county. Brine probably would be produced from wells in these rocks.

Rocks of Mississippian age are present in only part of southwestern Cavalier County (Ballard, 1963, pl. 17-19). Ballard has assigned these rocks to the Bottineau interval (Lodgepole facies) of the Madison Group. Because of the presence of anhydrite, a very soluble calcium sulfate mineral, water from these rocks would almost certainly be a brine.

Rocks of Triassic and Jurassic ages have not been sufficiently studied in Cavalier and Pembina Counties to allow formational names to be applied with confidence. All of the study area is underlain by these rocks except for narrow areas in eastern and southeastern Pembina County (fig. 7).

No well in the two-county area is known to produce water from the rocks of Triassic and Jurassic age. Very limited amounts of ground water probably are available, but due to the presence of large quantities of dissolved minerals, the water likely would be unacceptable for most purposes.

Rocks of Triassic and Jurassic age act as a barrier of low permeability between the underlying and the overlying aquifers. The very slow ground-water movement through these rocks has a pronounced effect on the quality of the water. Generally speaking, the water in aquifers below this barrier is several times more highly mineralized than the water in the overlying aquifers.

Dakota Aquifer

The Dakota aquifer is potentially the most productive bedrock aquifer in Cavalier and Pembina Counties. The Dakota aquifer underlies all of Cavalier County and about half of Pembina County. Depths to the top of the aquifer range from about 250 feet (76 m) below land surface in central Pembina County to 1,300 feet (400 m) in western Cavalier County. The aggregate thickness of sandstone beds is shown in figures 9 and 10. The thickest sandstone sequence is in the vicinity of Mountain (Pembina County). Generally the sandstone beds decrease in thickness east and west of the Mountain area and are absent in much of eastern Pembina County.

Water-level measurements have been recorded in only three wells tapping the Dakota aquifer and these are in Cavalier County. The measurements, made during July 1963, are as follow:

	Water level, in feet	
Well number	**Below land surface**	**Above mean sea level**
159-57-35CDB4	523	907
159-60-34BCA4	628	962
161-58-18DDB4	694	917

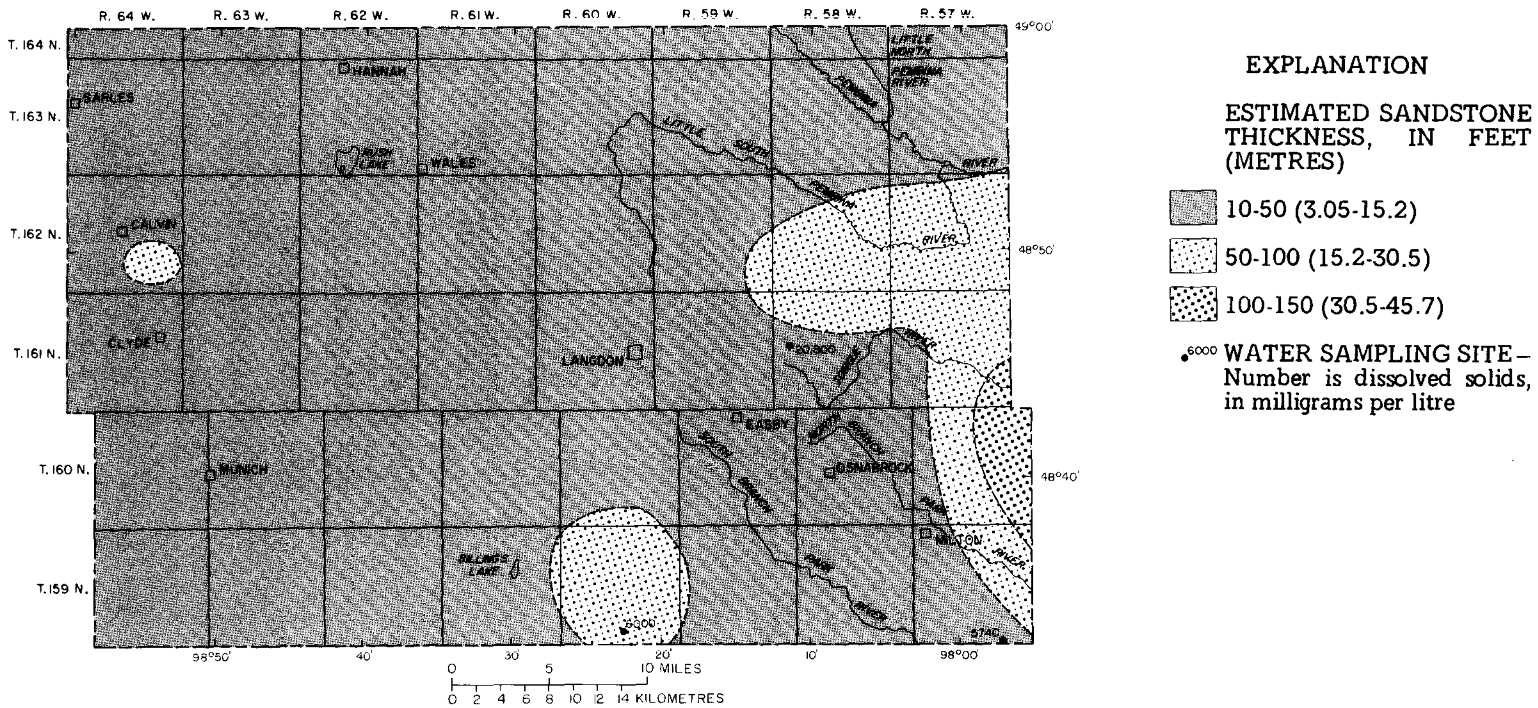
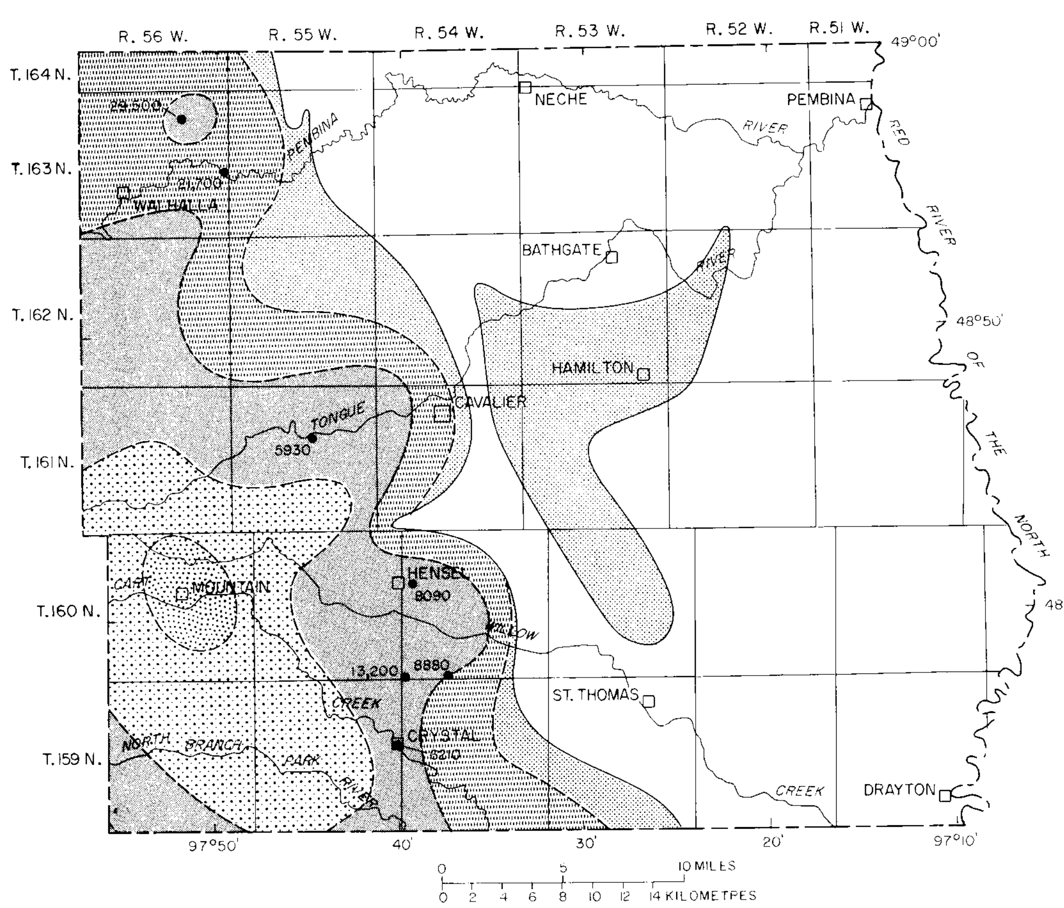


FIGURE 9.—Sandstone thickness and dissolved-solids concentration in water in the Dakota aquifer, Cavalier County.



EXPLANATION

ESTIMATED SANDSTONE THICKNESS, IN FEET (METRES)

░ 0-10 (0-3.05)

▥ 10-50 (3.05-15.2)

▒ 50-100 (15.2-30.5)

⁚ 100-150 (30.5-45.7)

▓ 150-200 (45.7-61)

● 5930 WATER SAMPLING SITE—Number is dissolved solids, in milligrams per litre

FIGURE 10.—Sandstone thickness and dissolved-solids concentration in water in the Dakota aquifer, Pembina County.

If the water levels, in feet above mean sea level, are plotted on a map of Cavalier County, they show a declining head from west to east. Because ground water moves from higher to lower heads, the general movement of ground water through the Dakota aquifer is from west to east.

In northwestern Pembina County, wells tapping the Dakota aquifer probably will flow at land-surface altitudes of about 900 feet (274 m) or less (fig. 11). Elsewhere in the county the potentiometric surface is as much as 200 feet (61 m) below land surface.

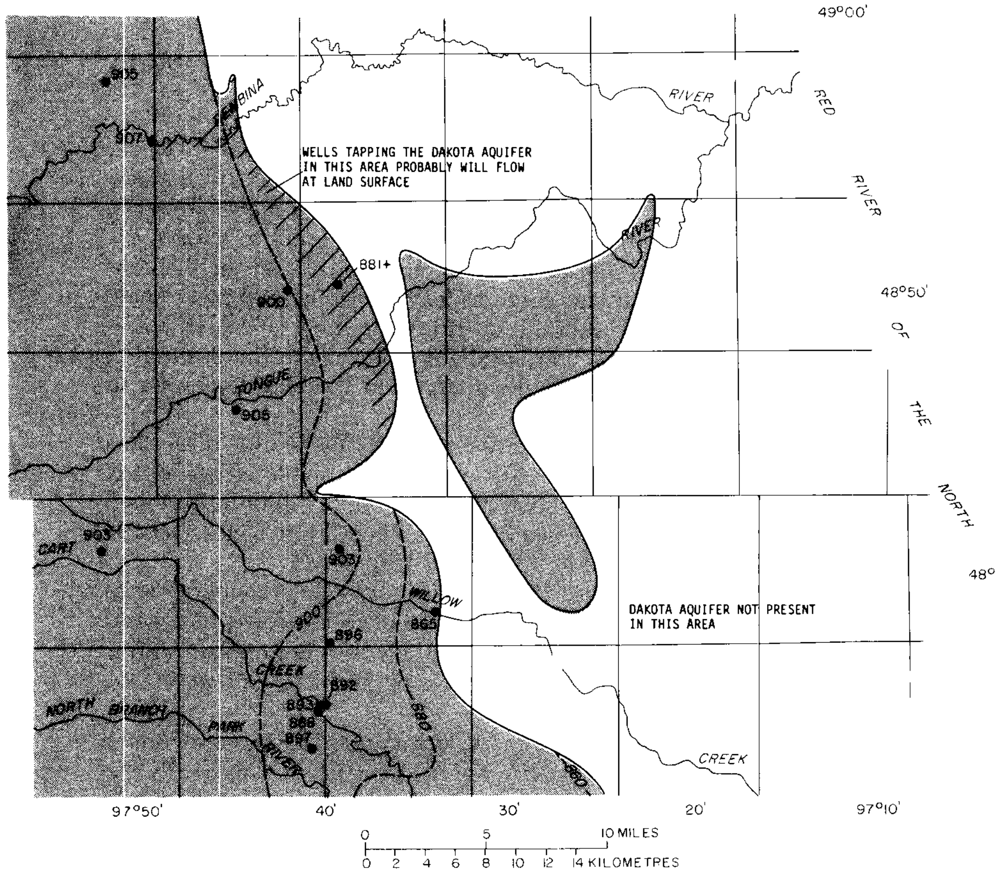
As shown in figure 11, the potentiometric surface has a very low gradient west of the 900-foot (274-m) contour line. The eastern edge of the Dakota aquifer is bounded by deposits of glacial sand and gravel or sandy till that are generally less permeable than the Dakota aquifer. As the water moves from the aquifer into the glacial units, the gradient of the potentiometric surface increases — as shown by the closer spacing of contour lines east of the 900-foot (274-m) line. Also, the Dakota aquifer contains less sandstone and more shale towards its eastern edge and this condition contributes to the increased hydraulic gradient in that direction. No data are available to evaluate the position of the potentiometric surface or the hydraulic gradient in the Dakota aquifer in the area around Hamilton.

Chemical analyses of water from the aquifer are available for only three sites in Cavalier County. The analyses show the water to be moderately to very saline with a dissolved-solids concentration ranging from 5,740 to 20,800 mg/l (fig. 9). Sodium, chloride, and iron concentrations range from 1,800 to 6,150 mg/l, 2,300 to 10,300 mg/l, and 180 to 9,240 ug/l, respectively.

Water from the Dakota aquifer in Pembina County also is moderately to very saline and ranges in dissolved solids from 5,930 to 29,500 mg/l. In general the water is a sodium chloride type. In seven samples, the sodium concentration ranged from 2,030 to 8,830 mg/l, chloride from 2,890 to 15,900 mg/l, and iron from 0 to 26,000 ug/l (fig. 10).

Little use is made of the water from the Dakota aquifer in Cavalier County because of the availability of better quality water at shallower depths. In the past the Dakota aquifer in Pembina County was probably more widely used as a source of large quantities of water than it was in the early 1970's. The decline in use has been due mostly to the general decline in population of the area, the decline of water levels in flowing wells, which in turn required the installation of pumping equipment, and the general unsuitability of the water in modern plumbing and household appliances. In the past many farms made general use of the water, but in 1973 the water was used for potato washing and some livestock watering, mostly in the Crystal-Hensel area of southern Pembina County. Virtually no records were kept on the pumpage of water from the Dakota aquifer, but it probably does not exceed 100,000 gal/d (380 m^3/d) in the two-county area.

Old wells at Crystal have reportedly produced up to 350 gal/min (22 l/s) from the Dakota aquifer. New wells located in the thicker parts of the aquifer may yield as much as 500 gal/min (32 l/s).



EXPLANATION

▨ DAKOTA AQUIFER

--900-- POTENTIOMETRIC CONTOUR–Contour interval is 20 ft (6.10 m). Datum is mean sea level

●905 CONTROL POINT–Number is altitude of potentiometric surface in 1969

FIGURE 11. —Potentiometric surface of the Dakota aquifer in Pembina County, 1969.

Belle Fourche, Greenhorn, and Carlile Formations

As much as 600 feet (180 m) of shale, siltstone, and marlstone separate the Dakota aquifer and overlying Niobrara aquifers. Very little is known about the water-yielding properties of the Belle Fourche, Greenhorn, and Carlile Formations, but they probably yield little or no water to wells and any water that is produced is likely to be highly mineralized.

Niobrara Aquifer

The Niobrara Formation conformably overlies the Carlile Formation and is exposed at many places along the Pembina escarpment and in the valley of the Pembina River. At these exposures the Niobrara is about 150 feet (46 m) thick and consists of two members. The lower member is a massive light-gray white-specked calcareous shale or marlstone. The upper member is a yellowish-brown marly shale that forms conspicuous cliffs.

Large interconnected joints and fractures in the Niobrara Formation may yield small to moderately large quantities of water to wells. The Niobrara aquifer probably yields adequate water supplies in western Pembina County and northeastern Cavalier County. In this area, the Niobrara directly underlies the glacial drift, which provides seepage of ground water as a source of recharge.

Water samples were collected from two wells tapping the Niobrara aquifer. These wells (161-56-6DDD and 164-57-32DAC) are 45 and 35 feet (14 and 11 m) in depth, respectively, and yield water of widely differing chemical characteristics. Water from these wells had respective concentrations of 390 to 2,500 mg/l dissolved solids, 236 and 1,630 mg/l hardness, 105 and 1,340 mg/l sulfate, and 12 to 52 mg/l chloride.

Pierre Aquifer

The Pierre Formation lies conformably on the Niobrara Formation and underlies the glacial-drift deposits in nearly all of Cavalier County and a small part of southwestern Pembina County. The hard fractured siliceous shale in the upper 50-200 feet (15-61 m) of the Pierre Formation forms an aquifer that is used as a source of water for many of the farms and homes in Cavalier County. The city of Osnabrock also derives its water supply from this source. No wells in Pembina County are known to use this source.

The occurrence of water in the Pierre aquifer is not clearly understood. Although test drilling and interviews with local well drillers have established that the water-yielding zones in the Pierre aquifer are nearly always associated with hard layers of shale, the individual layers are believed to have small areal extent and grade both laterally and vertically into softer, more plastic shale. Water-transmitting fractures and joints in the more brittle shale layers would not be formed or maintained in the softer shale. Correlation of layers of highly fractured shale zones between test holes spaced at distances of no more than a few hundred feet has been made with limited success, but virtually no correlation has been possible between test holes spaced 1 mile (1.6 km) or more apart using the data obtained during this investigation.

Alternating hard and soft layers in the Pierre aquifer appear to be the cause of large differences in water levels and water quality at various depths. In order to evaluate the changes that take place vertically in the aquifer, potentiometer clusters were installed at three locations in Cavalier County. The three locations are at 161-59-22BBB (4 miles, or 6 km, east of Langdon), 159-62-21AAA (10 miles, or 16 km, southeast of Munich), and 162-57-27CDB (8 miles, or 13 km, southwest of Walhalla).

The potentiometers in each cluster were spaced 10 feet (3 m) apart and finished at depths of 20, 60, 100, 150, and 200 feet (6, 18, 30, 46, and 61 m). The 20-foot (6-m) potentiometers are 4 inches (100 mm) in diameter and slotted in the lower 5 feet (1.5 m). All others are 1¼ inches (32 mm) in diameter and are finished with 3-foot (0.9-m) sandpoints. The finished sections of all potentiometers are gravel packed and sealed with concrete.

Data collected at the three potentiometer sites in Cavalier County (table 3) show that (1) differences in water level can occur with depth within the Pierre aquifer; (2) recharge occurs locally to the Pierre aquifer; (3) water quality becomes more mineralized with depth in the aquifer; (4) water type changes from sodium sulfate to sodium chloride with depth; (5) the upper part of the aquifer, which is the most productive, yields the best quality water.

TABLE 3.—Changes in water levels and water quality with depth in the Pierre aquifer, Cavalier County

Local well number and location	Well depth (ft)	Water level (ft)	Sodium (Na) (mg/l)	Sulfate (SO_4) (mg/l)	Chloride (Cl) (mg/l)	Hardness (Ca, Mg) (mg/l)	Dissolved solids (mg/l)	Specific conductance (umhos/cm at 25°C)
161-59-22BBB1	20	[1]1,653.38	181	77	17	67	554	848
22BBB2	60	[1]1,639.84	1,050	1,940	21	179	3,340	4,570
22BBB3	100	[1]1,637.64	1,110	2,080	97	175	3,650	5,000
22BBB4	150	[1]1,636.92	1,570	20	2,330	288	4,430	7,880
22BBB5	200	[1]1,632.80	2,070	63	3,380	622	6,020	10,300
159-62-21AAA1	57	[2]1,558.52	741	751	85	112	2,140	3,150
21AAA3	100	[2]1,556.65	865	512	537	81	2,390	3,810
21AAA4	150	[2]1,556.98	1,250	158	1,460	198	3,550	5,910
21AAA5	200	[2]1,555.70	2,560	272	3,900	568	7,400	12,600
162-57-27CDB1	20	[1]1,458.72	31	68	7.2	298	402	645
27CDB2	60	[1]1,453.38	907	1,160	228	89	2,780	4,030
27CDB3	100	[1]1,448.05	853	473	535	81	2,450	3,960
27CDB4	150	[1]1,427.19	1,230	72	1,770	142	3,320	6,040
27CDB5	200	[1]Dry (below 1,270.41)	—	—	—	—	—	—

[1] Measurements made on September 9, 1970, adjusted to mean sea level datum.
[2] Measurements made on September 8, 1970, adjusted to mean sea level datum.

Water levels in the Pierre aquifer fluctuate seasonally and from year to year in response to natural as well as man-induced variations in recharge and discharge. Nearly everywhere in the study area the Pierre aquifer is overlain by till, which has a vertical hydraulic conductivity of about 0.002 ft/d (0.001 m/d). The thickness of this overlying poorly permeable material, the occurrence of ground frost, and precipitation are the most important natural factors influencing water-level fluctuations in the Pierre aquifer.

Seasonal fluctuations of water levels in the Pierre aquifer were measured in 25 observation wells during this study. Nineteen of these wells were more than 50 feet (15 m) deep and overlain by 40 to 90 feet (12 to 27 m) of till, whereas six were shallow wells (less than 50 feet, or 15 m, deep) overlain by as little as 3 feet (1 m) of till.

In the deep wells, such as 159-58-31AAA (fig. 12), the water levels respond slowly to precipitation. The highest water levels occur most frequently in the

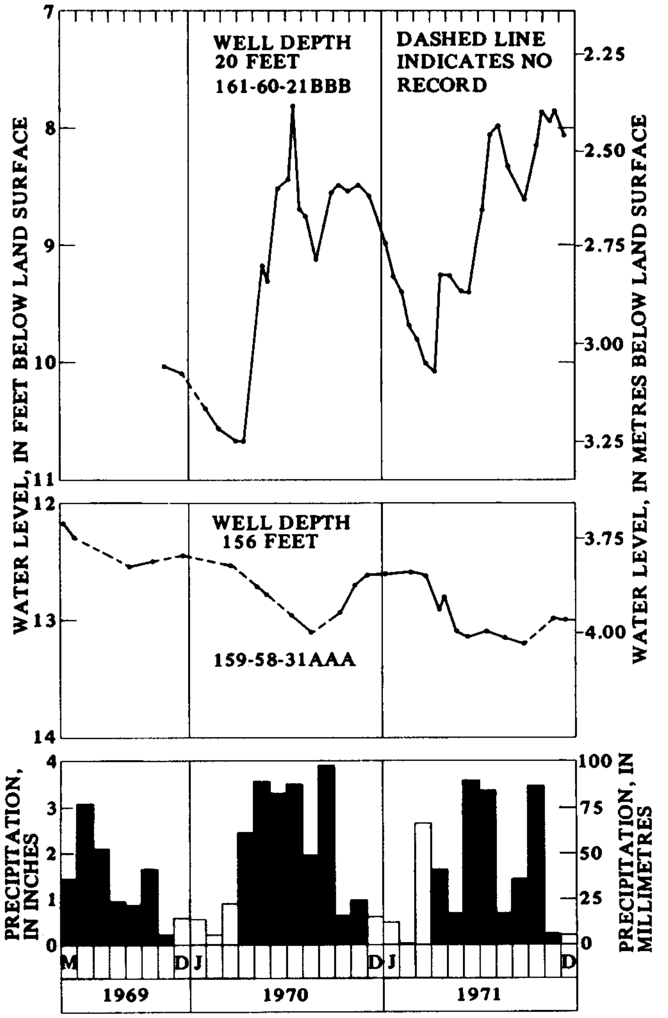


FIGURE 12. —Water-level fluctuations in the Pierre aquifer and monthly precipitation at Langdon, 1969-71. Snowfall periods are shown unshaded on precipitation graph.

winter and lag behind the greatest precipitation period (spring and summer) by several months. The lowest water levels most frequently occur in the summer and lag behind the lowest precipitation period by several months.

In the shallow wells, such as 161-60-21BBB, water levels respond quickly to rain received in the area and the highest water levels correspond with the periods of greatest precipitation (fig. 12). However, when the ground is frozen, water is not available to recharge the aquifer.

In order to evaluate the importance of ground frost on water-level fluctuations, a series of calibrated thermistors were installed about 10 feet (3 m) from observation well 161-59-22BBB1 at depths of 0.5 foot (0.15 m), 1.0 foot (0.30 m), 2.0 feet (0.60 m), 3.0 feet (0.90 m), 5.0 feet (1.5 m), and 6.6 feet (2.0 m). Ground temperatures were measured periodically from July 10, 1970, through April 1971. According to these measurements, frost developed at the beginning of November 1970 and penetrated to an estimated depth of 6.9 feet (2.1 m) by late May 1971. During most of this period the water level in the nearby observation well declined steadily and nearly paralleled the formation of ground frost (fig. 13). The water-level decline is due to (1) lack of recharge, (2) the flow of ground water to discharge areas, and (3) the movement of water to the frost zone through capillary-size openings in the soil. Capillary movement of water increases with decreasing temperature due to greater cohesion between water particles and to greater adhesion between water and soil particles.

Recharge to the Pierre aquifer, probably from nearby prairie potholes, was indicated in well 161-59-22BBB1 by the gradual rise in the water level beginning in mid-April 1971. Ground frost, however, did not begin melting at the site until the end of April and followed the melting of the snowpack in the area. According to the temperature measurements, ground frost began melting from the surface downward about the end of April and was present until early July. The highest water levels were recorded in the well in late summer and fall, several months after the greatest potential recharge period. A similar pattern of ground-frost accumulation and water-level decline began in November 1971 (fig. 13).

Frost in the ground for at least 7 months of the year (November through June) greatly reduces the amount of recharge to the Pierre aquifer and reduces the long-term potential yield that can be obtained from wells.

In order to obtain information on the hydraulic properties of the Pierre aquifer, two aquifer tests were made using wells that tap the aquifer in Cavalier County. The first of these tests was conducted on well 159-59-35BAC owned by the U.S. Army Corps of Engineers.

Analysis of the data obtained from this test indicates the transmissivity of the Pierre aquifer is between 22 and 38 ft^2/d (2.0 and 3.5 m^2/d). These values compare favorably with transmissivities of 66 and 121 ft^2/d (6.1 and 11.2 m^2/d) reported by Aronow, Dennis, and Akin (1953) for the aquifer at Michigan City (37 miles, or 60 km, south in Nelson County). Downey (1973, p. 26) also reported a similar transmissivity value from a short test made 9 miles (14 km) south at 157-58-18DDD (Walsh County).

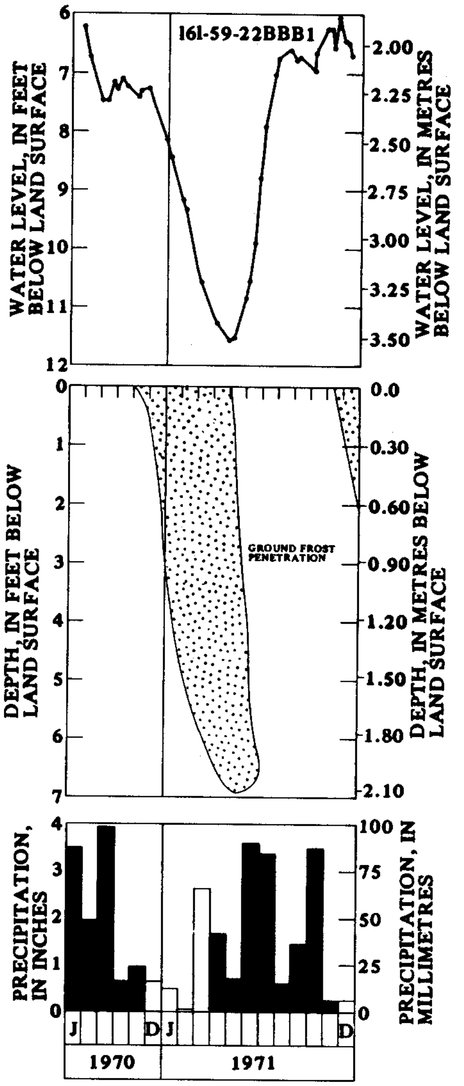


FIGURE 13.— Water-level fluctuations in the Pierre aquifer, depth of penetration of ground frost, and monthly precipitation at Langdon, 1970-71. Snowfall periods are shown unshaded on precipitation graph.

The second test on the Pierre aquifer was conducted in November 1969 using well 162-60-17DDD, located about 6 miles (10 km) northwest of Langdon.

The rate of pumping, the amount of drawdown, and the recovery were determined at frequent intervals during this test. An attempt was made to pump the well at a constant rate of discharge of 10 gal/min (0.64 l/s), but the rate varied considerably, and resulted in an erratic drawdown curve. During the last 322 minutes of pumping, however, a constant discharge of 8.5 gal/min (0.54 l/s) was maintained. After pumping for 1,487 minutes, the total drawdown was 54 feet (16.5 m), which indicates a specific capacity of about 0.2 (gal/min)/ft [0.04 (l/s)/m].

Recovery data from the test were much more consistent and more applicable to analysis than the drawdown data. The residual drawdown during the recovery period is plotted in figure 14 against the logarithm of the ratio of time since pumping began and time since pumping stopped. Using the method developed by Cooper and Jacob (1946), the transmissivity (T) of the Pierre aquifer at the test site was calculated as 11.8 ft^2/d (1.10 m^2/d).

Two water samples were collected from well 162-60-17DDD during the aquifer test. The water had concentrations of 2,250 and 2,520 mg/l dissolved solids, 202 and 352 mg/l sulfate, and 668 and 1,000 mg/l chloride. These concentrations exceeded the U.S. Public Health Service (1962a) recommended limits for drinking water but are probably representative of the ground water from the Pierre aquifer that is most often used for domestic purposes in this part of Cavalier County.

Because of the rather low transmissivities of the Pierre aquifer, most wells would not yield much more than 10 gal/min (0.6 l/s) for relatively long periods of time. However, a system of wells, properly spaced so as to cause a minimum of interference with each other, might be constructed to yield substantially more water.

In order to assist in determining the best arrangement for wells in such a system, the following table has been prepared.

Theoretical drawdowns at various distances from a well pumping continuously at 10 gal/min (0.6 l/s) from an *areally extensive aquifer*

(Transmissivity 20 ft^2/d (1.9 m^2/d); storage coefficient 0.0004)

Time since pumping started	Drawdowns, in feet						
	Distance from pumping well, in feet						
	10	100	300	500	700	1,000	5,000
1 day	53.8	18.9	4.8	1.1	0.0	0.0	0.0
10 days	71.4	36.2	19.7	12.5	.0	.0	.0
100 days	89.1	53.8	37.0	29.2	.4	.0	.0
1 year	99.4	63.7	46.9	39.1	4.0	1.5	.1
5 years	111.7	76.4	59.2	51.5	13.4	8.7	3.8
10 years	116.9	81.6	64.5	56.8	18.4	13.3	7.5

The drawdown values in the table were computed by means of the Theis nonequilibrium formula (Theis, 1935). Where the cones of influence of several

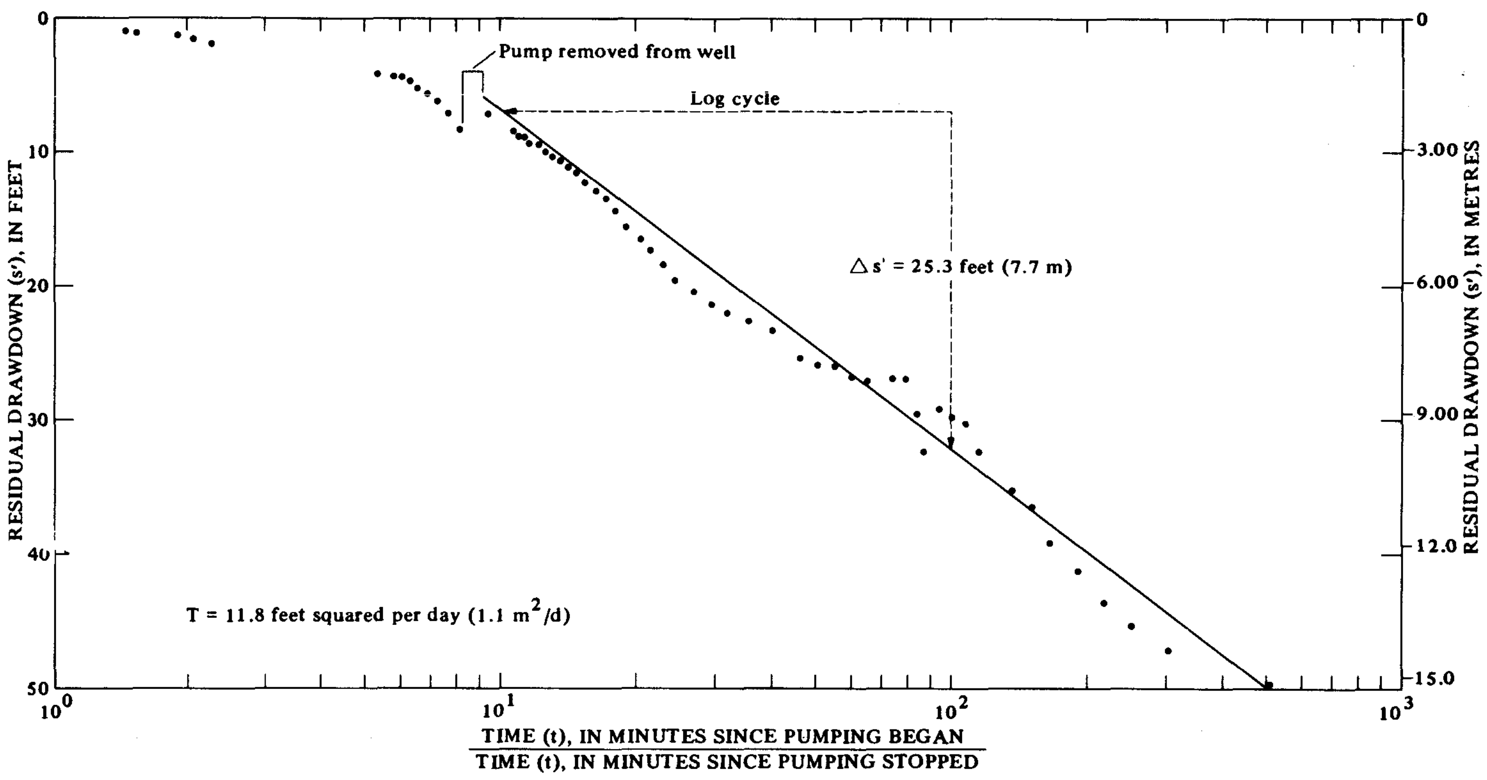


FIGURE 14. —Semilogarithmic plot of time-residual drawdown data for well 162-60-17DDD during a test of the Pierre aquifer.

pumping wells overlap, the effect at any point is the sum of the influences produced at that point by all of the wells. Also, the drawdown effects are directly proportional to the pumping rate, so that the effect of pumping 5 gal/min (0.32 l/s) at any place and time would be half that of pumping 10 gal/min (0.63 l/s).

Large quantities of water are occasionally obtained from the Pierre aquifer. R. G. Burnett, U.S. Army Corps of Engineers (written commun. to the North Dakota State Water Comm., January 12, 1972), reported that water was pumped continuously for 4 weeks at a rate of about 300 gal/min (19 l/s) from an excavation for a sewage lift station at 159-60-15 (1 mile, or 1.6 km, north of Nekoma). The water reportedly was coming from fractures in the shale located 28 to 32 feet (8.5 to 9.8 m) below land surface. The chemical analysis supplied by Mr. Burnett showed the water to be a very hard calcium magnesium sulfate type with dissolved solids of 700 mg/l.

Analyses of 125 samples of water from the Pierre aquifer indicate that the chemical quality of the water differs widely within the aquifer. Median values of selected chemical parameters are as follow: total iron, 240 ug/l; sodium, 631 mg/l; sulfate, 595 mg/l; chloride, 105 mg/l; dissolved solids, 2,000 mg/l; and hardness, 182 mg/l. The median concentrations of sulfate and dissolved solids exceed the U.S. Public Health Service (1962a) recommended drinking-water standards and the high sodium concentration may be of concern to people on sodium-restricted diets.

The quality of water from the Pierre aquifer seems to be suitable for most livestock use. The water cannot be used for irrigation, even if an adequate quantity could be located, because of the high sodium-adsorption ratio and high specific conductance (median values are 26 and 3,410 micromhos, respectively), according to the standard classification of the U.S. Salinity Laboratory Staff (1954).

Ground Water in the Glacial Drift

Deposits of glacial drift cover nearly all of Cavalier and Pembina Counties. These deposits, which are unconsolidated, consist of clay, silt, sand, and gravel. In Pembina County the deposits commonly are sorted and stratified into beds of a dominant texture, whereas in Cavalier County the deposits are mainly unsorted and unstratified (commonly referred to as till). The maximum known thickness is about 450 feet (137 m), but the average is about 150 feet (46 m). Generally the deposits are thickest in Pembina County and thinnest in Cavalier County. Aquifers in the glacial deposits have the greatest potential for gound-water development in Cavalier and Pembina Counties. The aquifers occur as (1) buried sand and gravel deposits, (2) surficial sand and gravel deposits, (3) silt deposits formed in glacial Lake Agassiz, and (4) glacial till. For convenience of discussion and identification in this report and for future reference, the individual aquifers are named after nearby prominent geographic features such as cities, streams, State parks, and deltas. The order of discussion is on the basis of economic importance — from most productive to least productive.

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

The potential yields of the aquifers to wells are shown on the ground-water availability maps (pls. 1 and 2, in pocket). The accuracies of the estimated yields were strengthened by data from pumping tests made at several locations in selected aquifers during the present study.

The aquifers generally are lenticular in cross section and the largest yields are usually obtainable from the thickest parts. Wells penetrating aquifers in narrow valleys often have lower yields than wells tapping aquifers of comparable thickness but having larger areal extent.

The ground-water availability maps should be used with the understanding that the estimated yields are for fully penetrating, properly screened and developed wells of adequate diameter. The maps are intended as a general guide in the location of ground water and not as a map to locate specific wells. Few, if any, aquifers are so uniform in extent and physical properties that production wells may be drilled in them without preliminary test drilling.

Munich Aquifer

The most productive glacial-drift aquifer in the two-county area is in the southwestern part of Cavalier County in Tps. 160-161 N., Rs. 63-64 W. The aquifer underlies about 30 mi^2 (77 km^2) near the city of Munich (pl. 1), for which it is named.

The Munich aquifer ranges in thickness from 0 to nearly 200 feet (60 m; fig. 15), and averages about 40 feet (12 m).

It consists of shaly sand and gravel interbedded with clay and silt. The thicker part of the aquifer was deposited in a preexisting valley cut in the Pierre Formation and is everywhere confined beneath about 20 to 50 feet (6 to 15 m) of glacial till.

Recharge to the Munich aquifer is derived mainly from precipitation in the immediate area of the aquifer. The precipitation must, however, percolate through the till that covers the aquifer, and hydrographs (fig. 16) show that maximum water levels generally are not attained until late fall or early winter. Also, some recharge probably is received by underflow from the Pierre Formation.

Discharge from the Munich aquifer is limited mainly to pumping wells, inflow to potholes, and evapotranspiration. Evapotranspiration from potholes is probably greatest in the southern half of the aquifer area where water levels are near the land surface. Evapotranspiration is greatest during the summer when air temperatures are warmest. Discharge by wells is small. Only about 15 farms used water from the aquifer in 1971 and collectively pumped about 5,000 gal/d (19 m^3/d). This rate of pumpage is far below the potential available yield.

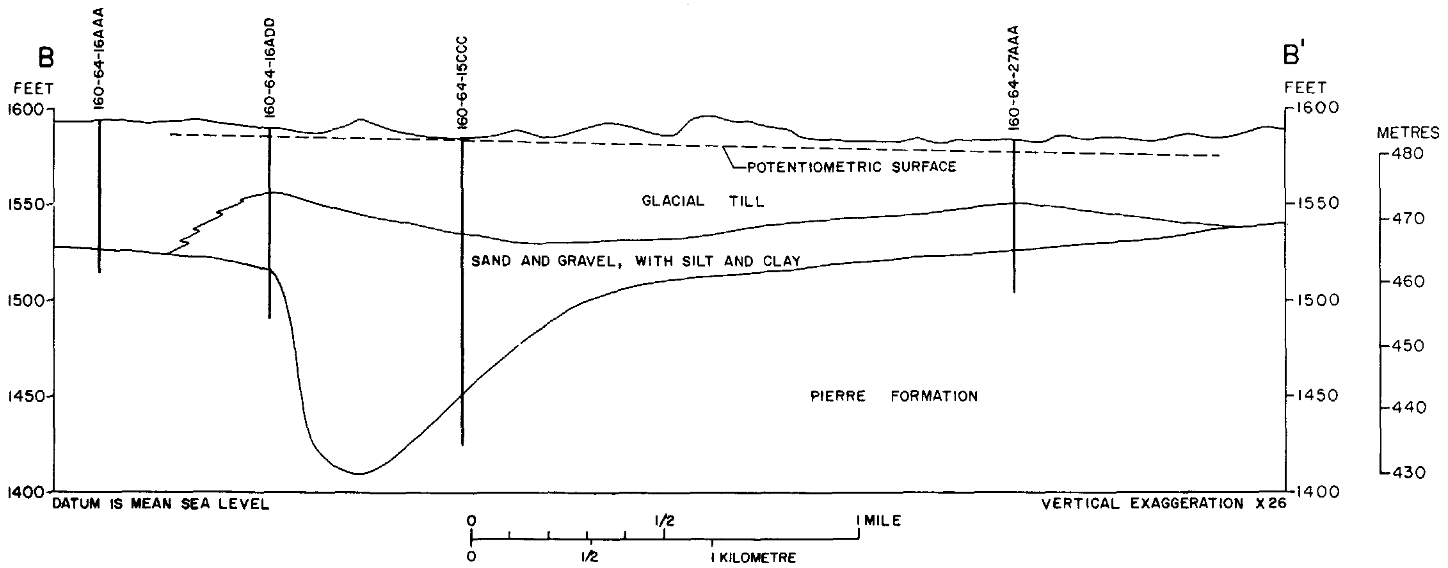


FIGURE 15. —Hydrogeologic section through the Munich aquifer, Cavalier County.

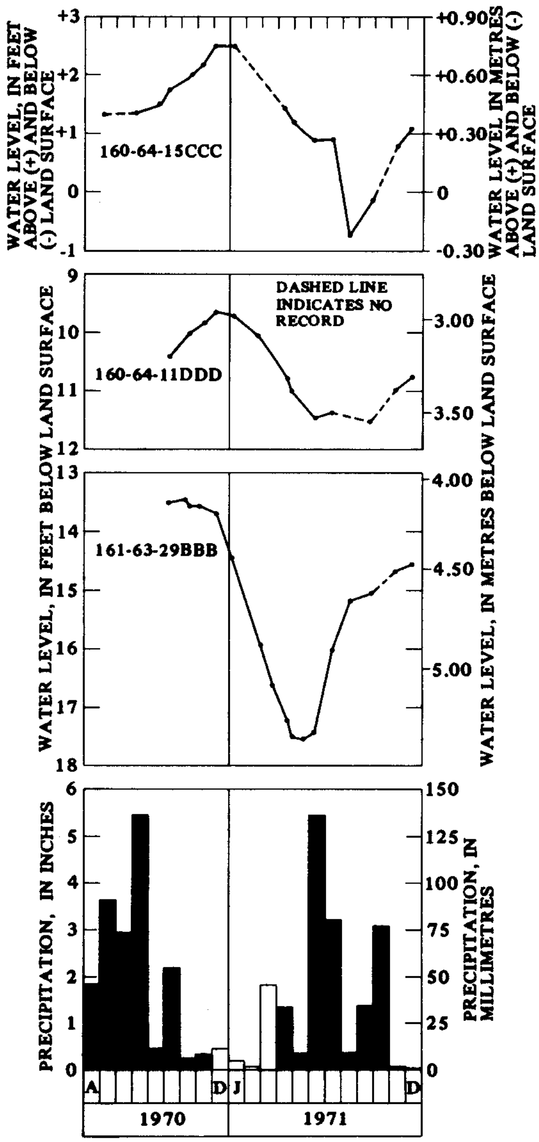


FIGURE 16. —Water-level fluctuations in the Munich aquifer and monthly precipitation at Munich, 1970-71. Snowfall periods are shown unshaded on precipitation graph.

Water from the Munich aquifer is predominantly very hard, slightly saline, and is a sodium sulfate type with a rather high concentration of iron (table 4). The median concentrations of iron, sulfate and dissolved solids exceed the 1962

U.S. Public Health Service recommended standards for drinking water. With iron removal and softening, the water should be acceptable for most domestic and public uses.

TABLE 4. — Quality of water from the Munich aquifer (Concentrations are in milligrams per litre, except as indicated; based on 16 analyses)

Constituent	Median	Range
Silica (Si)	28	26-30
Iron (Fe)	2.8	.07-5.9
Manganese (Mn)	.04	0-1.8
Calcium (Ca)	178	74-268
Magnesium (Mg)	60	27-69
Sodium (Na)	280	12-517
Potassium (K)	16	4-18
Bicarbonate (HCO_3)	542	331-670
Sulfate (SO_4)	728	102-859
Chloride (Cl)	80	1.8-229
Fluoride (F)	.4	.3-.9
Nitrate (NO_3)	2.5	.5-11
Boron (B)	.54	.03-1.2
Dissolved solids	1,630	417-2,180
Hardness (Ca, Mg)	721	350-918
Noncarbonate hardness	274	0-405
Sodium-adsorption ratio (units)	4.5	.3-9.8
Specific conductance (micromhos per centimetre at 25°C)	2,240	673-3,090
pH (units)	7.7	7.4-8.0
Temperature (°C)	6.0	5.0-6.0

According to the classification for irrigation water proposed by the U.S. Salinity Laboratory Staff (1954, fig. 6) the water is in the very high salinity, medium-sodium class (C4-S2). Boron concentrations also would limit the use of the water to semitolerant and tolerant plants such as wheat, barley, alfalfa, and sugarbeets.

An aquifer test was conducted on the Munich aquifer in August 1971. The test site was located in parts of secs. 15, 21, and 22, T. 160 N., R. 64 W., about 3 miles (5 km) west of Munich and near the southern end of the thicker and more productive part of the aquifer. The production well (160-64-22BBA3) was drilled to a depth of 90 feet (27 m) and had a diameter of 8 inches (200 mm). The well was cased to a depth of 50 feet (15 m) and finished with 40 feet (12 m) of screen having 12- to 25-slot (0.012- to 0.025-inch or 0.30- to 0.64-mm) openings. A vertical turbine pump was used during the test and discharge was measured using a flowmeter and recorder. The discharge rate was maintained at 225 gal/min (14.1 l/s) for 4 days and 4 hours (6,000 minutes).

Water-level measurements were made in the production well and 13 observation wells during both the pumping and recovery phases of the test. Eight of the wells were equipped with water-level sensors and recorders. The remaining wells were measured using chalked steel tapes. The observation wells were located at distances of 100 to 30,000 feet (30 to 9,100 m) from the production well and penetrated aquifer thicknesses ranging from 3 to 20 feet (1 to 6 m).

Data from the Munich aquifer test were analyzed using methods developed by Theis (1935) and Cooper and Jacob (1946) to determine the transmissivity and storage coefficient. The transmissivity at the aquifer site was 4,200 ft^2/d (390 m^2/d) and the storage coefficient was 0.0004.

Based on these values, a graph (fig. 17) was constructed to show the drawdown effects that a discharging well would have on water levels in the aquifer at distances of 10 to 3,000 feet (3 to 914 m) and after 1 to 300 days of continuous pumping at a rate of 200 gal/min (12.6 l/s). As an example of the use of the graph, a dashed line parallel to the constant-distance and variable-time line (AC) was drawn so as to intersect the index line (AO) at a scale distance of 1,000 feet (305 m). Water-level drawdowns of 2.3, 4.0, and 5.6 feet (0.7, 1.2, and 1.7 m) would be expected at the end of 1, 10, and 100 days, respectively.

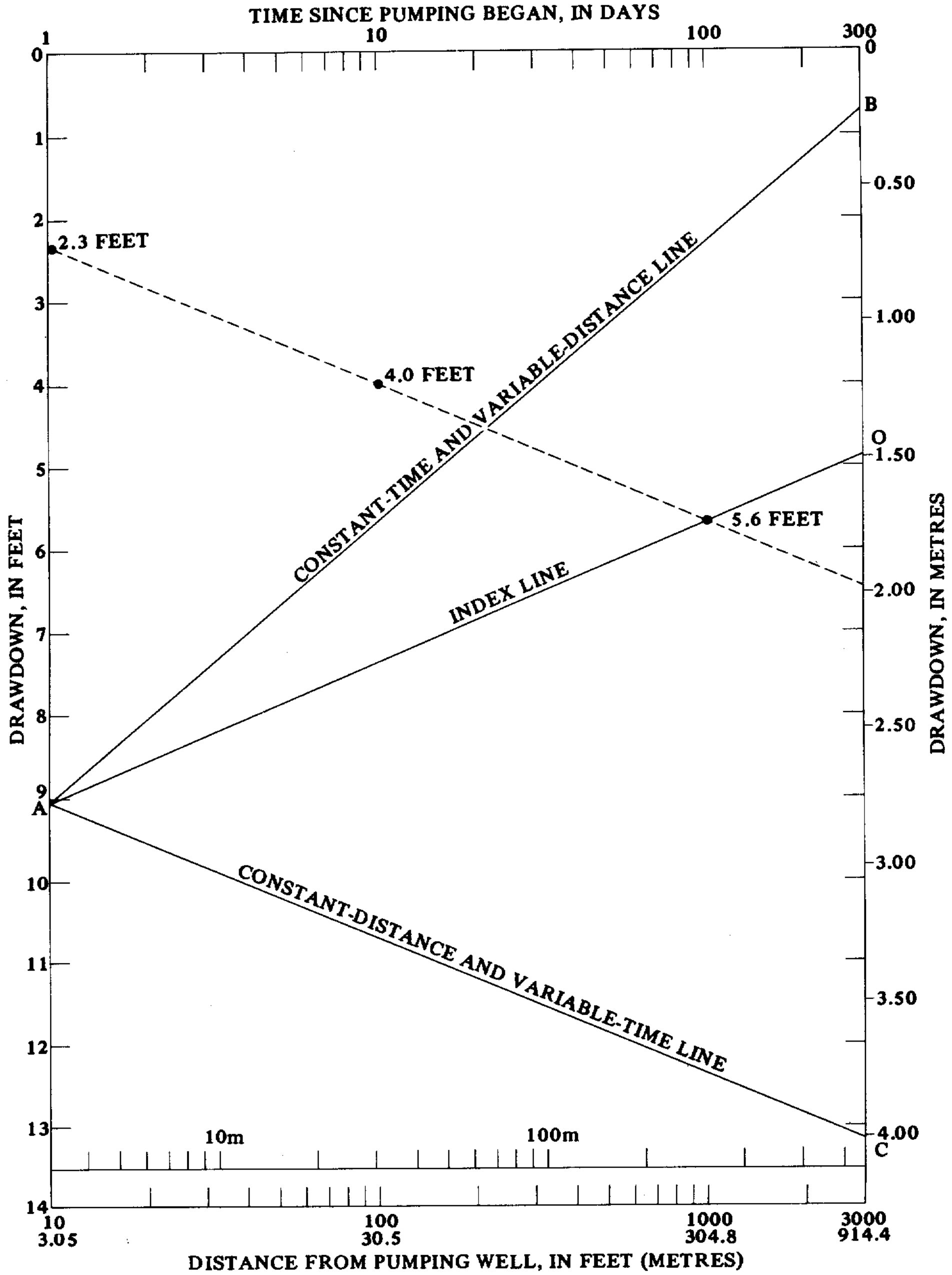
The effects of pumping at lower or higher rates than 200 gal/min (12.6 l/s) can be estimated easily because of the direct proportionality relationship between pumping rate and drawdown. Using the example given in figure 17, the drawdown after 1, 10, and 100 days at 20 gal/min (1.3 l/s) would be one-tenth of the values shown. Conversely, if a pumping rate of 400 gal/min (25.2 l/s) is used, the drawdown would be twice the values given by the graph.

Figure 17 should be of assistance to water managers in planning development of water-supply systems using the Munich aquifer. The graph can be used to select pumping rates and distances between pumping wells so as to reduce well interference and to avoid excessive drawdown. Well interference causes a decline in production from individual wells and increases the cost of pumping. In construction of the graph shown in figure 17, no attempt was made to correct the estimated drawdown values for the effects of impermeable aquifer boundaries or recharge. Wells located near the aquifer boundaries would have greater drawdowns than indicated by the graph. An increase in recharge induced by pumping would have the effect of lessening the amount of drawdown from those shown by the graph.

Based on an area of 19,200 acres (30 mi^2 or 77.7 km^2), an average thickness of 40 feet (12 m), and a long-term specific yield of 15 percent, about 1.1 million acre-feet (1.4 km^3) of water is available from storage in the Munich aquifer. Properly constructed wells penetrating the aquifer should yield as much as 500 gal/min (32 l/s; pl. 1).

Pembina River Aquifer

The most potentially productive glacial-drift aquifer in Pembina County is located in the valley of the Pembina River in Tps. 163-164 N., Rs. 53-56 W. A



EXPLANATION

TO DETERMINE THE DRAWDOWN FOR A CONSTANT DISTANCE AT VARIABLE TIMES–Draw a line parallel to line AC through the point of intersection of the constant distance and the index line AO. Points on the constructed line represent the drawdown at variable times as read on the left and top scales, respectively

TO DETERMINE THE DRAWDOWN FOR A CONSTANT TIME AT VARIABLE DISTANCES–Draw a line parallel to line AB through the point of intersection of the constant-time and the index line AO. Points on the constructed line represent the drawdown at variable distances as read on the left and bottom scales, respectively

FIGURE 17. —Theoretical time- and distance-drawdown graph for the Munich aquifer 4 miles (6 km) west of Munich.

small part of the aquifer is located in Cavalier County in T. 163 N., R 57 W. The aquifer underlies about 19 square miles (49 km^2) of Pembina County and about 1 square mile (3 km^2) of Cavalier County (pls. 1 and 2).

The Pembina River aquifer is as much as 35 feet (11 m) thick and has an average thickness of nearly 20 feet (6 m). The aquifer is confined between river silt at the top and fine-grained lake deposits beneath. In the vicinity of Walhalla the aquifer consists mostly of very shaly sand and gravel with interbedded silt and clay beds. Eastward from Walhalla the aquifer material progressively becomes more fine grained. Near Neche the aquifer is mostly fine sand and a large amount of silt. The aquifer material probably was deposited by the ancestral Pembina River at a time when the river had a greater competence than at present. The bed of the modern Pembina River is incised into the top of the aquifer from near Walhalla eastward to at least as far as Neche (pl. 3, in pocket).

Recharge to the Pembina River aquifer is mainly from precipitation that percolates through the overlying silt deposits. Recharge also occurs when the stage of the river rises and is higher than the water level in the adjacent aquifer.

Hydrogeologic sections on plate 3 show the stream-aquifer relationships at four locations between Walhalla and Neche. The Pembina River penetrates the top of the sand and gravel aquifer in each of the sections and the potentiometric surface in the aquifer is shown to be continuous with the stream surface.

Hydrographs of the stream and three wells in the aquifer about 4 miles (6 km) east of Walhalla are shown in figure 18. Analysis of figure 18 and section D-D′ on plate 3 indicates that just prior to spring melting in early April 1970, ground-water movement was toward and into the Pembina River. As the stream level rose sharply above the water level in the adjacent aquifer, the hydraulic gradient at the interface was reversed and water moved from the stream into the aquifer. Consequently the discharge of ground water into the stream ceased. However, ground water continued to move from the valley margins toward the stream, but its progress was blocked by the opposing gradient. As a result, the ground water that normally would have been discharged into the stream was temporarily stored. This is indicated by corresponding rises in the water level in the observation wells. The hydrographs show that during this period the stream rose about 15 feet (4.6 m) and smaller rises in ground-water levels occurred at increasing distances from the stream. Soon after the peak stream stage, the water in bank storage began to move back into the stream as a gradient toward the stream was reestablished.

Water levels continued to decline through the summer and fall months, and the discharge from the aquifer provided the base flow to the stream. Several sharp rises in stream stage that are shown in the record correspond to periods of heavy precipitation and are due to direct overland runoff. However, most of these events were of short duration and had no effect on the water level in the aquifer.

Because of the close relationship between ground water and surface water, management of the water resources in the Pembina River valley must consider the entire hydrologic environment. At the present time the city of Neche relies

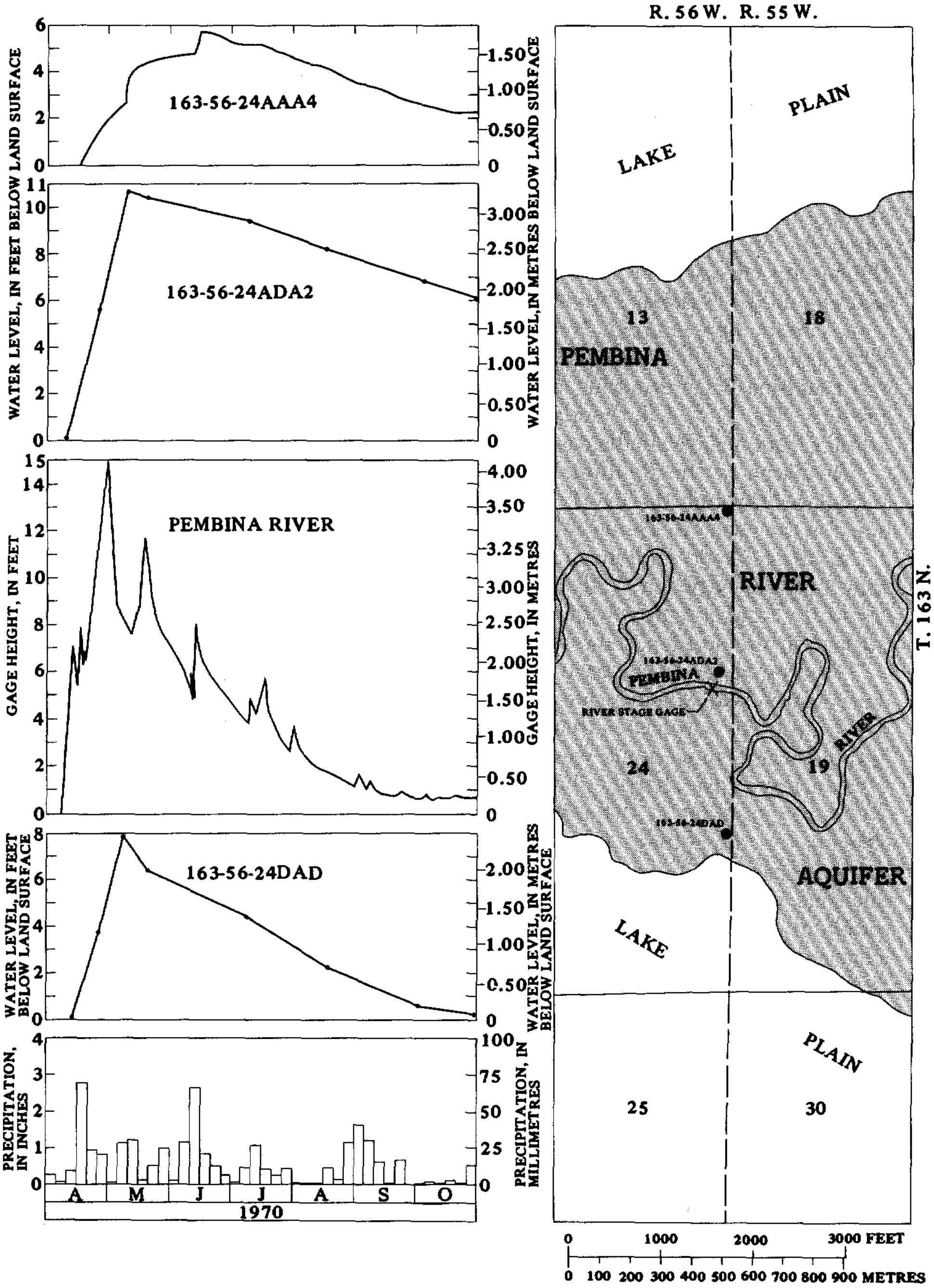


FIGURE 18. —Location of observation wells in the Pembina River aquifer 4 miles (6 km) east of Walhalla, and hydrographs showing ground-water and surface-water fluctuations from April through October 1970. Five-day precipitation at Walhalla.

on streamflow for its water supply, whereas the city of Walhalla uses the Pembina River aquifer for its source of water supply. Development of large-scale ground-water systems could cause a significant reduction of base flow of the stream. Conversely, large reservoirs on the stream above the aquifer to control floodflow could reduce the amount of recharge available to the aquifer.

Water from the Pembina River aquifer is predominantly very hard, fresh, and a calcium magnesium bicarbonate type; however, water in the Neche area tends to be a sodium bicarbonate type. The median concentration of iron is 350 ug/l in 11 chemical analyses. Other median concentrations are: sodium, 37 mg/l; sulfate, 129 mg/l; chloride, 27 mg/l; dissolved solids, 624 mg/l; and hardness, 416 mg/l. The water is used for domestic and public supplies even though the median values for iron and dissolved solids exceed the 1962 U.S. Public Health Service recommended drinking-water standards.

According to the classification for irrigation water proposed by the U.S. Salinity Laboratory Staff (1954), the water is generally in the medium- to high-salinity, low-sodium classes (C2-S1 and C3-S1).

An aquifer test was conducted on the Pembina River aquifer in July 1968 using Walhalla city well 163-56-29DBB, which is located about 1,000 feet (300 m) south of the Pembina River. The 39-foot (12-m) well was screened in the aquifer from 22 to 32 feet (6.7 to 9.8 m). The discharge from the well was maintained at 100 gal/min (6.3 l/s) for 25 hours. Water-level measurements were made in the production well and an observation well located 104 feet (31.7 m) south of the production well during both the drawdown and recovery phases of the test. Results of the test indicated a transmissivity value of about 2,500 ft^2/d (230 m^2/d) and a storage coefficient of about 0.001.

Based on these values of transmissivity and storage coefficient, table 5 was prepared to show the approximate drawdown effects a discharging well would have on water levels in the Pembina River aquifer at distances of 10 to 1,000 feet (3 to 305 m) and after 1 day to 1 year of continuous pumping. Although the table is based on a pumping rate of 100 gal/min (6.3 l/s), the effects of pumping at lower or higher rates can be estimated easily because of the direct relationship between pumping rate and drawdown. For example, pumping at 200

TABLE 5. — Theoretical drawdowns at various distances from a well pumping continuously at 100 gal/min (6.3 l/s) from the Pembina River aquifer near Walhalla

(Transmissivity 2,500 ft^2/d (230 m^2/d); storage coefficient 0.001)

	Drawdown, in feet					
	Distance from pumping well, in feet					
Time since pumping started	10	100	300	500	700	1,000
1 day	6.7	3.9	2.5	1.9	1.5	1.1
10 days	8.1	5.3	3.9	3.3	2.9	2.5
100 days	9.5	6.7	5.3	4.7	4.3	3.9
1 year	10.3	7.5	6.1	5.5	5.1	4.7

gal/min (12.6 l/s) would cause twice the drawdowns indicated in table 5 and pumping at 50 gal/min (3.2 l/s) would cause water-level drawdowns of only half of the values given. In calculating the data in table 5, no attempt was made to correct the estimated drawdowns for the effects of aquifer boundaries. A recharging boundary, such as the Pembina River, would cause the drawdown estimates obtained from table 5 to be too large. Whereas, an impermeable boundary would cause the drawdown estimates to be too small.

Based on an area of 20 square miles (12,800 acres or 52 km^2), average thickness of 20 feet (6 m), and a long-term specific yield of 15 percent, about 38,000 acre-feet (50 hm^3) of ground water is available from storage in the Pembina River aquifer. Properly constructed wells that fully penetrate the aquifer could yield as much as 250 gal/min (15.8 l/s; pl. 2).

Icelandic Aquifer

The Icelandic aquifer is the largest glacial-drift aquifer in the two-county area (pl. 2). The aquifer is more than 20 miles (32 km) long, as much as 9 miles (14 km) wide, and underlies about 82 mi^2 (210 km^2).

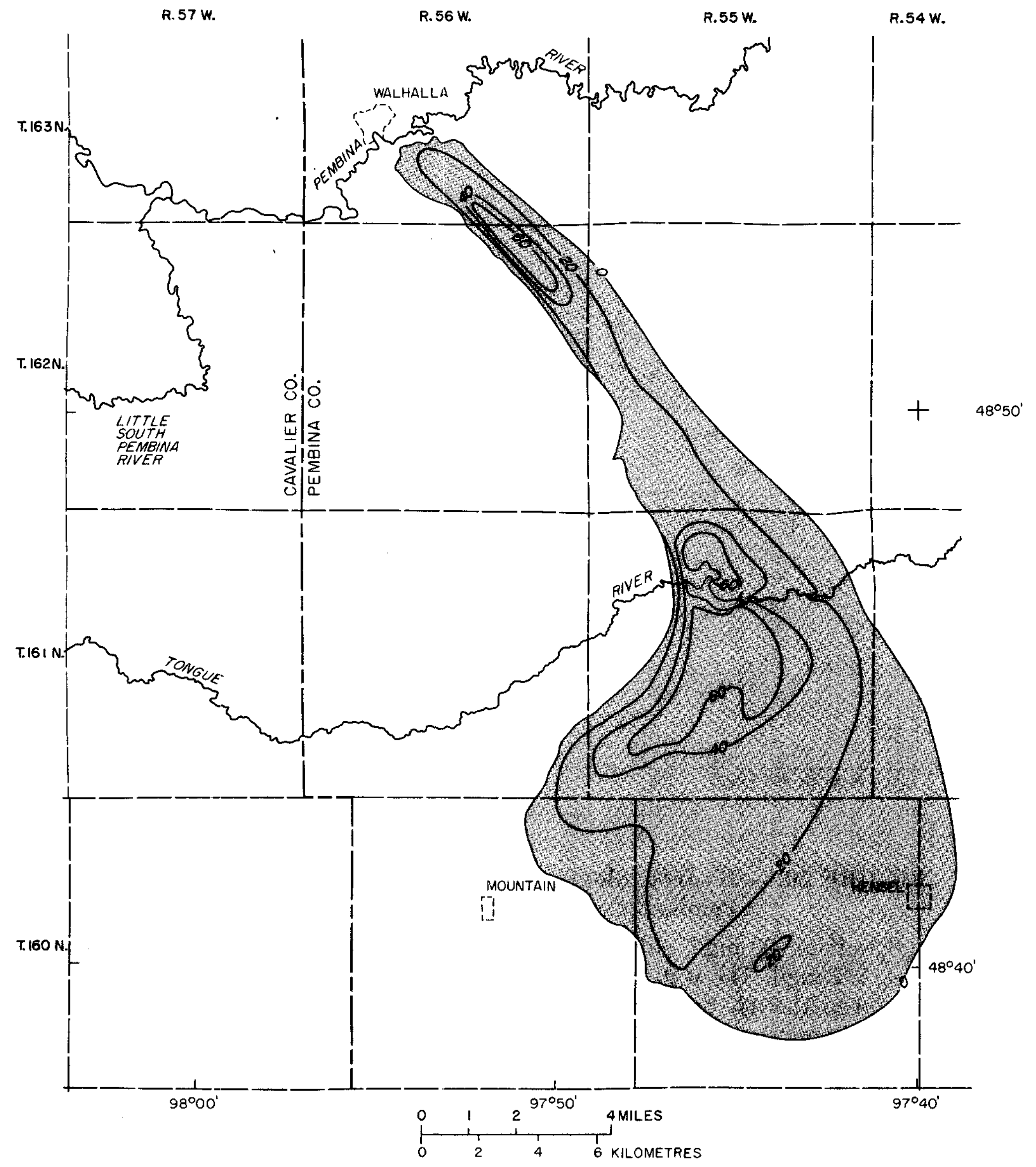
The Icelandic aquifer, which was named after Icelandic State Park, has a maximum saturated thickness of about 70 feet (21 m; fig. 19). The thickest parts are in and about sec. 22, T. 161 N., R. 55 W., and sec. 2, T. 162 N., R. 56 W. The aquifer consists mostly of very fine to medium sand interbedded with silt and clay. The aquifer, which is unconfined at the top and underlain by clay (fig. 20), generally becomes finer grained with increasing depth and from west to east.

The aquifer materials were deposited as a hooked spit in glacial Lake Agassiz by waves and currents that moved along the eastern edge of the Pembina delta. The delta deposits marked the edge of the glacial lake at that stage of its development and were the principal source of material that formed the spit. Because of its mode of formation, the material forming the Icelandic aquifer becomes finer grained from north to south and gradually changes from fine sand to silt near its eastern and southern edges.

Recharge to the Icelandic aquifer is mainly from precipitation that is received on the surface of the aquifer. Hydrographs from selected observation wells (fig. 21) show that recharge causes water levels to rise abruptly and usually reach a maximum height in the spring. Water levels generally are lowest in late winter because of the lack of recharge.

Discharge from the aquifer is mainly underflow into adjacent glacial lake deposits to the east, to flow into the Tongue River, to evapotranspiration, and to pumping from farm wells. About 100 farm wells tapped the aquifer in 1971, and collectively these wells probably pumped about 20,000 gal/d (80 m^3/d). This pumpage rate is far below the potential yield that is available.

Water from the Icelandic aquifer is predominantly very hard, fresh, and a calcium magnesium bicarbonate type. The median concentration of 17 chemical analyses of iron is 500 ug/l. Other median concentrations are: sodium, 4



EXPLANATION

▨ **ICELANDIC AQUIFER**

—50— **LINE OF EQUAL SATURATED THICKNESS—Interval 20 ft (6.10 m)**

FIGURE 19. —Saturated thickness of the Icelandic aquifer, Pembina County.

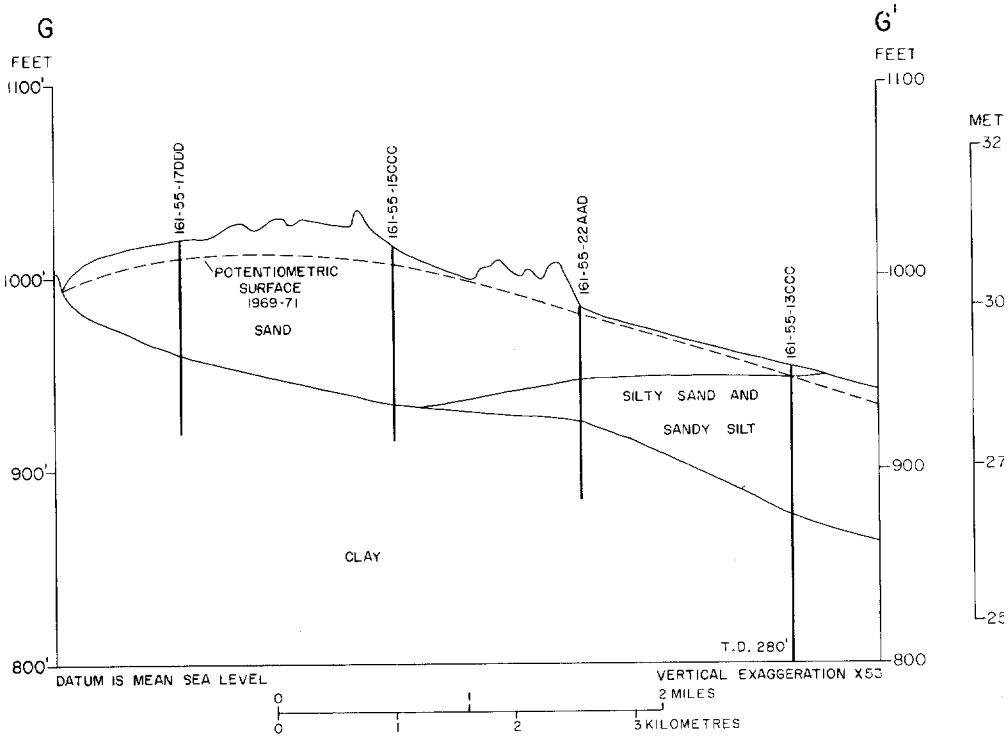


FIGURE 20. —Hydrogeologic section through the Icelandic aquifer, Pembina County.

mg/l; sulfate, 20 mg/l; chloride, 3 mg/l; dissolved solids, 251 mg/l; and hardness, 192 mg/l. The water should be acceptable for most domestic and public uses even though the median value for iron exceeds the 1962 U.S. Public Health Service recommended drinking-water standard.

According to the classification for irrigation water proposed by the U.S. Salinity Laboratory Staff (1954), the water is generally in the medium-salinity, low-sodium class (C2-S1).

An aquifer test was made in the Icelandic aquifer in July 1971. The production well, 161-55-22ABC9, about 6 miles (10 km) southwest of Cavalier, was drilled to a depth of 80 feet (24 m). The well was cased with 60 feet (18 m) of 8-inch (200-mm) casing and 4- to 8-slot screen was set from 60-80 feet (18-24 m). Seven observation wells, 161-55-22ABC1-7, were installed at distances ranging from 74 to 376 feet (23 to 115 m) from the production well. These wells were cased with 1¼-inch (32-mm) plastic pipe and were screened in the same interval as the production well. The aquifer material penetrated by the wells consisted of sand, silty and clayey sand, and contained silt and clay interbeds. Discharge from the production well was maintained at about 30 gal/min (2 l/s) for 1,500 minutes (25 hours).

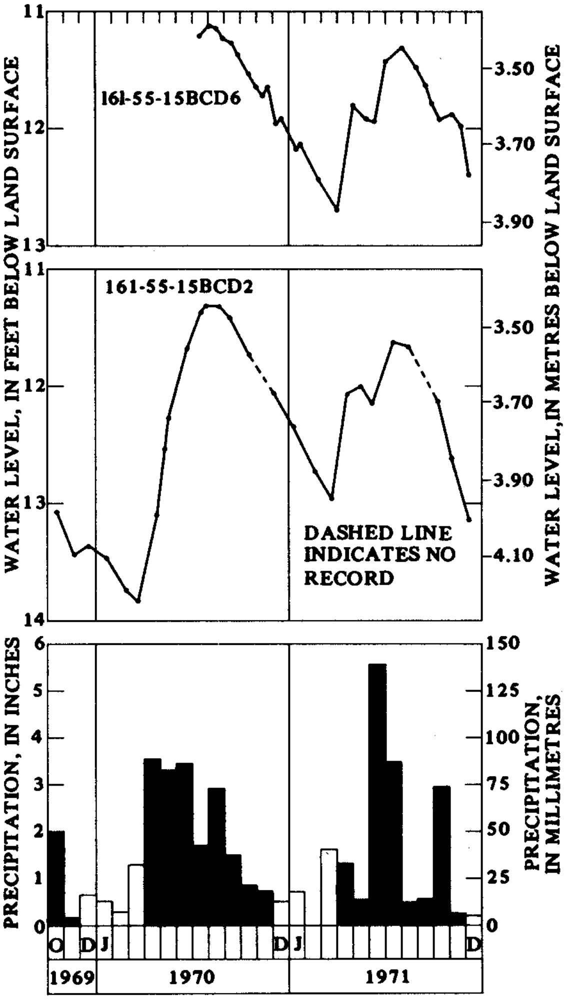


FIGURE 21. —Water-level fluctuations in the Icelandic aquifer and monthly precipitation at Cavalier, 1969-71. Snowfall periods are shown unshaded on precipitation graph.

Data gathered during the Icelandic aquifer test were analyzed according to methods developed by Theis (1935), Cooper and Jacob (1946), Stallman (1965), and Prickett (1965). The transmissivity at the aquifer test site was between 200 and 450 ft^2/d (20 and 42 m^2/d). A reliable storage coefficient could not be calculated because of the short length of the test.

The specific capacity of the production well at the end of the drawdown test was 0.8 (gal/min)/ft [0.2 (l/s)/m] of drawdown with a well efficiency of 80 percent.

Based on an area of 52,500 acres (210 km^2), average saturated thickness of 30 feet (9 m), and a specific yield of 15 percent, about 240,000 acre-feet (300 hm^3) of water is available from storage in the Icelandic aquifer. Based on test drilling and the aquifer test, properly constructed wells, fully penetrating the aquifer, could yield as much as 50 gal/min (3.2 l/s; pl. 2). The largest yield rate would be available where the saturated thickness is greatest (fig. 19).

Pembina Delta Aquifer

The Pembina delta consists of clay, silt, sand, and gravel deposited by the ancestral Pembina River where it flowed into glacial Lake Agassiz near Walhalla in eastern Cavalier and western Pembina Counties. Deposition of sediment was caused by the rapid reduction in current velocity at the confluence of the stream and lake water. The coarse particles settled out first; the finer material was carried further and eventually came to rest in deeper water. Much of the sediment was carried southward from the Pembina River gorge by lake currents. The delta presently is about 71 mi^2 (180 km^2) in area, but was once somewhat larger — as evidenced by the steep wave-cut northeastern edge of the deposit. Sediment eroded from this edge was redeposited as the spit deposit that forms the Icelandic aquifer.

The Pembina Delta aquifer is underlain by shale bedrock along its western margin and by glacial till and thick deposits of lake clay and silt to the east (fig. 22). The greatest known thickness of the delta sediments is about 170 feet (52 m) and the average thickness is nearly 100 feet (30 m). The thickness of the material increases rapidly from west to east.

The median grain size of the delta sediments decreases from west to east from gravel and very coarse sand to very find sand and silt (fig. 23). This gradation of median grain size is consistent with the increased distance of transport across the top of the growing delta.

Although the Pembina delta deposit extends over a large area and is as much as 170 feet (53 m) thick, only a small portion of this deposit is saturated with water. The saturated thickness ranges from 0 feet (0 m) to a little more than 50 feet (15 m) in the central part (fig. 23). The depth to the top of the zone of saturation (water table) ranges from less than 10 feet (3 m) in the southeastern part of the aquifer to as much as 150 feet (46 m) in the northeastern part (fig. 24).

Recharge to the Pembina Delta aquifer is mainly from precipitation that is received in the immediate area. The precipitation must, however, percolate through several tens of feet of sediment before reaching the water table in much of the area. Hydrographs of selected observation wells (fig. 25) show that where the water table is close to the land surface (161-56-22BCB) the water level responds to melting of the winter snowpack and to spring rains. In wells where the water table is many feet below land surface (162-56-20AAA) the water levels respond slowly to recharge and respond only to long-term trends in precipitation.

Ground-water movement through the aquifer is generally from west to east, as indicated by contour lines drawn on the water table (pls. 1 and 2).

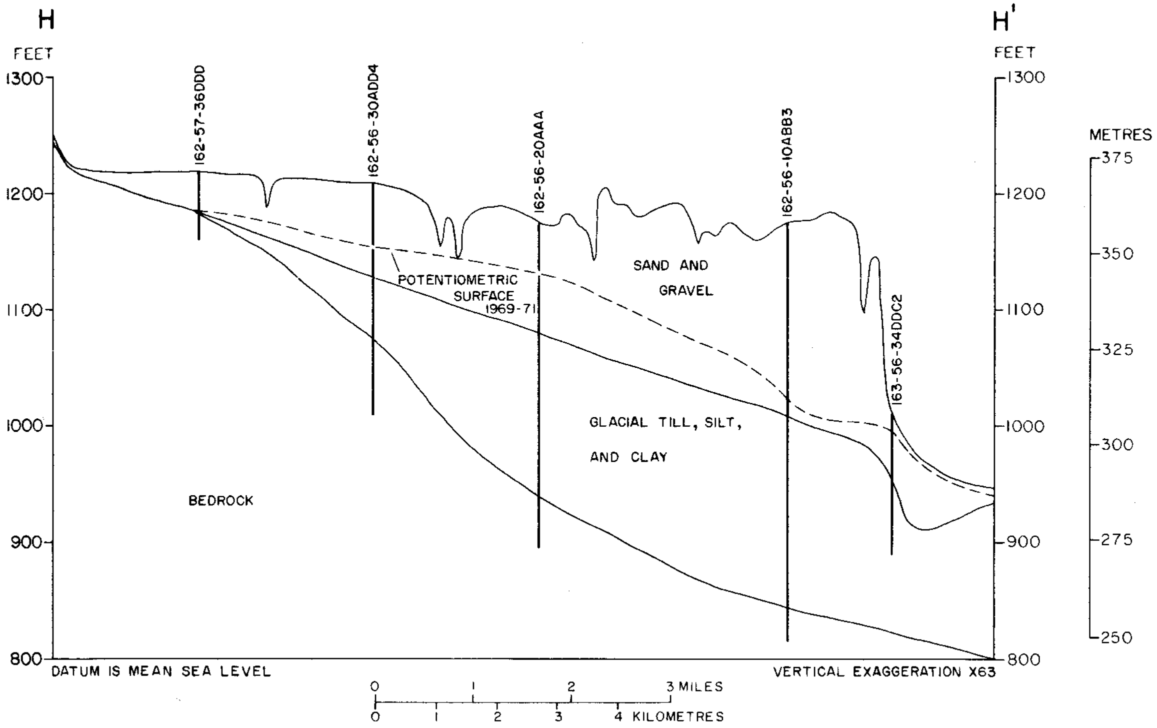
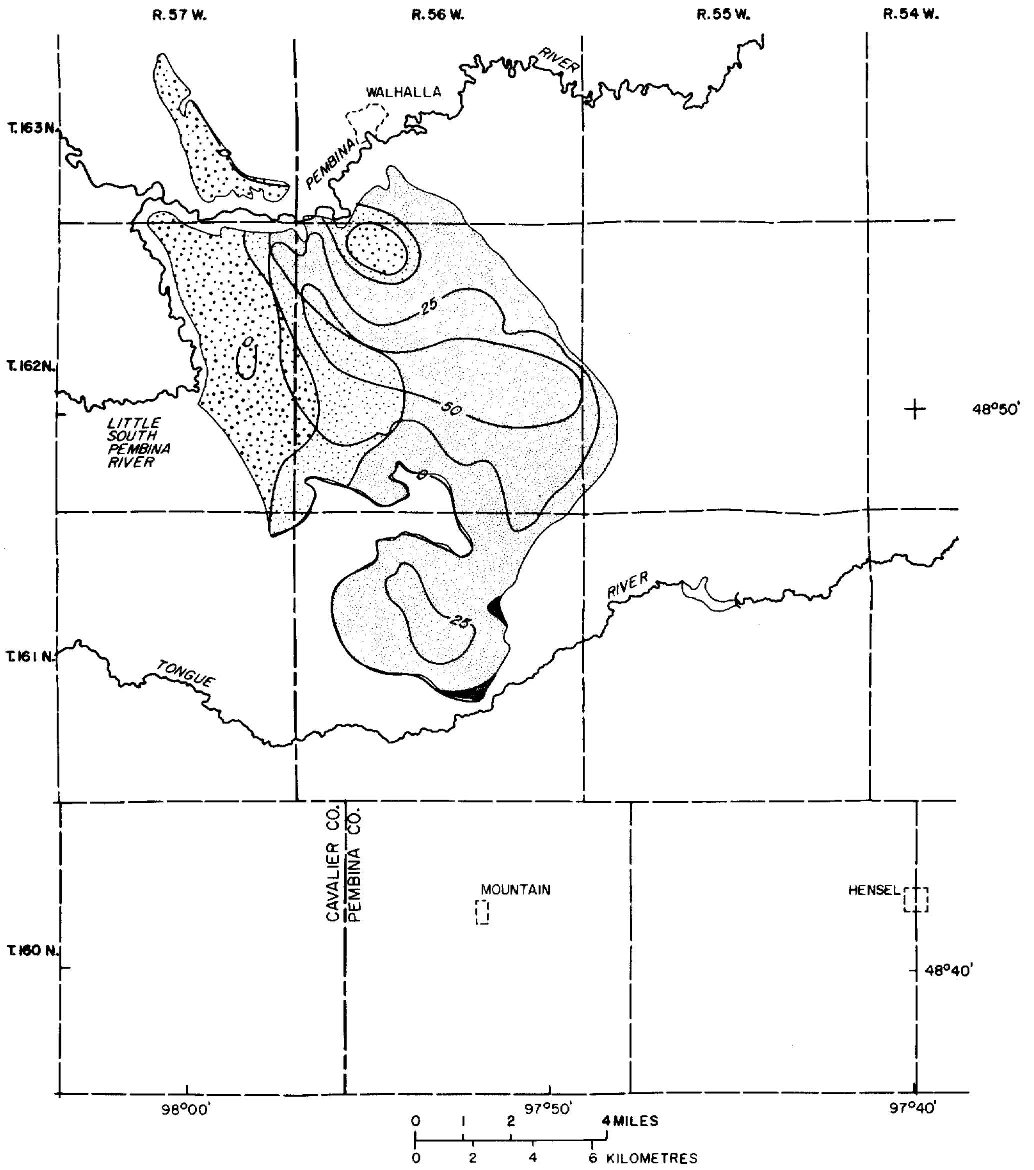


FIGURE 22. —Hydrogeologic section across Pembina Delta aquifer.



EXPLANATION

GRAIN SIZE REFERS TO THE WENTWORTH (1922) SIZE SCALE

▨ **Coarser than coarse sand**

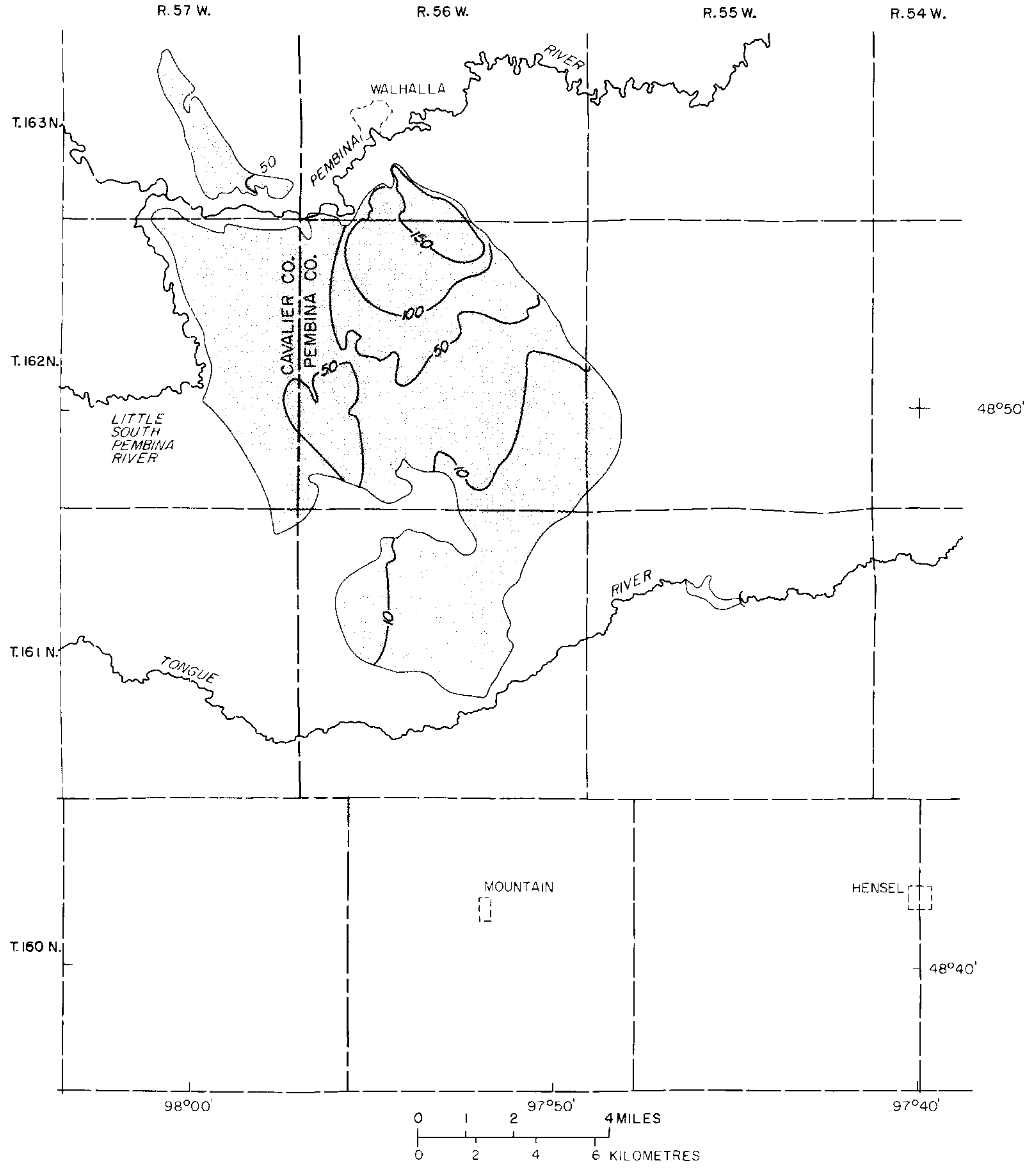
▨ **Coarse to medium sand**

░ **Medium to fine sand**

■ **Finer than fine sand**

—50— **LINE OF EQUAL SATURATED THICKNESS-Shows approximate saturated thickness. Interval 25 ft (7.62 m)**

FIGURE 23. —Median grain size and saturated thickness of the Pembina Delta aquifer material, Cavalier and Pembina Counties.



EXPLANATION

▨ PEMBINA DELTA AQUIFER

—50— LINE OF EQUAL DEPTH TO WATER–Interval is variable. Datum is land surface

FIGURE 24. —Depth to water in the Pembina Delta aquifer, Cavalier and Pembina Counties, 1969-71.

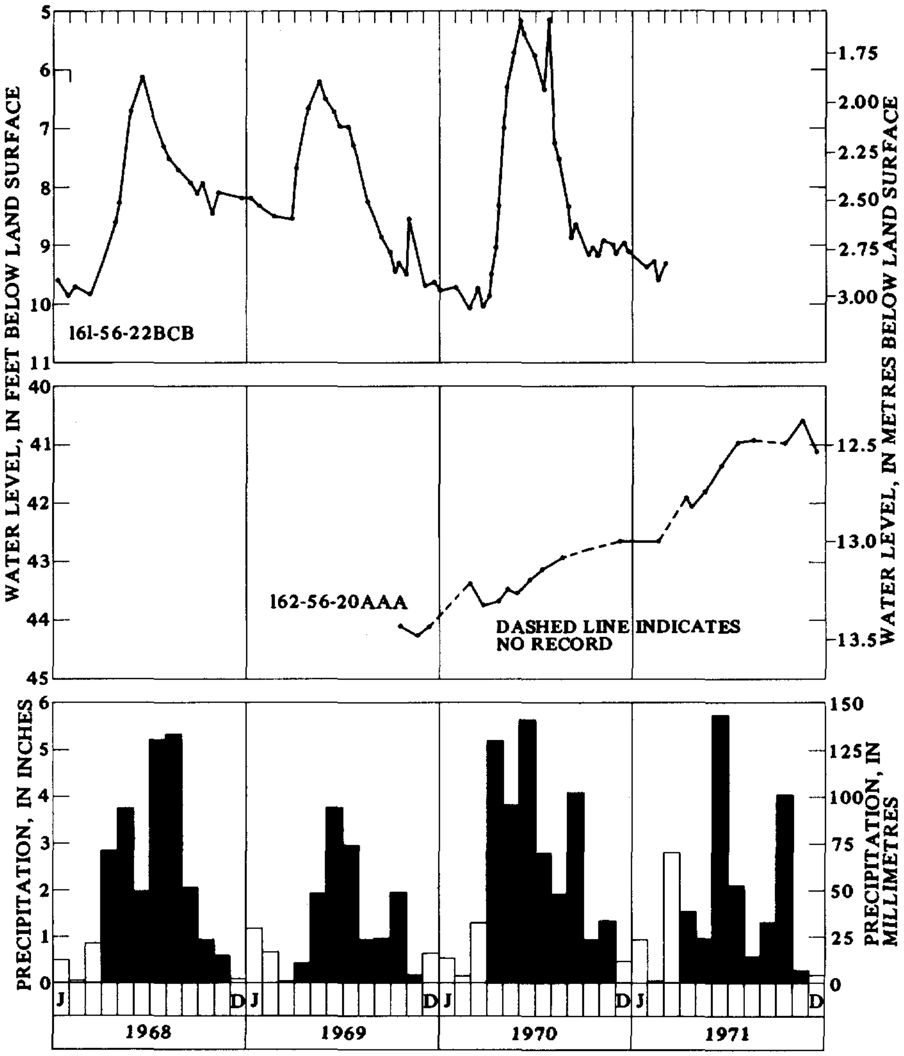


FIGURE 25. —Water-level fluctuations in the Pembina Delta aquifer and monthly precipitation at Walhalla, 1968-71. Snowfall periods are shown unshaded on preciptation graph.

Discharge of the ground water is mainly by seepage into the few streams that are entrenched into the aquifer, by springs along the margins of the aquifer, by evapotranspiration in areas where the water table is within about 10 feet (3 m) of the land surface, and by underflow into adjacent water-bearing material. Discharge from the aquifer by wells is small. Only about 30 farms used water from the aquifer in 1971 and collectively pumped about 6,000 gal/d (20 m^3/d).

Water from the Pembina Delta aquifer is predominantly very hard, fresh, and a calcium magnesium bicarbonate type. The median concentration of six chemical analyses of iron is 80 ug/l. Other median concentrations are: sodium, 14 mg/l; sulfate, 36 mg/l; chloride, 3 mg/l; dissolved solids, 342 mg/l; and hardness, 282 mg/l. The water is used for most domestic and public uses even though the concentration of iron in some of the analyses exceeds the 1962 U.S. Public Health Service recommended drinking-water standards.

According to the classification for irrigation water proposed by the U.S. Salinity Laboratory Staff (1954), the water is generally in the medium-salinity, low-sodium class (C2-S1).

Based on an area of 37,000 acres (150 km^2), average saturated thickness of 25 feet (7.6 m), and a specific yield of 15 percent, about 140,000 acre-feet (1.7 hm^3) of water is available from storage in the Pembina Delta aquifer. From test drilling and interviews with well owners, properly constructed wells that fully penetrate the aquifer could yield as much as 50 gal/min (3.2 l/s). No ground water is available from about 20 percent of the Pembina delta deposit where it does not contain sufficient thicknesses of saturation.

Hamilton Aquifer

The Hamilton aquifer underlies the city of Hamilton in east-central Pembina County (pl. 2) and has an areal extent of about 32 mi^2 (83 km^2). The aquifer, which is composed of glacial melt-water deposits of sand and gravel, is underlain by till and overlain by deposits of clay and silt from Lake Agassiz. Thickness of the sand and gravel ranges from about 1 foot (0.3 m) to about 60 feet (18 m) and averages about 25 feet (8 m).

Few data are available on the extent and thickness of the aquifer. Test hole 161-53-2AAA penetrated 29 feet (8.8 m) of fine- to coarse-grained sand from 119 to 148 feet (36.3 to 45.1 m). Test hole 161-52-7DDD penetrated 59 feet (18 m) of very fine to fine-grained clayey and silty sand between 91 and 160 feet (27.7 and 48.8 m). Test hole 162-53-26AAA penetrated 11 feet (3.4 m) of gravelly sand from 132 to 143 feet (40.2 to 43.6 m), 7 feet (2.1 m) of very fine to medium-grained sand from 146 to 153 feet (44.5 to 46.6 m), and 27 feet (8.2 m) of sandy gravel from 153 to 180 feet (46.6 to 54.9 m). Sand and gravel deposits in other test holes in the area were either too thin or contained too much fine-grained material to be considered a significant part of the Hamilton aquifer.

The Hamilton aquifer is overlain by thick, fine-grained glacial deposits and recharge to it probably is derived largely from upward migration of water from aquifers in the underlying rocks, although some may migrate laterally from the Dakota aquifer and the till.

The potentiometric surface in the aquifer is at or slightly above land surface. The water levels in observation wells 161-53-2AAA and 162-53-26AAA were 2 and 4 feet (0.6 and 1.2 m) above land surface, respectively, in 1971. Because the water level in the aquifer is higher than the water table in the overlying glacial lake deposits, ground water in the Hamilton aquifer discharges into the overlying material. Few, if any, farm wells tapped the aquifer in 1971.

Water from the Hamilton aquifer is more highly mineralized than water from any other aquifer in the counties, except the Dakota and deeper bedrock aquifers from which much of the water in the aquifer probably is derived. Water from wells 161-53-2AAA and 162-53-26AAA was very hard, very saline, and was a sodium chloride type with a dissolved-solids concentration of more than 11,000 mg/l. With the exception of iron and fluoride, all of the chemical constituents in the water were present in concentrations exceeding the maximum recommended by the U.S. Public Health Service (1962a) for drinking water.

Based on an area of 20,500 acres (83 km^2), average saturated thickness of 25 feet (7.6 m), and a specific yield of 15 percent, the Hamilton aquifer contains about 150,000 acre-feet (1.8 hm^3) of water in available storage. Based on test drilling data, wells tapping the Hamilton aquifer could produce up to 50 gal/min (3.2 l/s). Although the water is generally not suitable for most present needs in the area, the water could be used for fire fighting and cleansing purposes such as potato washing.

Minor Glacial-Drift Aquifers

Aquifers in the Lake Agassiz beach deposits.–Many of the beaches of Lake Agassiz consist of long, narrow deposits of sand and gravel. Test holes drilled into these deposits show that they are thin and overlie till or lake silt and clay having low hydraulic conductivity. In the two counties the average thickness of the beach deposits is about 10 feet (3 m), but the thickness may be as much as 20 feet (6 m). Many farms are dependent on the beach deposits for their water supply.

Direct infiltration of precipitation is probably the only source of recharge to these aquifers. The water table may fluctuate 3 or 4 feet (0.9 or 1.2 m) annually, and during prolonged dry periods, wells tapping these aquifers may go dry.

Because the water table in the beach deposits is shallow, usually less than 10 feet (3 m) below land surface, substantial quantities of ground water are discharged by evapotranspiration. Also, large quantities of ground water are discharged by springs and seeps. Precipitation infiltrating through the beach deposits moves downward and laterally along the contact with the underlying till or clay toward seepage zones along the steeper east-facing slopes.

Water in the beach aquifers is fresh and generally is satisfactory for use on lawns, gardens, and for household use. Contamination of water in the beach aquifers from barnyard sources and domestic waste-disposal systems can occur, however, because of the shallow depth of the water table.

The amount of water available to wells tapping beach aquifers is dependent upon the storage capacity of the deposits, the total discharge that can be salvaged, and the amount of recharge that can be induced to the aquifers. Using conventional well-construction techniques, most wells in these deposits will not yield more than about 10 gal/min (0.6 l/s).

Aquifers in the Lake Agassiz deposits.–In the eastern and central parts of Pembina County silt deposits that accumulated in glacial Lake Agassiz form an extensive but low-yield aquifer. The aquifer has a maximum thickness of about 35 feet (11 m) and is underlain by a very plastic lake clay that is as much as 150 feet (46 m) thick.

Water in the silt deposits is unconfined and, in most places, the water table is only a few feet below the land surface. Minor amounts of precipitation upon the surface of the deposits often result in abrupt rises of water levels because of the very low specific yield.

Water from the Lake Agassiz silt deposits is very hard, slightly saline, and is a calcium sulfate to sodium sulfate type. The median concentration of 24 chemical analyses of iron is 280 ug/l. Other median concentrations are: sodium, 52 mg/l; sulfate, 388 mg/l; chloride, 57 mg/l; dissolved solids, 1,280 mg/l; and hardness, 900 mg/l. Water from about one in every six wells has a dissolved-solids concentration of more than 3,000 mg/l. The depths of the 24 wells sampled range from 9 to 33 feet (3 to 10 m) and have a median value of 20 feet (6 m).

Contamination of water in the silt deposits from barnyard sources and domestic waste-disposal systems can occur because of the shallow depth of the water table and the close connection between ground water and surface water. More than half of the wells tapping the silt deposits yield water with nitrate greater than the maximum recommended under the 1962 U.S. Public Health Service drinking-water standards. These standards set 45 mg/l as the upper limit of nitrate in drinking water. The median value from the silt aquifers in the study area is 87 mg/l and is as high as 593 mg/l. All wells sampled were near farmhouses and high concentrations of nitrate probably indicate contamination by sewage or other oganic material and the ingestion of such water can be poisonous to both man and farm animals (National Academy of Sciences — National Academy of Engineering, 1972).

Till and undifferentiated sand and gravel aquifers. – Many wells in Cavalier and Pembina Counties tap deposits of till. Most of these wells failed to penetrate any significant thickness of sand or gravel, but the wells yield sufficient water to meet the needs of small farm operations. In some places the water is produced from thin sand and gravel lenses interbedded with the till, in other places the water comes from joints and fractures in the till.

Many test holes drilled during the study penetrated small bodies of sand and gravel that apparently are isolated in the till. Description of each of these small aquifers is impractical, but because they may be locally important sources of ground water, the aquifer interval and the total thickness of the aquifer material are shown in plates 1 and 2. Because these aquifers are rather restricted, both in lateral and vertical extent, only thicknesses of 10 feet (3 m) or more are shown on the plates.

Till is exposed at the land surface in nearly all parts of Cavalier County, except the extreme northeastern part (Arndt, 1975, pl. 1). The maximum known thickness is in test hole 162-63-22AAA where till was penetrated from the surface to a depth of 370 feet (113 m). The till was interbedded with 11 feet

(3 m) of gravel from 26 to 37 feet (8 to 11 m) and 43 feet (13 m) of very clayey sand from 37 to 80 feet (11 to 24 m).

The till and undifferentiated sand and gravel aquifers are covered with thick lake deposits in all parts of Pembina County except in a narrow band along the Cavalier County border south of State Highway 5. The maximum known thickness of till penetrated in Pembina County was 307 feet (93.6 m) in test hole 160-54-13AAA. The till, which extended from 140-447 feet (42.7-136 m) below land surface, was interbedded with very clayey and silty sand in the intervals from 147 to 161 feet (44.8 to 49.1 m) and 169 to 278 feet (51.5 to 84.7 m); gravel was present in the interval from 278 to 285 feet (84.7 to 86.9 m). Although the aggregate thickness of sand and gravel penetrated in this test hole was 130 feet (39.6 m), the aquifer could not be correlated with confidence to any other test hole in the area. An observation well installed in the test hole and screened from 257 to 263 feet (78.3 to 80.2 m) showed the water to be very saline and a sodium chloride type with dissolved solids of 22,900 mg/l.

Wells that tap jointed or fractured till yield greater quantities of water than those that tap unjointed and unfractured till; however, well yields greater than about 2 gal/min (0.1 l/s) should not be expected. Yields of wells tapping sand and gravel within the till may exceed 100 gal/min (6.3 l/s) in deposits such as those found in Cavalier County at 162-63-22AAA and in Pembina County at 160-54-13AAA. Test drilling has shown, however, that such deposits are discontinuous and are highly variable in grain size over relatively short distances. Yields of most wells tapping sand and gravel in the till deposits generally do not exceed 10 gal/min (0.6 l/s).

Records of water levels in wells tapping the till aquifers commonly show large fluctuations. Well 159-62-21AAA2 (fig. 26), which is 20 feet (6 m) in depth, responded quickly to recharge from melting snow and ice in the spring of 1971. However, water levels in the deeper till-associated sand and gravel deposits respond more slowly because they are not recharged as rapidly as the till aquifers near the surface. For example, observation well 160-54-13AAA showed a water-level change of only 0.48 foot (0.15 m) from July 22, 1970, to December 7, 1971.

Chemical quality of water from till aquifers differs widely from one location to another. Samples of water collected from wells tapping these aquifers had dissolved-solids concentrations ranging from fresh waters of 544 mg/l to brines with 42,800 mg/l. This wide difference of water quality is mainly due to variations in sources of recharge and hydraulic connection with other aquifers.

Median concentrations of selected chemical constituents in water from till aquifers in Cavalier and Pembina Counties are compared in table 6. These data show that the till aquifers in Pembina County yield more highly mineralized water than in Cavalier County. In both counties, however, the median concentrations of iron, sulfate, chloride, and dissolved solids exceed the 1962 U.S. Public Health Service recommended standards for drinking water. Also, the water is very hard.

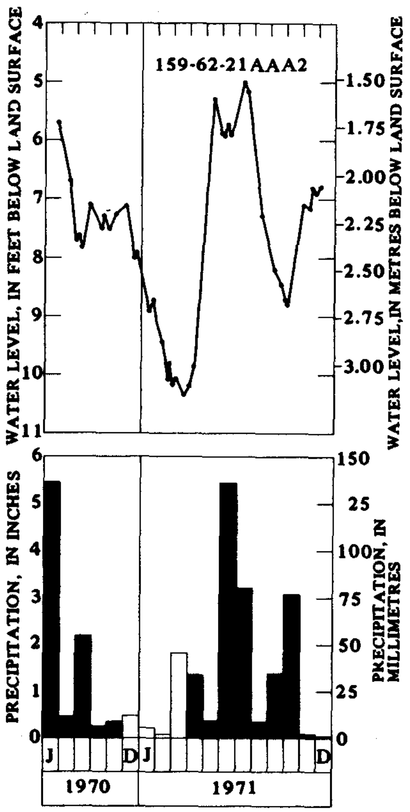


FIGURE 26. —Water-level fluctuations in a till aquifer and monthly precipitation at Munich, 1970-71. Snowfall periods are shown unshaded on precipitation graph.

TABLE 6. — Median concentrations of selected chemical constituents in water from till aquifers

(Concentrations in milligrams per litre)

Constituent	Cavalier County (16 analyses)	Pembina County (15 analyses)
Iron (Fe)	0.4	4
Sodium (Na)	332	694
Sulfate (SO_4)	406	460
Chloride (Cl)	135	2,820
Dissolved solids	1,430	6,130
Hardness (Ca, Mg)	418	1,980

REGIONAL GROUND-WATER FLOW SYSTEM AND GEOCHEMICAL RELATIONS

Cavalier and Pembina Counties are located near the eastern edge of a large and complex regional ground-water flow system. The flow system appears to be quite similar to the one in south-central Saskatchewan that Meyboom (1966) has described as the Prairie Profile. By definition, the Prairie Profile consists of a central topographic high bounded at either side by an area of lower altitude. Geologically, the Prairie Profile is made up of two layers — the upper layer having a much lower hydraulic conductivity than the lower layer.

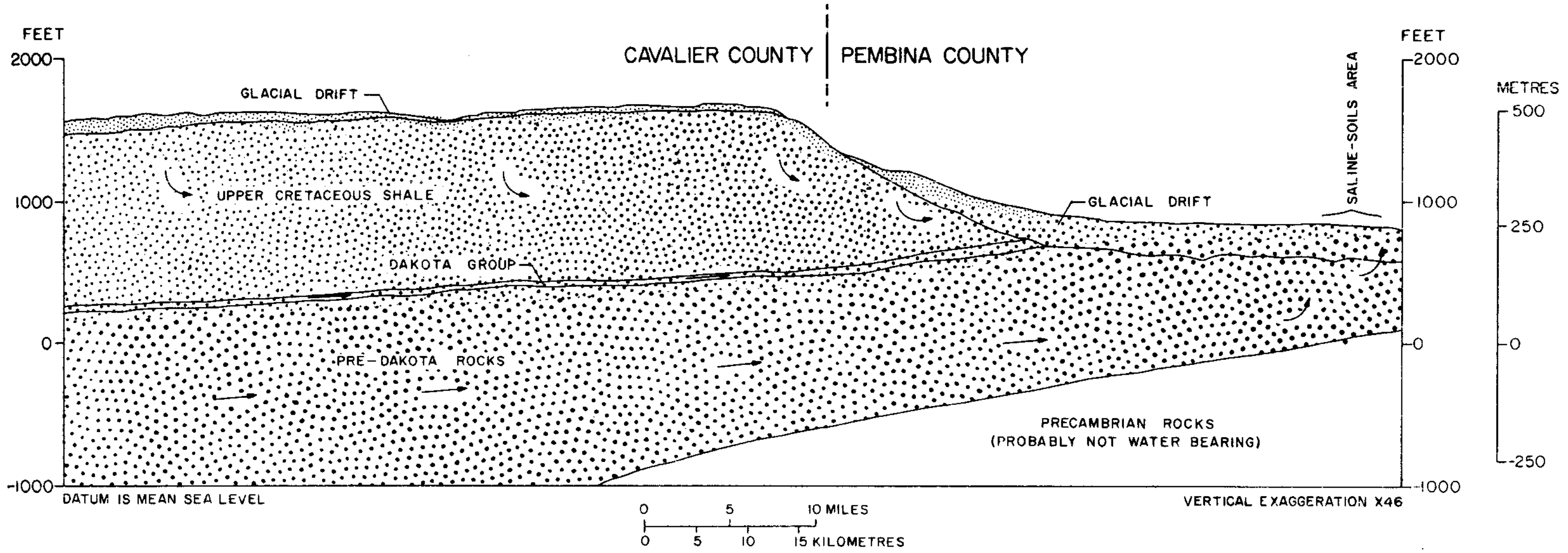
Figure 27 illustrates the ground-water flow system operating in Cavalier and Pembina Counties. An area of recharge to the flow system is in Cavalier County where ground water is moving vertically downward through the glacial drift and the Upper Cretaceous shale. This recharge area is characterized by wells having decreasing heads with increasing depth, as described in the discussion of potentiometers installed in the Pierre Formation at 159-62-21AAA, 161-59-22BBB, and 162-57-27CDB (p. 26). Vertical head loss through the glacial drift and Upper Cretaceous shale to the Dakota Group in Cavalier County is between 500 and 700 feet (150 and 210 m).

In the more permeable strata of the Dakota Group and pre-Dakota rocks (fig. 27), ground-water flow becomes more lateral than in the overlying shale units. Because heads in the Dakota aquifer slope from west to east, the flow of ground water is to the east. Information on head distribution in the pre-Dakota rocks is unavailable, but ground-water flow in these rocks presumably is also towards the east.

Eastern Pembina County is an area of ground-water discharge, mostly from Ordovician rocks (fig. 7), as evidenced by the presence of saline soils. The saline-soils area forms a north-south band that extends from near Drayton almost to Pembina, a distance of about 26 miles (42 km), and reaches a width of at least 6 miles (10 km) east of Hamilton. Salinity in these soils is caused by evaporation near the surface of highly mineralized ground water. This leads to the accumulation of readily soluble salts in the soil. Soils of this type are sometimes referred to as "ground-water soils" (Meyboom, 1966). Strongly saline soils are very poor to unsuitable for cropland and are of limited value for pastureland. Doering and Benz (1972) have described a method to improve saline soils in eastern Grand Forks County by controlling the discharge of saline ground water.

The discharge area of saline ground water is also characterized by several small saline lakes. Well 162-51-31AAA is located near one of these lakes and yields water with a dissolved-solids concentration of about 53,000 mg/l.

Regional ground-water flow systems and related geochemical variations are discussed in more detail by Maclay and Winters (1967) and Charron (1962, 1969). Maclay and Winters discussed ground water in an adjacent area of Minnesota whereas Charron described ground water in south-central Manitoba. Kelly and Paulson (1970) and Downey (1973) described briefly the flow systems and associated water-quality transformations in Grand Forks, Nelson, and Walsh Counties.



EXPLANATION

- ░ **Fresh to slightly saline water (0-3000 mg/l dissolved solids)**
- ▒ **Moderately saline to very saline water (3000-35,000 mg/l dissolved solids)**
- ▓ **Brine (over 35,000 mg/l dissolved solids)**
- → **Inferred direction of regional ground-water flow**

FIGURE 27. —Generalized regional ground-water flow system and related variations in geochemical characteristics of water, Cavalier and Pembina Counties.

The general chemical changes that occur as the ground water moves eastward beneath Cavalier and Pembina Counties are shown in figure 27. The water in the shallow near-surface deposits of Cavalier and western Pembina County is generally fresh to slightly saline. As the water moves downward and to the east it dissolves mineral matter and increases in salinity. Water in the Upper Cretaceous shale and Dakota Group is predominantly moderately saline to very saline; water in the pre-Dakota strata is mostly brine.

UTILIZATION OF GROUND WATER

The residents of Cavalier and Pembina Counties are largely dependent on ground water for their domestic and stock water needs. Using 1970 population figures, about 11,200 people, or 60 percent of the two-county population, rely on ground water for their water needs. About 83 percent of the residents using ground water have self-supplied systems and 17 percent depend on public-supply systems. Five communities — Cavalier, Drayton, Langdon, Neche, and Pembina — obtain water from surface sources. In addition, about 2,000 people use water hauled from these communities because ground-water supplies are inadequate or too highly mineralized at their residences. Neche also supplies water to two Canadian communities.

Self-Supplied Domestic and Stock Water Systems

Most farm units in the two-county area have at least one well for their domestic and livestock uses, but no records are available to determine accurately the quantity of water used. The following table shows only an approximation of the quantity of water used in 1970.

Estimated ground-water pumpage for domestic and livestock supplies in Cavalier and Pembina Counties, 1970

Use	Individual requirements (gal/d)	Population	Pumpage (gal/d)
Domestic, self-supplied	[1]40	11,200	448,000
Cattle and calves	15	[2]39,000	585,000
Milk cows	35	[2]2,000	70,000
Hogs	2	[2]15,000	30,000
Sheep	1.5	[2]10,000	15,000
Horses	10	[2]600	6,000
Poultry	.04	[2]15,000	600
Total			[3]1,154,600

[1] Average per-person use in Cavalier and Pembina Counties based on public-supply data.

[2] Based on U.S. Bureau of the Census (1971b) data, rounded.

[3] Equivalent to 1,290 acre-feet (1.59 hm^3) per year.

The quantities in the table may be somewhat higher than the amount of ground water used because some farms are vacant during the winter and some livestock get part of their water from ponds or sloughs.

Public Water Supplies

Mountain

The city of Mountain, southwestern Pembina County, obtains water from two wells, which are finished in Lake Agassiz beach deposits at 160-56-17AAA and 16BDA. A partial analysis of water from 160-56-17AAA shows it to be very hard (476 mg/l) and a calcium bicarbonate type with a specific conductance of 656 micromhos per centimetre at 25°C. The nitrate in this 23-foot (7-m) well was 11 mg/1, indicating possible contamination from organic material.

Pumpage records are not kept at Mountain but the supply is adequate for the 146 residents (1970 census) of the city. The wells probably are pumped at an average rate of about 5,000 gal/d (20 m^3/d). Akin (1946, p. 18) concluded that a water supply of at least 30,000 gal/d (110 m^3/d) could be developed from the beach deposits about half a mile west of the city. This quantity should be adequate for the foreseeable future.

Osnabrock

The city of Osnabrock, southeastern Cavalier County, obtains water from two wells in the Pierre aquifer. These wells (160-58-20ABB1 and 20ABB2) are 60 and 90 feet (18 and 27 m) deep, respectively, and reportedly are capable of supplying 10,000 gal/d (40 m^3/d), although the average use is about 6,000 gal/d (20 m^3/d). The wells are relatively new (drilled in 1968 and 1969) and should be adequate to supply the basic water needs of the 255 residents (1970 census) for many years.

Water pumped by the Osnabrock wells is soft (46 mg/l) and a sodium bicarbonate sulfate type with a dissolved-solids concentration of about 800 to 1,000 mg/l. Only the dissolved-solids concentration exceeds the 1962 U.S. Public Health Service recommended drinking-water standards. Because the Pierre aquifer is covered by many feet of fine-grained glacial till, there is little possiblity of contamination of the water supply from surface sources.

Additional water supplies could be developed from the Pierre aquifer if the need develops in the future. New wells should be spaced at distances of at least 1,000 feet (300 m) in order to reduce the effects of well interference. Well logs from eight sites within a 3-mile (5-km) radius of Osnabrock failed to locate any significant sand and gravel deposits that could be utilized by the city. Well 160-58-31BCC, located 3 miles (5 km) southwest of the city, penetrated 20 feet (6 m) of shaly sand, but only 8 feet (2 m) of the material was saturated with water. The well was pumped at 22 gal/min (1.4 l/s) and had a specific capacity of about 0.3 (gal/min)/ft [0.6 (l/s)/m]. Most of the production probably came from the Pierre aquifer rather than the sand.

Walhalla

The city of Walhalla (population 1,471 in 1970) is supplied by three wells, 163-56-29ABB, 29ABD, and 29DBB; these are city wells 1, 2, and 3, respectively. The wells obtain water from the Pembina River aquifer from depths ranging from 25 to 35 feet (8 to 11 m) and have a combined capacity of 300,000 gal/d (1,100 m^3/d). The average daily use in 1970 was about 97,000 gallons (370 m^3). Water use in the winter is higher, averaging about 113,000 gal/d (430 m^3/d), due to potato washing. The city also provides water for hauling to outlying places.

Each of the city wells yields very hard water. The water is a calcium bicarbonate type and the dissolved-solids concentration ranges between 600 and 800 mg/l, which exceeds that recommended by the U.S. Public Health Service drinking-water standards.

Additional ground-water supplies could be developed from the Pembina River aquifer if required. Undoubtedly much of the water pumped from the existing wells is derived from induced infiltration from the Pembina River. Ground-water supplies should be adequate for at least as long as the river continues to flow. However, no flow was recorded at the U.S. Geological Survey stream-gaging station at Walhalla on 230 days in the 1940 water year, 145 days in 1941, 88 days in 1953, 3 days in 1959, 30 days in 1961, 84 days in 1962, and 52 days in 1963.

Irrigation

A variety of factors influence the suitability of an area for irrigation, but probably the most important is an adequate supply of suitable quality water. Concurrently with the present investigation, the U.S. Bureau of Reclamation conducted a reconnaissance of parts of Cavalier and Pembina Counties to determine the suitability of the land for irrigation. Their findings show that most of western Pembina County and a small part of extreme northeastern Cavalier County are underlain by soils of acceptable drainage and texture to be used for irrigation. These areas generally coincide with the Icelandic, Pembina Delta, and Pembina River aquifers. The aquifers could provide water of suitable quality for irrigation. However, a sufficient quantity of water may not be available to support a large-scale irrigation program because the maximum yield for a well in the most productive part of these aquifers is estimated to be only 250 gal/min (15.8 l/s). Irrigation wells typically must produce at least 500 gal/min (32 l/s). A battery of large-diameter wells in these aquifers may provide adequate quantities of ground water to support irrigation.

According to the 1969 census of agriculture (U.S. Bureau of the Census, 1971b), only one farm in the two counties practiced irrigation. This farm pumped 54 acre-feet (0.07 hm^3) of water to irrigate 30 acres (12 hm^2).

SUMMARY AND CONCLUSIONS

The nature and distribution of rock material, together with topography and drainage, control the distribution of ground-water resources in Cavalier and Pembina Counties.

The distribution, thicknesses, and lithologies of formations below the Dakota Group are known only from a relatively few exploratory tests and little is known of their water-yielding potential. The water in these formations is probably saline to brine. Because of their great depth, their probable water quality, and the availability of other sources of supply, pre-Dakota formations have not yet been fully explored for water.

Dakota aquifer wells in Pembina County have artesian heads ranging from within a few feet of land surface to about 200 feet (61 m) below land surface. Heads in Cavalier County average about 600 feet (180 m) below land surface. The Dakota has not been extensively explored as an aquifer because of its relatively great depth below land surface and highly mineralized water. Locally, however, the Dakota is an important source of supply for uses other than drinking. Water wells may yield as much as 500 gal/min (32 l/s) from parts of the Dakota.

The Pierre Formation forms the bedrock surface below the glacial drift and crops out locally in Cavalier County. Most wells in this shale aquifer have small to moderate yields of water that is fresh to moderately saline. The water is used for domestic and livestock purposes throughout Cavalier County. Water from the wells in the Pierre is preferred for laundry because water from the overlying glacial drift is generally harder.

Glacial-drift aquifers include (1) buried sand and gravel deposits, (2) surficial sand and gravel deposits, (3) silt deposits formed in glacial Lake Agassiz, and (4) till. The buried aquifers were probably formed in glacial valleys and are usually confined or semiconfined between material of lower hydraulic conductivity. These aquifers contain about 1.7 million acre-feet (2.1 km^3) of water in storage. The surficial sand and gravel aquifers include spit, bar, beach, and delta deposits formed in Lake Agassiz in western Pembina County and northeastern Cavalier County. Surficial sand and gravel aquifers are unconfined to semiconfined. Silt aquifers yield small and locally inadequate quantities of water to wells in Pembina County. The silt aquifers are probably unconfined. The water-yielding characteristics of till are largely controlled by the presence of sand and gravel lenses and fractures. Till aquifers are usually semiconfined or confined.

Two of the largest and most productive buried aquifers are the Munich and Pembina River aquifers. The Munich aquifer underlies about 30 mi^2 (80 km^2) of southwestern Cavalier County near the city of Munich. The average thickness of the aquifer is about 40 feet (12 m), but locally may reach 200 feet (61 m) in thickness. The aquifer, which contains about 1.1 million acre-feet (1.4 km^3) of water in storage, supplies many domestic and stock wells and is a potential source of supply for the city of Munich. Where the effects of impervious boundaries are not too great, properly constructed wells should be capable of yielding as much as 500 gal/min (32 l/s). Water from the Munich aquifer is predominantly very hard, slightly saline, and a sodium sulfate type with a high concentration of iron.

The Pembina River aquifer, mostly in Pembina County, has an average thickness of nearly 20 feet (6 m), and consists of shaly sand and gravel interbedded with silt and clay lenses. East of Walhalla the aquifer material becomes finer grained. The aquifer contains about 38,000 acre-feet (50 hm^3) of water in storage. Wells in the western part of the aquifer may produce as much as 250 gal/min (16 l/s). Water from the Pembina River aquifer is predominantly very hard, fresh, and a calcium magnesium bicarbonate type, but changes to a sodium bicarbonate type near Neche.

The Hamilton aquifer, in east-central Pembina County, is a buried glacial-drift aquifer that is capable of yielding up to 50 gal/min (3.2 l/s) to wells. The aquifer contains about 150,000 acre-feet (180 hm^3) of water in storage. Samples from two wells show that the water is very hard, very saline, and a sodium chloride type with a dissolved-solids concentration of more than 11,000 mg/l. Because of the poor quality, the water is not suitable for most uses in the area.

Surficial sand and gravel aquifers include the Icelandic and Pembina Delta aquifers of Pembina County and northeastern Cavalier County. The maximum well yield that can be expected from these aquifers is about 50 gal/min (3.1 l/s); water quality is, however, among the best in the two-county area. The Icelandic aquifer contains about 240,000 acre-feet (300 hm^3) of water in storage and the Pembina Delta aquifer contains about 140,000 acre-feet (170 hm^3) in storage.

Geochemical relationships and data on the potentiometric surface indicate that the main direction of regional ground-water movement in Cavalier and Pembina Counties is eastward. Ground water is recharged in the topographically high areas of Cavalier County and regions to the west. The water becomes increasingly more mineralized as it moves from the recharge areas to the discharge areas in eastern Pembina county. Saline soils and saline lakes have been formed in eastern Pembina County as a result of natural discharge.

About 11,200 people, 60 percent of the population of the two counties, rely on ground-water supplies for their water needs. Of this population, 83 percent have self-supplied systems and 17 percent use public systems. The total ground-water use in 1970 is estimated to be about 1.15 Mgal/d (4,350 m^3/d).

Mountain, Osnabrock, and Walhalla presently use ground water for municipal water systems. Adequate ground-water resources for the foreseeable future are available near these cities.

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DEFINITIONS OF SELECTED TERMS

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

Artesian well – a well in which the water level stands above an artesian or confined aquifer. A flowing artesian well is a well in which the water level is above the land surface. See confined ground water.

Confining bed – a body of relatively impermeable material adjacent to one or more aquifers. In nature, the hydraulic conductivity of a confining bed may range from near zero to some value distinctly lower than that of the adjacent aquifer. This term replaces aquiclude, aquitard, and aquifuge.

Confined ground water – water in an aquifer that is contained by a confining bed, and under pressure significantly greater than atmospheric.

Hardness – is the characteristic of water that receives the most attention in industrial and domestic use. Hardness is caused almost entirely by compounds of calcium and magnesium. Other constituents — such as iron, manganese, aluminum, barium, strontium, and free acid — also cause hardness, although they usually are not present in quantities large enough to have any appreciable effect.

As a general reference, the U.S. Geological Survey uses the following classification of water hardness.

Calcium and magnesium hardness, as $CaCO_3$ (milligrams per litre)	**Hardness description**
0-60	Soft
61-120	Moderately hard
121-180	Hard
More than 180	Very hard

Water ranging in hardness from 0 to 60 mg/l generally is suitable for public or domestic use without softening. Water with hardness greater than 60 mg/l is improved by softening to reduce soap consumption and accumulation of scum on water fixtures.

Hydraulic conductivity – a term replacing field coefficient of permeability and expressed as feet per day or metres per day. The ease with which a fluid will pass through a porous material. This is determined by the size and shape of the pore spaces in the rock and their degree of interconnection. Hydraulic conductivity may also be expressed as cubic feet per day per square foot, gallons per day per square foot, or cubic metres per day per square metre. Hydraulic conductivity is measured at the prevailing water temperature.

Potentiometric surface – the surface that represents the static head. It may be defined as the level to which water will rise in tightly cased wells. A water table is a potentiometric surface.

Sodium-adsorption ration (SAR) – the sodium-adsorption ratio of water is defined as

$$\mathrm{SAR} = \frac{(\mathrm{Na}^{+})}{\sqrt{\dfrac{(\mathrm{Ca}^{+2})+(\mathrm{Mg}^{+2})}{2}}}$$

where ion concentrations are expressed in milliequivalents per litre. Experiments cited by the U.S. Department of Agriculture Salinity Laboratory (1954) show that SAR predicts reasonably well the degree to which irrigation water tends to enter into cation-exchange reactions in soil. High values for SAR imply a hazard of a sodium replacing adsorbed calcium and magnesium. This replacement is damaging to soil structure.

Specific capacity – the rate of discharge of water from a well divided by the drawdown of the water level, normally expressed as gallons per minute per foot of drawdown.

Specific yield – the ratio of the volume of water which a rock or soil, after being saturated, will yield by gravity to the volume of the rock or soil. Generally expressed as a percentage or decimal fraction.

Storage coefficient – the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In an artesian aquifer the water derived from storage with decline in head comes mainly from compression of the aquifer and to a lesser extent from expansion of the water. In an unconfined, or water-table, aquifer the amount of water derived from the aquifer is from gravity drainage of the voids.

Till – an unsorted, unstratified glacial deposit composed of particles that normally range in size from clay to boulders.

Transmissivity – the rate at which water, at the prevailing temperature, is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is normally expressed in units of square feet per day, but can be expressed as the number of gallons of water that will move in 1 day under a hydraulic gradient of 1 foot per foot through a vertical strip of aquifer 1 foot wide extending the full saturated height of the aquifer.

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

Water year – the 12-month period beginning on October 1.

Zone of saturation – in the saturated zone of an aquifer all voids are ideally filled with water under pressure greater than atmospheric. The water table is the upper limit of this zone. In nature, the saturated zone may depart from the ideal in some respects. A rising water table may trap air in parts of the zone and other natural fluids may occupy voids in the lower part of an aquifer.