GROUND-WATER RESOURCES

OF

McKENZIE COUNTY, NORTH DAKOTA

By

M. G. Croft

U.S. Geological Survey

COUNTY GROUND-WATER STUDIES 37 — PART III
North Dakota State Water Commission
Vernon Fahy, *State Engineer*

BULLETIN 80 — PART III
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Prepared by the U.S. Geological Survey
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SELECTED FACTORS FOR CONVERTING ENGLISH UNITS TO THE INTERNATIONAL SYSTEM (SI) OF UNITS

A dual system of measurements — inch-pound units and the International System of Units (SI) — is given in this report. The SI is an organized system of units adopted by the 11th General Conference of Weights and Measures in 1960. Selected factors for converting inch-pound units to SI units are given below.

Multiply inch-pound unit	By	To obtain SI unit
Acre	0.4047	hectare (ha)
Acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
Foot (ft)	0.3048	meter (m)
Foot per day (ft/d)	0.3048	meter per day (m/d)
Foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
Foot per second (ft/s)	0.3048	meter per second (m/s)
Foot per year (ft/yr)	0.3048	meter per year (m/yr)
Foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
Gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
Gallon per minute (gal/min)	0.06309	liter per second (L/s)
Gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter [(L/s)/m]
Inch (in.)	25.4	millimeter (mm)
Mile (mi)	1.609	kilometer (km)
Million gallon per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
Pound per cubic foot (lb/ft^3)	0.0163	gram per cubic centimeter (g/cm^3)
Pound per cubic inch ($lb/in.^3$)	27.69	gram per cubic centimeter (g/cm^3)
Pound per square inch ($lb/in.^2$)	0.07031	kilogram per square centimeter (kg/cm^2)
Square inch per pound ($in.^2/lb$)	1,422	square millimeter per kilogram (mm^2/kg)
Square mile (mi^2)	2.590	square kilometer (km^2)

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by the equation:

$$°C = (°F - 32) \times 5/9$$

National Geodetic Vertical Datum of 1929: A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

Ground water suitable for domestic and livestock supplies in McKenzie County is available from three aquifer systems in semiconsolidated rocks of Late Cretaceous and Tertiary age. Ground water from aquifers in unconsolidated sand and gravel of Quaternary age is suitable for domestic, livestock, municipal, industrial, and irrigation uses. Rocks older than Late Cretaceous age extend to 15,000 feet (4,572 meters) and generally contain brackish water that is unsuitable for most purposes.

The Fox Hills and basal Hell Creek aquifer system is used as a source for livestock and domestic supplies. It generally is 1,100 to 1,800 feet (335 to 549 meters) in depth, and the transmissivity is 200 to 300 feet squared per day (19 to 28 meters squared per day). The water is lower in dissolved solids than water in overlying aquifers of Tertiary age and has a median dissolved-solids concentration of about 1,325 milligrams per liter. Wells may yield 100 gallons per minute (6.3 liters per second).

Six aquifers, each consisting of 50 to 176 feet (15 to 54 meters) of unconsolidated sand and gravel of Quaternary age, occur in McKenzie County. The sand and gravel could yield 100 to more than 500 gallons per minute (6.3 to 32 liters per second). The water from four of the aquifers generally is a sodium bicarbonate type and has a median dissolved-solids concentration of 1,100 to 2,330 milligrams per liter. Water from the Charbonneau, Tobacco Garden, and Yellowstone-Missouri aquifers is suitable for irrigation.

INTRODUCTION

The investigation was made cooperatively by the U.S. Geological Survey, North Dakota State Water Commission, North Dakota Geological Survey, and McKenzie County Water Management District. The results of the investigation are published in three separate parts of the bulletin series of the North Dakota Geological Survey and the county ground-water series of the North Dakota State Water Commission. Part I is an interpretive report describing the geology and is in preparation by the North Dakota Geological Survey; part II (Croft, 1985) is a compilation of the ground-water basic data; and this report, part III, describes the ground-water resources. Part II contains well logs, chemical analyses, and water-level data collected during the county investigation; it is a reference for parts I and III. Data referred to in this report are in part II unless otherwise referenced.

Purpose of the Investigation

The ground-water investigation of McKenzie County (fig. 1) was made to provide geologic and hydrologic information needed for the orderly development of water supplies for municipal, domestic, livestock, irrigation, and industrial uses. The hydrologic investigation began in October 1978. Specifically, the objectives were to: (1) Determine the location, extent, and nature of the major aquifers and confining beds; (2) determine the movement of ground water, including the sources of recharge and discharge; (3) estimate the potential yields of wells; and (4) evaluate the chemical quality of ground water.

Acknowledgments

The collection of data for this report was aided by the cooperation of the McKenzie County Commissioners, McKenzie County Water Resource District, U.S. Forest Service, and residents of the county. Allen Comeskey and Alan Wanek, geologists with the North Dakota State Water Commission, logged most of the test holes. M. O. Lindvig, Director, Hydrology Division, North Dakota State Water Commission, provided coordinating assistance for the agency.

Location-Numbering System

The location-numbering system used in this report is based on a system 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 a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre or 4-ha tract). For example, well 150-104-15ADC is in the SW¼SE¼NE¼ sec. 15, T. 150 N., R. 104 W. Consecutive terminal numerals are added if more than one well or test hole is recorded within a 10-acre (4-ha) tract.

Climate

The climate of McKenzie County is cool and semiarid. The mean temperature at Watford City for 1971-80 was 43.1 °F or about 6.2 °C (fig. 3A; U.S. Department of Commerce, 1972-81). Temperatures average 70 °F (21.1 °C) or more in July and August. Winters are cold and temperatures frequently drop to −30 °F (−34.4 °C). The average growing season is about 125 days.

The mean annual precipitation recorded at Watford City, N. Dak. (fig. 3B) for 1971-80 was 15.9 in. (404 mm). About 70 percent of the precipitation

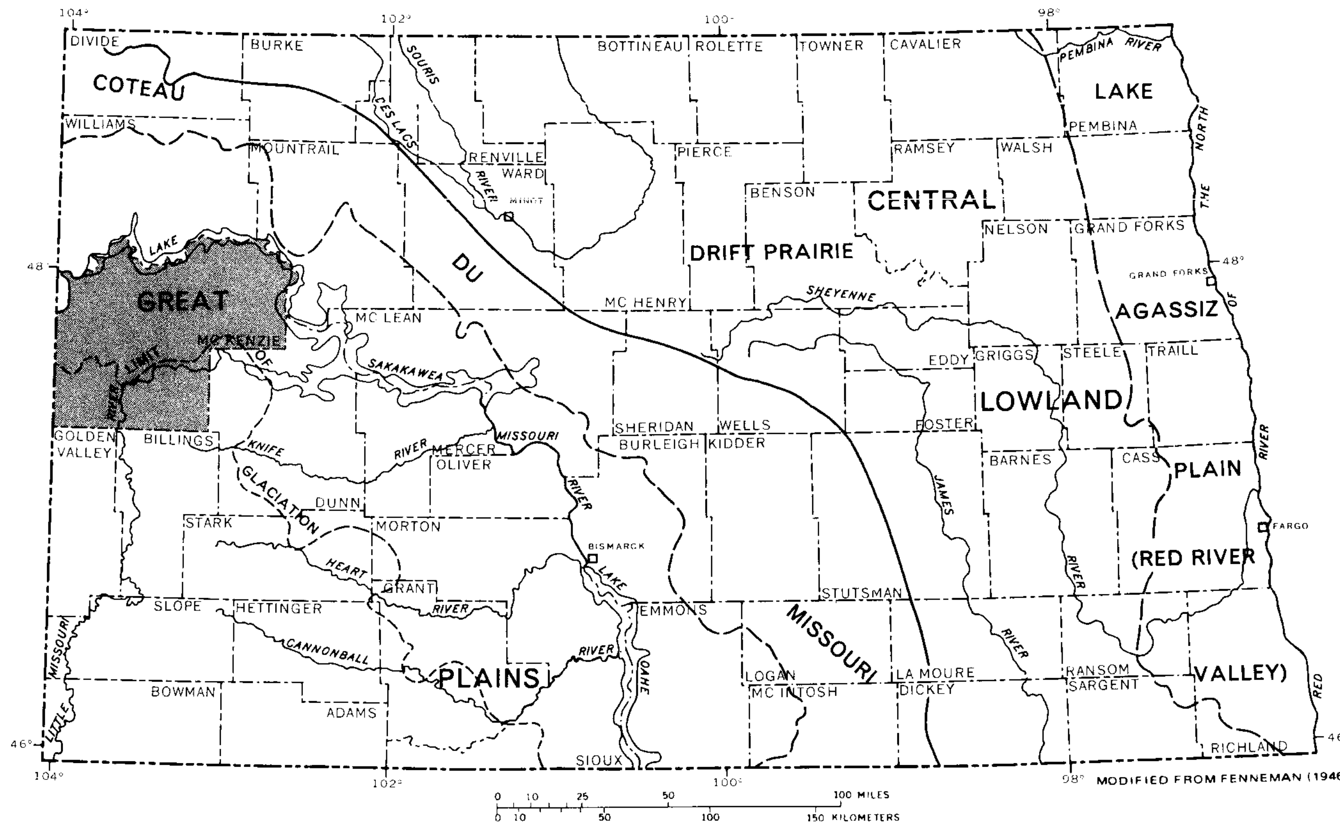


Figure 1.—Physiographic divisions in North Dakota and location of study area.

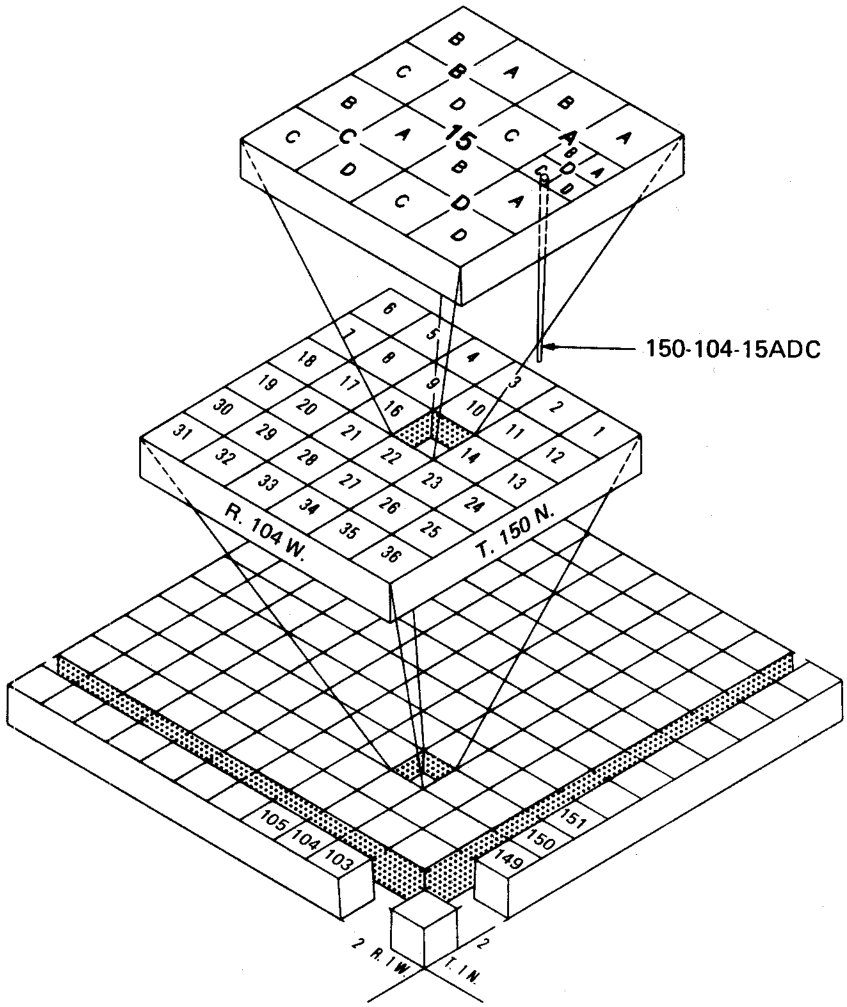


Figure 2.—Location-numbering system.

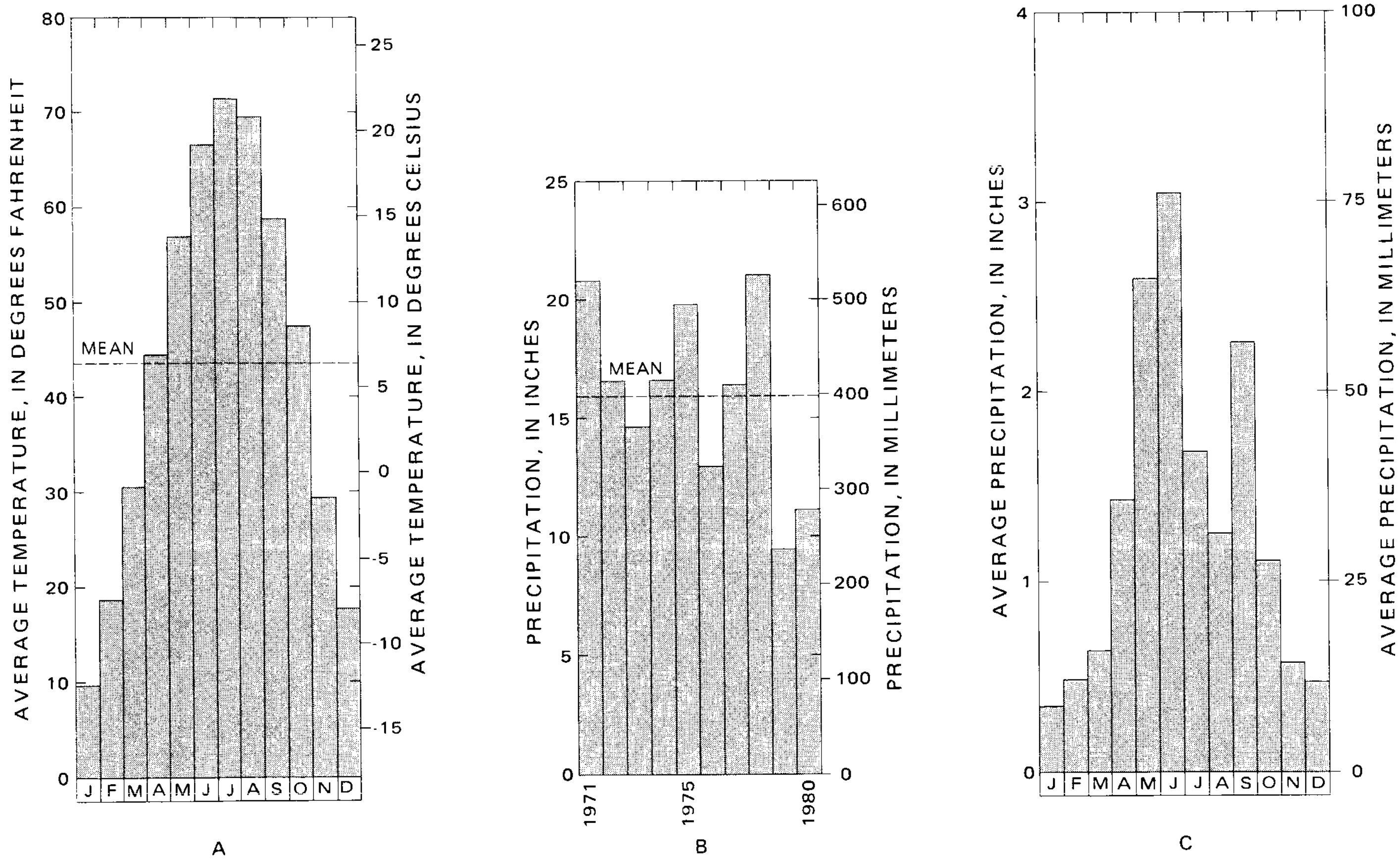


Figure 3.—Temperature and precipitation at Watford City, 1971-80 (U.S. Department of Commerce, 1972-81).

falls during the growing season (fig. 3C). Thunderstorms are common in June, July, and August.

Physiography and Drainage

McKenzie County has an area of 2,754 mi^2 (7,133 km^2). It lies partly within the unglaciated area of the Great Plains and partly within the glaciated area (fig. 1). The rolling uplands slope gently to the northeast and have a maximum altitude of about 2,850 ft (869 m) in the Blue Buttes east of Watford City. The principal streams, the Missouri and Little Missouri Rivers, are incised about 500 ft (152 m) below the upland surface. Drainage in the area is to the Gulf of Mexico. The most striking physiographic feature is the large valley carved by the Little Missouri River in the central part of the county.

The valleys of the Yellowstone, Little Missouri, and Missouri Rivers upstream from Garrison Dam are carved into three benches. The uppermost bench is the upland surface. Table 1 is a correlation of the interpretations of three investigators. The Flaxville bench and the Cartwright bench are glaciated, but the Crane Creek bench is postglacial. The photograph in figure 4 was taken on Red Wing Creek in 147-101-05 looking east toward Theodore Roosevelt National Park. The skyline is the Flaxville bench. Boulders in the foreground are granitic "glacial erratics" and lie on the Cartwright bench. The bottomlands are the Crane Creek bench.

The Flaxville Gravel is "patchy" and, where present, lies on the upland plateau and forms the physiographic feature referred to as the Flaxville bench. The sand and gravel generally is considered to be of Miocene and Pliocene age. Volcanic ash from the Flaxville Formation in Valley County, Mont., (Colton, 1962, p. 255), has been dated as 8.9 million years before present by R. B. Colton (U.S. Geological Survey, oral commun., January 1980). The incision of the upland surface probably is related to the subduction of the Farallon plate (Atwater, 1970) concurrent to the arching of the Western Interior in Miocene time.

TABLE 1. — Correlation of benches in western North Dakota and eastern Montana

Series	Alden (1932) in western North Dakota	Howard (1960) in western North Dakota	Colton (1962) in eastern Montana
Pleistocene	Bench #3	Crane Creek Gravel	Wiota Gravel
	Bench # 2	Cartwright Gravel	
Pliocene	Flaxville bench #1	Flaxville Gravel	Flaxville Formation
Miocene		Rimroad Gravel (part)	

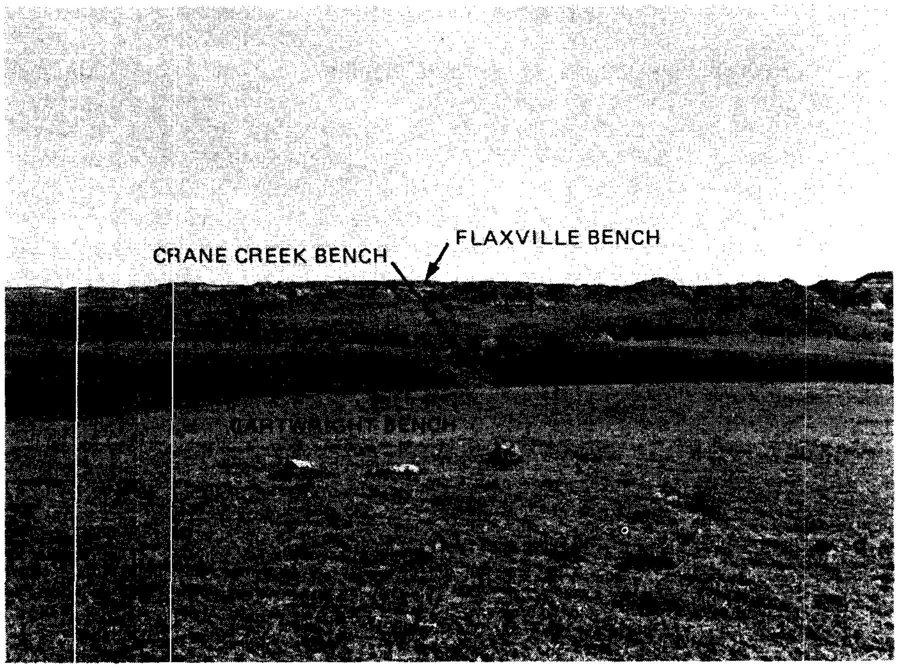


Figure 4.—Major benches in the Red Wing Creek area.

The Cartwright Gravel is on a bench about midway between the valley bottom and the upland surface. The slopes overlying the Cartwright are rounded, and the soils are well developed and mature. Fossils from gravels lying on the surface are dated as early Pleistocene (Howard, 1960). The Cartwright bench parallels the Missouri River between the confluence of the Missouri and Yellowstone Rivers and Garrison Dam. The occurrence of the bench indicates that this stretch of the Missouri River may have existed since early Pleistocene time.

The Crane Creek bench is dated late Pleistocene; soils are relatively immature, and slopes and gullies are steep and rugged. The terrace is about 20 to 30 ft (6 to 9 m) above the valley bottom.

Population and Economy

The population of McKenzie County was 7,132 in 1980 (U.S. Bureau of the Census, 1981). Watford City, the county seat, had a population of 2,119. The economy of the area is based on agriculture and petroleum. Agricultural products include small grains, corn, hay, and cattle.

Previous Investigations

Numerous geologic studies, spurred by the search for oil, gas, lignite, and uranium, have been made in western North Dakota and surrounding areas. The earliest geologic investigations pertinent to the study area were made by Lloyd and Hares (1915) and Stanton (1920). Recent geologic investigations have been made by Denson and Gill (1965) and Pipiringos and others (1965). Coal deposits in the western part of the Fort Berthold Reservation have been described by Bauer and Herald (1921). Geophysical and lithologic logs were made of about 60 lignite test holes in McKenzie County by Spencer (1978).

The first comprehensive report on the ground-water resources of North Dakota included a brief discussion of the geology, ground-water resources, and quality of ground water in McKenzie County (Simpson, 1929). A recent geochemical investigation of the ground water in the Fox Hills Sandstone and Hell Creek Formation in southwestern North Dakota and northwestern South Dakota was made by Thorstenson and others (1979). Other geology and ground-water reports of interest are listed in the selected references.

GEOHYDROLOGIC SETTING

The sedimentary rocks of McKenzie County were deposited near the center of the large subsiding Williston basin during the Paleozoic, Mesozoic, and Cenozoic eras (table 2). The rocks are about 15,000 ft (4,572 m) thick. Rocks older than the Fort Union Formation are not exposed at land surface and those older than the Fox Hills Sandstone are of interest mainly for oil and gas production.

The rocks of Paleozoic and Mesozoic age have been penetrated by numerous oil and gas test holes and have been divided into several formations by petroleum geologists. Well logs and lithologic descriptions are available from the North Dakota Geological Survey and are discussed in greater detail in part I. The rocks of Paleozoic age, mainly limestone, dolomite, sandstone, shale, and evaporites, generally contain brackish water. Samples commonly contain 100,000 mg/L dissolved solids or more, and thus, the water is too brackish for most uses.

Rocks of Mesozoic age largely are shale, but sandstone forms part of the Inyan Kara Formation of Early Cretaceous age and the Fox Hills Sandstone and Hell Creek Formation of Late Cretaceous age. The Inyan Kara is at depths of about 4,000 to 5,000 ft (1,219 to 1,524 m) in McKenzie County. A water sample from the Inyan Kara contained about 5,000 mg/L sodium chloride; thus, the water is too brackish for most uses.

The water from most beds above the Pierre Shale is suitable for industrial, livestock, and domestic use. Altitude at the top of the Pierre Shale ranges from about 220 to 880 feet (67 to 268 m) above sea level (fig. 5). The Pierre is about 2,300 feet (701 m) thick and consists mainly of dark-gray to black shale.

The rocks comprising the Fox Hills Sandstone and Hell Creek Formation were formed by a large high constructive delta during the Laramide orogeny.

TABLE 2. — McKenzie County stratigraphic column

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

Era	Period	Epoch	Age estimate in millions of years	Group	Formation and member		Approximate thickness (feet)	Remarks
Cenozoic	Quarternary	Holocene	0.010		Aluvium and colluvium.			Deposits contain the major aquifers in McKenzie County.
		Pleistocene			Crane Creek			
					Glacial drift			
			2		Cartwright			
	Tertiary	Pliocene	5		Flaxville		10	
		Miocene	24					
		Oligocene	38	White River			100	
		Eocene	55		Golden Valley		200	
		Paleocene			Fort Union	Sentinel Butte	600	
						Tongue River	700	
			63			Ludlow	700	
Mesozoic	Cretaceous				Hell Creek		400	
				Montana	Fox Hills			
					Pierre		2,300	Mainly shale.
				Colorado	Niobrara		350	
					Carlisle		200	
					Greenhorn		150	
					Belle Fourche		300	
				Dakota	Mowry		200	
					Newcastle		100	
					Skull Creek		150	
					Inyan Kara	Fall River	600	Contains brackish water suitable for oilfield use.
			138			Lakota		
	Jurassic				Morrison		300	
					Swift		200	
					Rierdon		200	
			205		Piper		400	
	Triassic		240		Spearfish		450	
Paleozoic	Permian				Minnekahta		50	Undifferentiated with regard to occurrence of aquifers. The beds generally contain brackish water.
					Opeche		200	
			290	Minnelusa	Broom Creek and Amsden		300	
	Pennsylvanian		330		Tyler		100	
	Mississippian			Big Snowy	Otter		200	
					Kibbey		300	
				Madison	Charles		600	
					Mission Canyon		800	
					Lodgepole		700	
			360		Bakken		200	
	Devonian				Three Forks			
					Birdbear and Duperow		400	
				Manitoba	Souris River		200	
					Dawson Bay		200	
			410	Elk Point	Prairie and Winnipegosis		150	
	Silurian		435		Interlake		800	
	Ordovician			Big Horn	Stony Mountain		200	
					Red River		600	
				Winnipeg			100	
			500		Deadwood		900	
	Cambrian		570					
	Precambrian				Crystalline rocks			

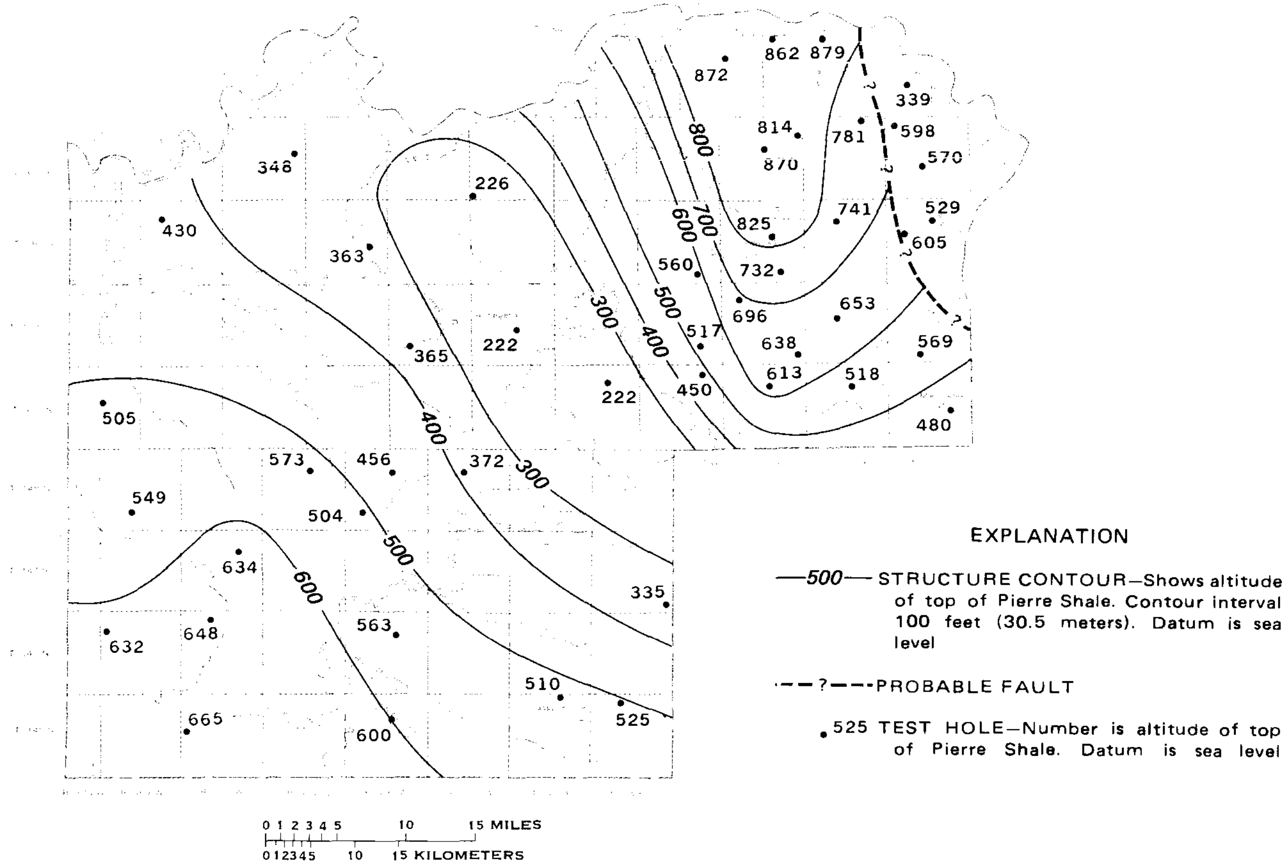


Figure 5.—Altitude of top of Pierre Shale.

These rocks generally are at depths of less than 2,200 ft (671 m). The beds are folded into the large north-south trending Nesson anticline (fig. 5). The east flank of the anticline dips steeply or probably is faulted.

The rocks of the Fort Union Formation are of Paleocene age, are largely deltaic, and are similar lithologically to the underlying Fox Hills Sandstone and Hell Creek Formation. Although in this report the Fort Union has been divided into only three members (table 2), other members have been described in areas adjacent to McKenzie County. The coarse-grained beds in the lower part of the Fort Union are equivalent to the Ludlow Member in the study area or the Tullock Member in Montana. Thick continuous beds of claystone within the upper part may be of marine or brackish water origin and, hence, are the Cannonball Member or Lebo Member in Montana. The Tongue River and Sentinel Butte Members are exposed at the surface, contain large lignite reserves, and generally are less than 1,200 ft (366 m) in depth. Tertiary rocks younger than the Fort Union Formation form buttes and high rolling hills and generally are not saturated.

A glacier overrode the northern and eastern parts of McKenzie County during the Quaternary period. The ice blocked north-flowing streams, altered the drainage pattern (fig. 6), and mantled the uplands with several feet of till. Water from the melting glaciers deepened many of the existing valleys and in some areas carved new ones. The Cartwright bench generally slopes northward in those valleys that existed prior to glaciation, but some streams that now occupy these valleys flow southward. As the glacier advanced southward over McKenzie County, a sinuous, shallow lake formed in the abandoned valley of the Little Missouri River (fig. 6) from the confluence of Red Wing Creek with the present Little Missouri River to Tobacco Garden Bay. Fine-grained sediments were deposited in the lake and overlie preglacial alluvium. The alluvial sand and gravel in the abandoned Little Missouri drainage system is considered to be of Cartwright age. Since retreat of the glacier, 20 to 40 ft (6 to 12 m) of fine-grained colluvial material derived from the till and the underlying bedrock has been deposited in the former valley on top of the Cartwright alluvial material, the till, and the lake beds.

During the time of maximum extent of the ice, the Little Missouri River was diverted eastward from the mouth of Red Wing Creek, and the river carved a large gorge eastward from Red Wing Creek through the north unit of Theodore Roosevelt National Park (fig. 6). The Cartwright bench is not present along the walls of the present Little Missouri gorge downstream from Red Wing Creek, indicating the gorge-cutting episode was in post-Cartwright time.

Clayton (1966) reported three glacial sequences and Colton and others (1963) reported two. However, the stratigraphy in the abandoned Little Missouri drainage system indicates only one glacial sequence. Clayton (1966, fig. 1) identified three significant late Pleistocene ice-margin positions in McKenzie County. The oldest, the Morton Drift (Drift A), is the most extensive and consists of scattered erratic boulders and rare patches of till; little original moraine topography remains. The till may be pre-Wisconsin, but the lack of

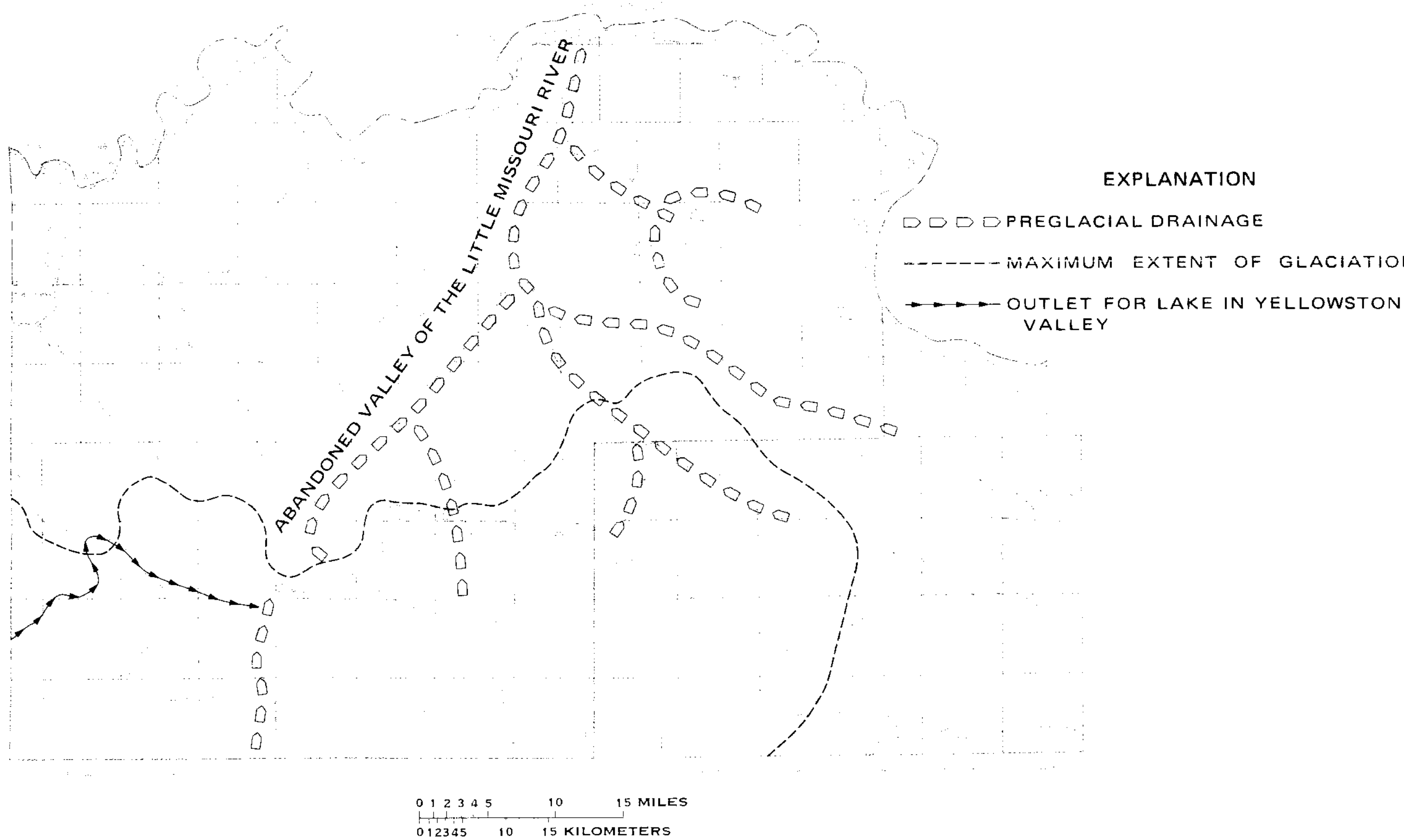


Figure 6.—Drainage pattern prior to glaciation.

deep weathering suggests that it is early Wisconsin in age. The second drift, the Napoleon Drift (Drift B), is in eastern McKenzie County and retains much of its original moraine topography, although few closed depressions remain. The drift is a thin blanket, a few tens of feet thick at most, and is draped over the rolling preglacial topography. The Charlson Drift (Drift C) is in northwestern McKenzie County and is the youngest. Drainage is slightly integrated in most areas and generally the drift lacks strongly developed dead-ice moraine. The topography is dominantly that of ground moraine.

The younger moraines, Napoleon and Charlson Drifts, were identified mainly by their topographic expressions and were not verifiable by the test drilling during this study. Railroad cuts and other outcrops were examined in many parts of the county, but the multiple tills described by Clayton (1966) and Colton and others (1963) were not observed. It is doubtful if they exist anywhere southwest of Keene.

During the glacial period, a lake formed to the west of McKenzie County in the valley of the Yellowstone River (Alden, 1932, pl. 28). When the lake was at its maximum level, overflow cut a valley (fig. 6) to Squaw Gap and water flowed into Spring and West and East Hay Draw Creeks (pl. 1, in pocket). A test hole drilled in the glacial channel about 4 mi (6 km) southwest of Squaw Gap (146-105-13ABB), at the topographic high between the Yellowstone and Little Missouri valleys, penetrated bedrock at a depth of 141 ft (43 m), indicating the lake in the Yellowstone valley had a maximum altitude of about 2,179 ft (664 m).

Most outwash channels and stream valleys in the county are backfilled with 100 to 200 ft (31 to 61 m) of outwash, alluvial, colluvial, and lacustrine material. These deep valleys were carved during periods of extensive continental glaciation when sea level was 100 to 200 ft (30.5 to 61 m) lower. During these periods of continental glaciation, streams adjusted their gradients to the lower sea level, approaching local pediplains.

Ground water suitable for domestic, livestock, municipal, industrial, and irrigation use occurs in the preglacial alluvium beneath the abandoned Little Missouri drainage system and in gravel found in channels carved by glacial melt water (pl. 1).

AVAILABILITY AND QUALITY OF GROUND WATER

The hydrology of the principal aquifers and the availability of ground water for domestic, industrial, and municipal supplies in McKenzie County are shown on plates 1 and 2 (in pocket). Well yields of more than 500 gal/min (31.6 L/s) of water suitable for agricultural, industrial, and municipal use can be developed in parts of the county from preglacial gravel and glacial-drift aquifers (pl. 1).

General Concepts

The ground water in McKenzie County is derived from precipitation. After precipitation falls on the Earth's surface, part is returned to the atmosphere by evapotranspiration, part runs off into streams, and the remainder infiltrates into the ground. Some of the water that enters the soil is held by capillarity to replace the water that has evaporated or been transpired by plants. After the soil and plant requirements have been satisfied, the excess water, if any, will percolate 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 from areas of higher potential to areas of lower potential, for example from areas of recharge to areas of discharge. The average lateral particle velocity through the aquifer is defined by equation (1) (Lohman, 1972):

$$\bar{V} = \frac{-K \frac{dh}{dl}}{\theta}, \qquad (1)$$

where $\bar{V}$ = average particle velocity,
K = hydraulic conductivity,
$\frac{dh}{dl}$ = hydraulic gradient, and
θ = porosity.

Calculations based upon this equation indicate that the rate of ground-water flow is only a few feet per year in the principal aquifers.

Steady-state flow of ground water is a theoretical condition in which there is no change of flow rates or head with time. Steady-state flow does not occur in nature but is a useful concept in that steady-state flow can be closely approached in nature and in aquifer tests. Transient flow is a condition in which flow rates and head change with time.

Hydraulic conductivity (K) has been related empirically (Levorsen, 1954) to the geometry of the rock texture according to equation (2),

$$K = \frac{2 \times 10^7 \times \theta^3}{(1-\theta)^2 S^2}, \qquad (2)$$

where K is expressed in millidarcies[1],

θ is porosity, and is dimensionless, and
S is the specific surface of the pores and is equal to the surface area of the solid material contained in one cubic centimeter of rock.

A graph (fig. 7) was constructed using this equation, which assumes the particles are perfect spheres. Therefore, the graph is not exact but only approximates the general relation for the bedrock and glacial aquifers in McKenzie County. Unconsolidated poorly sorted glacial drift will have values for hydraulic conductivity between those determined for unconsolidated well-

[1]K in millidarcies may be converted to K in ft/d by multiplying by 0.00243.

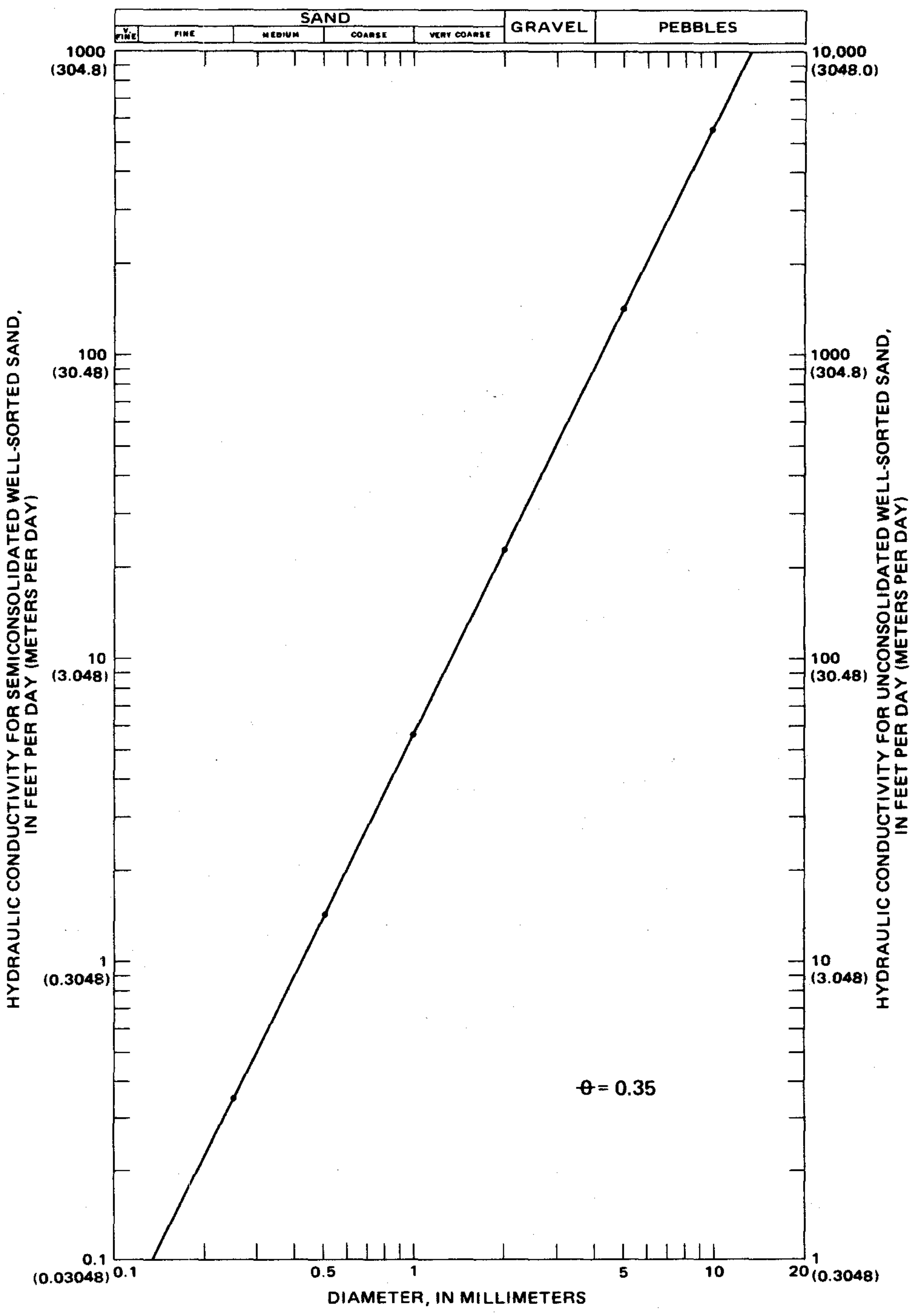


Figure 7.—Relation of texture to hydraulic conductivity (K).

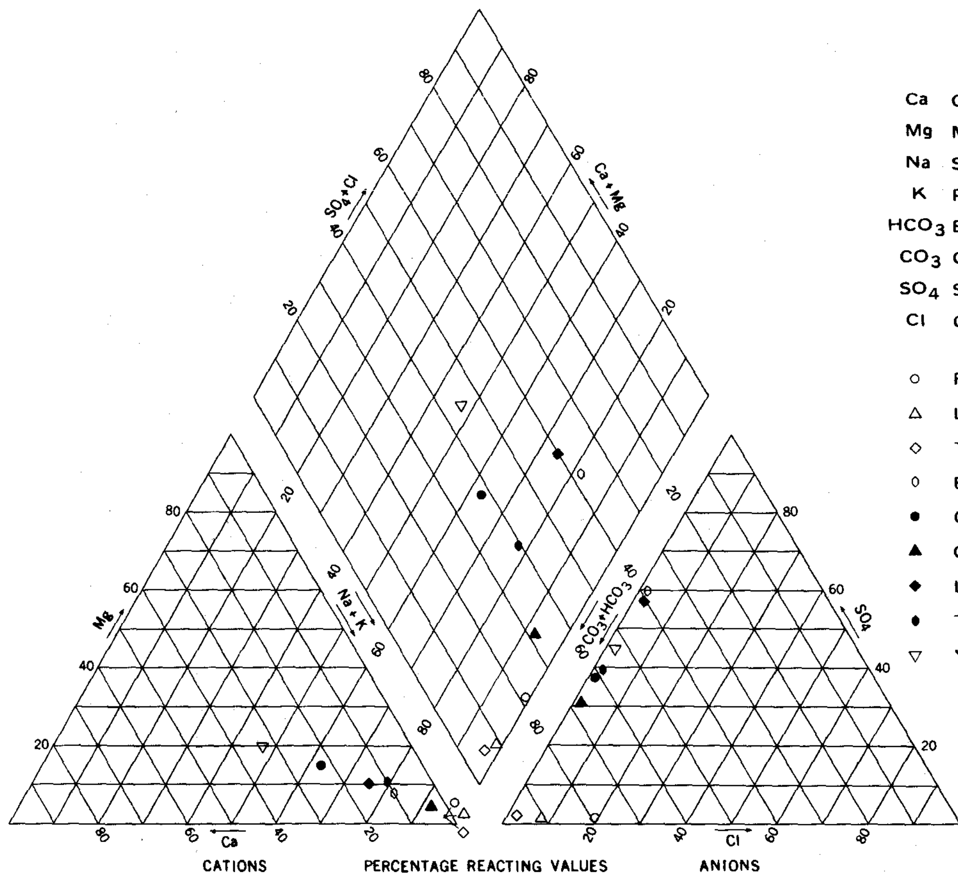
sorted sand and those for the semiconsolidated well-sorted sand. Well-consolidated deposits will have values of about one-third that determined for semiconsolidated well-sorted sand. When compared to the results of aquifer tests for deposits in the area, the graph (fig. 7) is reasonable and is a useful aid for constructing transmissivity and yield maps. However, determinations made with the graph should be considered only as crude estimates.

Transmissivity (T) maps can be used to estimate the yield of an aquifer. The relationship of transmissivity to yield is based on a chart (Meyer, 1963, p. 338-340, fig. 100) relating well diameter, specific capacity, and coefficients of transmissibility and storage. The chart shows that, for coefficients of storage less than 0.005 and for transmissibilities[2] within the range of most water wells, the ratio of transmissibility to specific capacity is about 2,000:1, where specific capacity is given in gallons per minute per foot of drawdown after 24 hours of pumping. Therefore, in unconsolidated deposits, the yield in gallons per minute of an efficient, fully penetrating well may be approximated by dividing the transmissivity by 267 and multiplying the result by the available drawdown. The diameter of the well also will affect the yield, but this effect is small compared to the uncertainty in estimating the transmissivity. The drawdown in unconsolidated aquifers is considered to be about 10 ft (3 m), and drawdown in semiconsolidated aquifers is considered to be about 50 ft (15 m).

The ground water in McKenzie County contains dissolved mineral matter in varying quantities. Rainfall begins to dissolve mineral matter upon contact with the land surface and continues to dissolve mineral matter as the water percolates through the soil. The amount and kind of dissolved mineral matter in the water depends mainly upon the solubility and types of rocks encountered; the amount of carbon dioxide, gases, and soil acids in the water; ion-exchange reactions; and bacterial processes. The behavior of the system is influenced by both temperature and pressure. Standard conditions, to which constants are referred, are 25°C and 1 atmosphere of pressure.

The suitability of water for various uses is determined largely by the kind and quantity of dissolved matter. The chemical constituents, physical properties, and indices most likely to be of concern are: Iron, sulfate, nitrate, fluoride, dissolved solids, hardness, taste, sodium-adsorption ratio (SAR), and percent sodium. The relative mean values of the major constituents for various aquifers, expressed in milliequivalents per liter, are plotted on a trilinear diagam (fig. 8); the median values for the constituents, in milligrams per liter, are given in table 3. Sources of the major chemical constituents, their effects on usability, and the recommended and mandatory limits (U.S. Environmental Protection Agency, 1976, 1977) are given in table 4. Additional information regarding recommended drinking water standards may be found in a report prepared by the U.S. Environmental Protection Agency (National Academy of Sciences-National Academy of Engineering, 1973). Water-quality criteria for public supplies, farmsteads, industrial, and agricultural use were established by the

[2]Transmissibility may be converted to the now commonly used term, transmissivity, by dividing by 7.48.



EXPLANATION

CONSTITUENTS ARE MEAN VALUES

Ca CALCIUM
Mg MAGNESIUM
Na SODIUM
K POTASSIUM
HCO_3 BICARBONATE
CO_3 CARBONATE
SO_4 SULFATE
Cl CHLORIDE

○ FOX HILLS AND BASAL HELL CREEK AQUIFER SYSTEM
△ LUDLOW AQUIFER SYSTEM
◇ TONGUE RIVER AQUIFER SYSTEM
0 BENNIE PEER AQUIFER
● CHARBONNEAU AQUIFER
▲ CHERRY CREEK AQUIFER
◆ LITTLE MISSOURI RIVER AQUIFER
⬮ TOBACCO GARDEN AQUIFER
▽ YELLOWSTONE-MISSOURI AQUIFER

Figure 8.—Major constituents in ground water from McKenzie County.

U.S. Federal Water Pollution Control Administration (1968). The North Dakota State Department of Health (1970) adopted a set of water-quality standards within the framework of the national guidelines for interstate streams. National Interim Primary Drinking Water Regulations were published by the U.S. Environmental Protection Agency (1976).

TABLE 3. — Median values of chemical constituents, hardness, and sodium-adsorption ratio

[Chemical constituents are in milligrams per liter; SAR, sodium-adsorption ratio]

Aquifer or aquifer system	Number of water samples	Dissolved solids	Chloride	Sulfate	Boron	Hardness	SAR
Fox Hills and basal Hell Creek	34	1,325	170	2.1	1.2	12	71
Ludlow	9	1,750	44	6.6	.80	17	81
Tongue River	16	1,830	29	11	30	22	70
Bennie Peer	8	3,060	7.5	1,450	.19	540	22
Charbonneau	13	1,100	5.4	320	.06	400	7
Cherry Creek	4	2,080	5	670	.12	170	25
Little Missouri River	5	2,330	11	920	.09	410	16
Tobacco Garden	52	947	5.1	210	.20	190	10
Yellowstone-Missouri	14	1,100	18	380	.09	540	4

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

The quality of water used for irrigation is an important factor in crop productivity and in effects on the soil. The U.S. Salinity Laboratory Staff (1954) developed an irrigation classification system based on SAR and specific conductance. SAR is related to sodium hazard and specific conductance is related

TABLE 4. — Chemical constituents in water — their sources, effects upon usability, and recommended and mandatory concentration limits

[Modified from Durfor and Becker, 1964, table 2. Concentrations are in milligrams per liter, mg/L, or micrograms per liter, ug/L]

Constituents	Major source	Effects upon usability	U.S. Environmental Protection Agency (1976, 1977) recommended and mandatory limits for drinking water
Silica (SiO_2)	Feldspars, quartz, and ferromagnesian and clay minerals.	In presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat transfer.	None.
Iron (Fe)	Natural sources: amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, carbonates, and clay minerals. Man-made sources: well casings, pumps, and storage tanks.	If more than 100 ug/L is present, it will precipitate when exposed to air; causes turbidity, stains plumbing fixtures, laundry, and cooking utensils, and imparts tastes and colors to food and drinks. More than 200 ug/L is objectionable for most industrial uses.	300 ug/L (recommended).
Manganese (Mn)	Soils, micas, amphiboles, and hornblende.	More than 200 ug/L precipitates upon oxidation. Causes undesirable taste and dark-brown or black stains on fabrics and porcelain fixtures. Most industrial uses require water containing less than 200 ug/L.	50 ug/L (recommended).
Calcium (Ca)	Amphiboles, feldspars, gypsum, pyroxenes, anhydrite, calcite, aragonite, limestone, 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. Excessive concentrations of magnesium have a laxative effect.	None.
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, magnesite, dolomite, and clay minerals.		
Sodium (Na) Potassium (K)	Feldspars, feldspathoids, micas, and exchange on clay minerals.	More than 50 mg/L sodium and potassium with suspended matter causes foaming, which accelerates scale formation and corrosion in boilers.	None.
Boron (B)	Tourmaline, biotite, and amphiboles.	Essential to plant nutrition. More than 2 mg/L may damage some plants.	None.
Bicarbonate (HCO_3) Carbonate (CO_3)	Limestone and dolomite.	Heating water dissociates bicarbonate to carbonate, carbon dioxide, or both. The carbonate can combine with alkaline earths (principally calcium and magnesium) to form scale.	None.
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 (recommended).
Chloride (Cl)	Halite and sylvite. Rainfall.	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 (recommended).
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.	Mandatory maximum limits depend on average of maximum daily air temperatures. Maximum limits range from 1.4 mg/L at 32°C to 2.4 mg/L at 10°C.
Nitrate (NO_3) as Nitrogen (N)	Organic matter, fertilizers, and sewage.	More than 20 mg/L may cause a bitter taste and may cause physiological distress. Concentrations in excess of 10 mg/L have been reported to cause methemoglobinemia (blue-baby disease) in infants.	10 mg/L (mandatory).
Dissolved solids	Anything that is soluble.	Less than 300 mg/L is desirable for some manufacturing processes. Excessive dissolved solids restrict the use of water for irrigation.	500 mg/L (recommended).

to the salinity hazard. The hazards increase as the numerical values of the indices increase. Irrigation classifications for selected water samples from McKenzie County are shown in figure 9.

Selected water samples were evaluated with WATEQF (table 5), a computer program by Plummer and others (1976). Values were measured in the field for pH and temperature and the samples were analyzed for dissolved gases. The evaluation indicated that ground water in McKenzie County generally is undersaturated with anhydrite ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$) and near saturation with respect to aragonite ($CaCO_3$) and calcite ($CaCO_3$). Downward percolating water dissolves gypsum from the soil zone. The gypsum is derived from weathering of pyritic minerals. Therefore, water from shallow aquifers contains a large proportion of calcium, magnesium, and sulfate in solution. Water from deep aquifers mainly contains sodium and bicarbonate due to the exchange of sodium for calcium and magnesium on clay minerals and lignite. The sulfate ion has been reduced and removed from solution (Thorstenson and others, 1979) in water from the deep bedrock aquifers.

TABLE 5. — WATEQF analysis of selected water samples

Well Number	Depth	Log ion-activity product/equilibrium constant[1]			
		Anhydrite ($CaSO_4$)	Gypsum ($CaSO_4 \cdot 2H_2O$)	Aragonite ($CaCO_3$)	Calcite ($CaCO_3$)
146-102-27BCA	1,310	-4.9	-4.6	0.01	0.30
151-104-04AAA	1,405	-4.9	-4.7	-.25	.02
153-097-02CDD	1,467	-5.4	-5.1	-.1	.12
145-102-24DDA	608	-3.5	-3.1	-.38	-.09
147-098-09AAC	710	-4.2	-3.8	.09	.38
153-098-33DCA	850	—	—	.007	.29
147-100-21DBB	151	-1.1	-.7	.77	-.73
148-099-35DCA	107	-1.3	-.9	.64	.95
150-098-06DAA1	104	-2.3	-2.0	.13	.44

[1]Positive values indicate saturation and negative values indicate undersaturation.

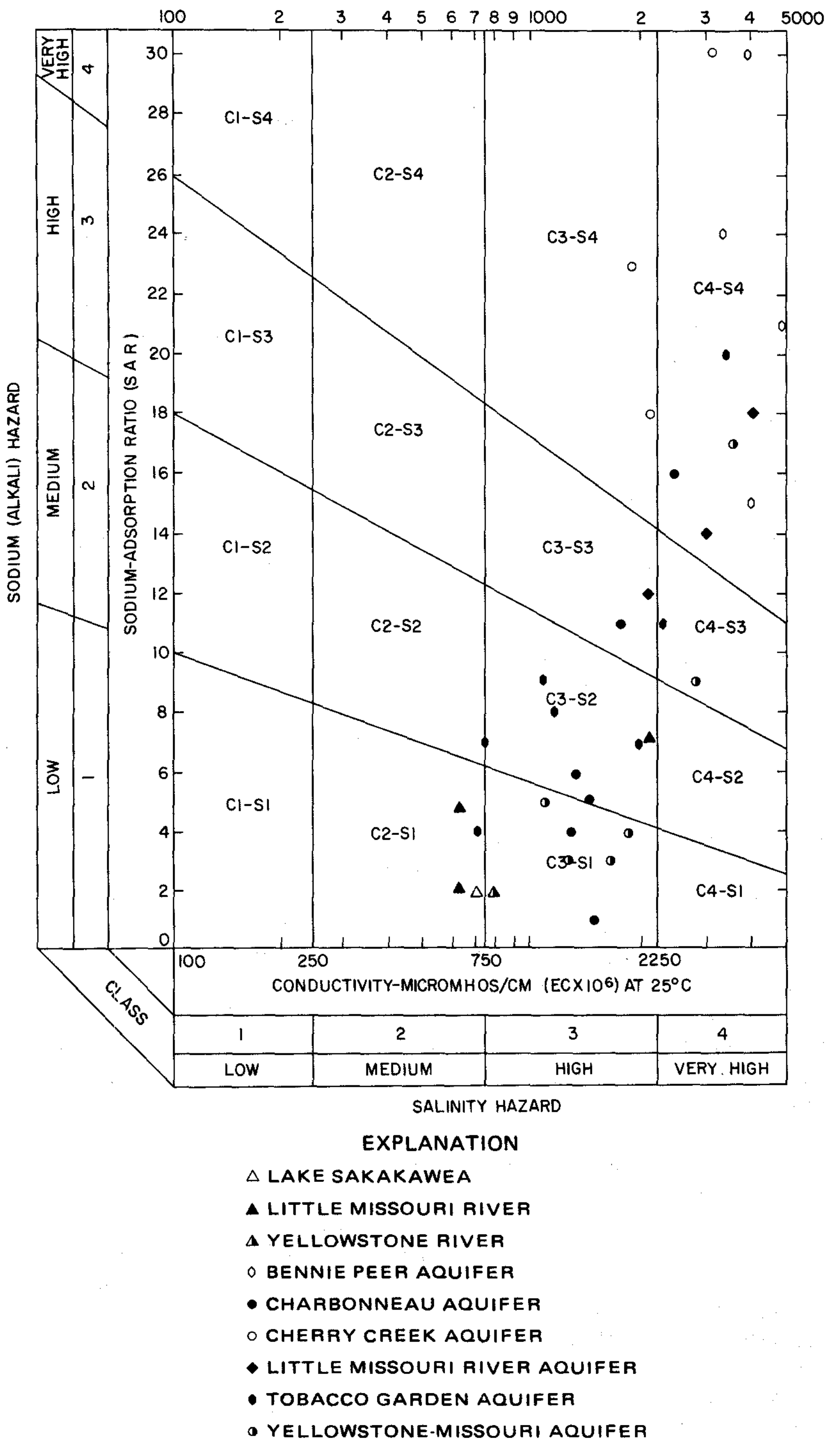


Figure 9.—Classification of selected water samples for irrigation purposes. (Diagram from U.S. Salinity Laboratory Staff, 1954).

Aquifers of Late Cretaceous Age

Fox Hills and Basal Hell Creek Aquifer System

The Fox Hills and basal Hell Creek aquifer system underlies all of McKenzie County and extends into adjoining counties. The aquifer system generally is 1,100 to 1,800 ft (335 to 549 m) below land surface. The shallowest depths are along the Little Missouri River valley, the Nesson anticline, and the shoreline of Lake Sakakawea. The aquifer matrix consists of fine- to medium-grained sandstone, siltstone, and claystone.

In adjoining areas the lower part of the aquifer system, that part equivalent to the Fox Hills, was formed as offshore-bar, sheet, and beach deposits. In McKenzie County, the Fox Hills Sandstone is difficult to identify and may be thin or absent. The upper part of the aquifer system is the basal part of the Hell Creek Formation that consists of mouth-bar and channel deposits composed of sandstone, siltstone, and claystone. The upper part of the Hell Creek Formation consists of delta-plain deposits that act as a confining bed. Frye (1969) named these confining beds the Bacon Creek Member of the Hell Creek. The Fox Hills and basal Hell Creek aquifer system is a little less than 400 ft (122 m) thick along section A-A′ (pl. 2).

Several loose grain mounts of sandstone from well 148-102-15DDA1 penetrating the Fox Hills and basal Hell Creek aquifer system to a depth of 1,180 ft (360 m) were examined in thin section (fig. 10) using a petrographic microscope. The examination showed that most of the sandstone consists of striated feldspar, quartz, and mottled volcanic rock fragments. Much of the quartz and other mineral grains is rounded to semirounded; in contrast, the sandstone from overlying formations is considerably more angular. Rounded grains form more permeable aquifers than angular grains.

The aquifer system is recharged primarily by subsurface inflow from adjacent areas to the south and by leakage from underlying beds. A map of the potentiometric surface of the aquifer system (fig. 11) indicates that ground water generally moves northeastward; the gradient is about 3 ft/mi (0.57 m/km). Discharge from numerous flowing stock and domestic wells in the gorge of the Little Missouri River, the Yellowstone valley, and adjacent to Lake Sakakawea has deflected the potentiometric contours upstream. Discharge from the aquifer is by outflow to the north and by upward leakage into the overlying aquifer systems.

Sidewall cores were obtained from several test holes and were analyzed by Core Laboratories, Inc. Most porosity values are between 25 and 35 percent. Porosity values calculated from bulk-density logs of these test holes are comparable. Values for hydraulic conductivity from the core samples generally are less than 30 ft/d (9 m/d). Those values above 6 ft/d (1.8 m/d) may be due to small fractures in the sample.

A drawdown and recovery test was made on well 148-102-15DDA1 in September 1979. The well is 1,695 ft (517 m) in depth and had a static water level of 210 ft (64 m) below land surface at the start of the test. The well was

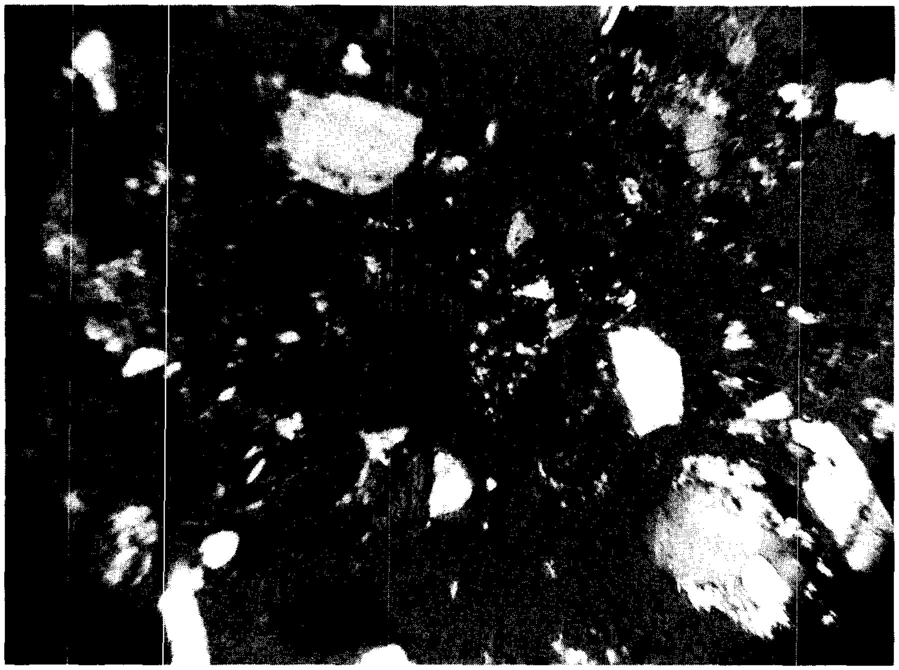


Figure 10.—Thin section of Cretaceous sandstone, 80x.

pumped for 500 minutes at 12 gal/min (0.76 L/s) and had a drawdown of about 6.2 ft (1.9 m). The results indicated a specific capacity of 1.9 (gal/min)/ft [0.39 (L/s)/m] of drawdown and a transmissivity of about 350 ft^2/d (32.5 m^2/d). Data from the test were analyzed by Thomas Johnson, North Dakota State Water Commission, using a time-drawdown semilogarithmic plot (Jacob, 1963).

The transmissivity map (fig. 12) indicates that values range from 200 to 300 ft^2/d (19 to 28 m^2/d) for most of the county. Data on the map were determined, in part, from formation factors calculated from resistivity curves of induction and electric logs using a graph from Croft (1971, fig. 2) to obtain a value for hydraulic conductivity. Other data were obtained from focused-current logs by totaling the sand thickness and multiplying by 2 ft/d (0.6 m/d), which is the average value for hydraulic conductivity of the sandstone from adjoining areas and the average value obtained from the resistivity curves of logs in the area. Actual values obtained from some tests on individual wells may be somewhat greater than the average value because of small fractures in the sandstone. Wells tapping the Fox Hills and basal Hell Creek aquifer system could yield about 100 gal/min (6.3 L/s).

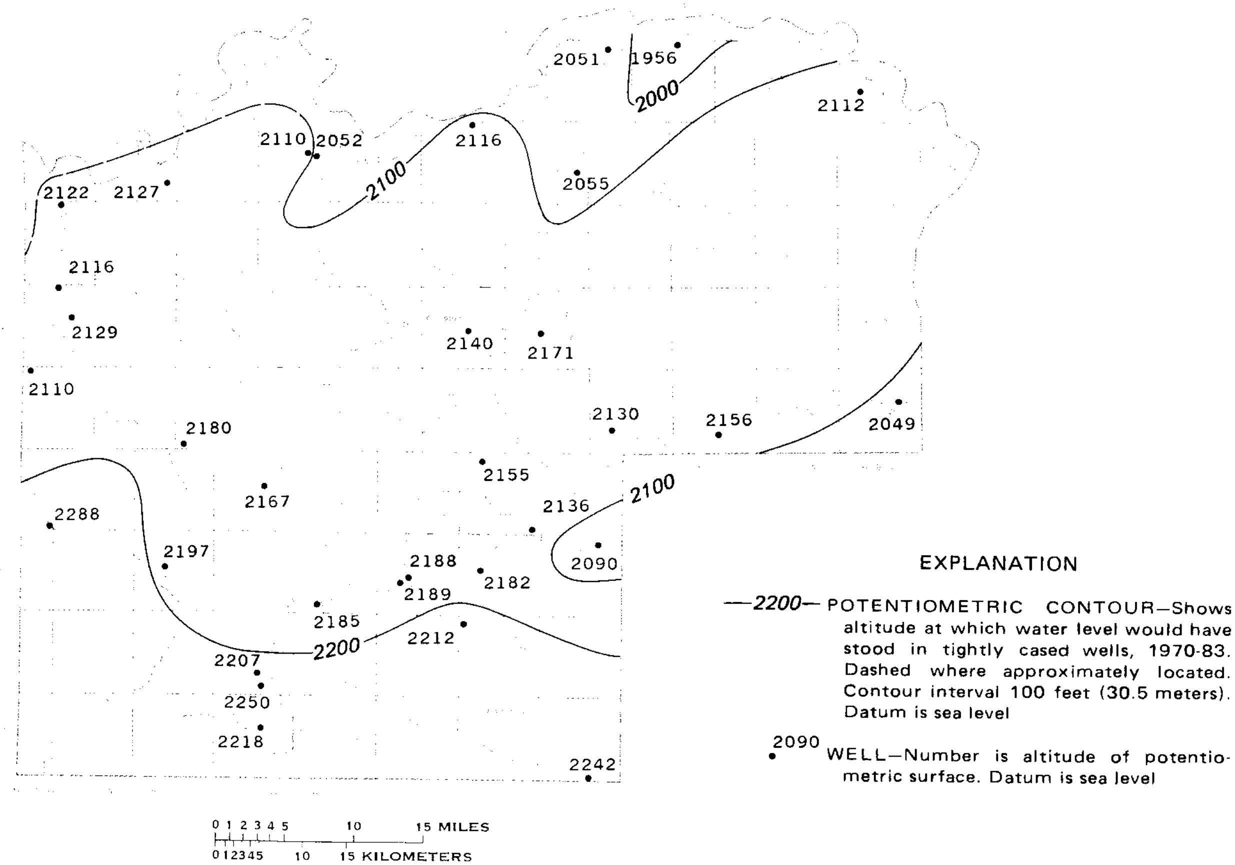


Figure 11.—Potentiometric surface of the Fox Hills and basal Hell Creek aquifer system, 1970-83.

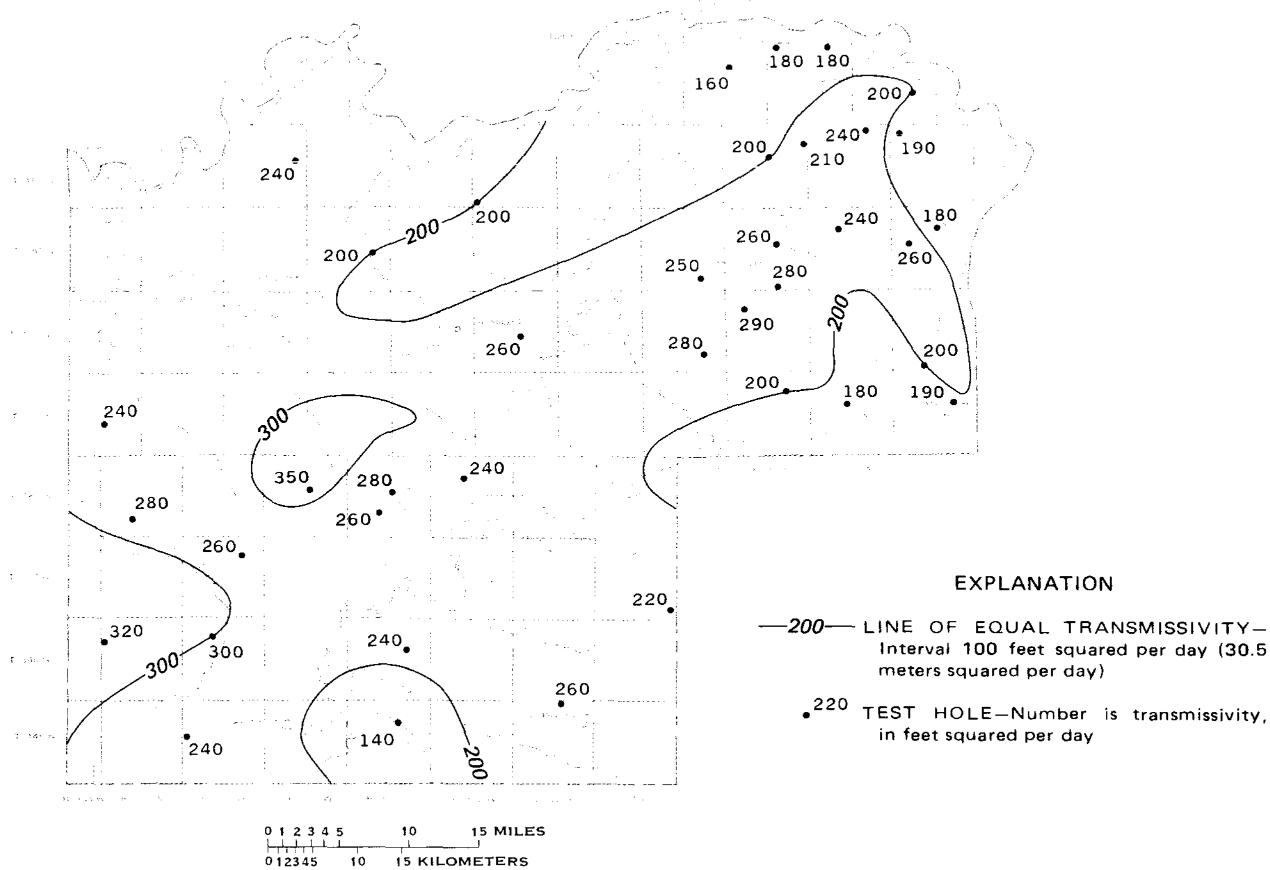


Figure12.—Transmissivity of the Fox Hills and basal Hell Creek aquifer system.

Values for the storage coefficient could not be calculated with the available data; therefore, an alternate method using sonic geophysical logs was used to make estimates. The vertical compressibility of the aquifer system, B_k, was obtained by solution of the formula (Birch, 1942, p. 64)

$$B_k = \frac{3\,(1-\sigma)}{(Vp^2 pk\,(1+\sigma)}, \qquad (3)$$

where σ = Poisson's ratio of the medium, expressed as a decimal fraction;
Vp = the velocity of the longitudinal sound waves in the medium, in feet per second; and
pk = the density of the aquifer skeleton, in pounds per cubic foot.

An assumed value of 0.10 was used for Poisson's ratio (Taylor, 1968, p. C194), and a value of 162.24 lb/ft^3 (2.65 g/cm^3), the density of quartz, was used for the mass density of the aquifer skeleton. Values for Vp were obtained from sonic logs from four sites in the county.

The storage coefficient (S) may, in turn, be calculated by substituting the value for vertical compressibility (B_k) into the formula (Jacob, 1950, p. 334)

$$S = \gamma_w \theta m (B + \frac{B_k}{\theta}), \qquad (4)$$

where γ_w = the specific weight of water, 3.61×10^{-2} lb/in.^{3} (1 g/cm^3) at the prevailing aquifer temperature;
θ = the porosity of the aquifer, expressed as a decimal fraction, a value of 0.33 was obtained from density logs;
B = the compressibility of water, approximately 3.3×10^{-6} in.^{2}/lb (0.004692 mm^2/kg);
m = the saturated thickness of the aquifer, in inches.

Calculated values for the storage coefficient (S) of the aquifer system ranged from 2.2×10^{-4} to 2.7×10^{-4}.

The storage coefficient (S) is equal to specific storage times thickness of the aquifer. Specific storage as well as hydraulic conductivity decreases with increasing stress on the aquifer skeleton (fig. 13). The estimated vertical stress on the aquifer skeleton, S_k, was computed with the following equation (Taylor, 1968):

$$S_k = S_1 - Sw = (m' + \frac{m}{2})\,\gamma_r - h\,\gamma_w, \qquad (5)$$

where S_1 = the stress on the aquifer due to the weight of the overburden,
Sw = the stress borne by the artesian aquifer
m' = the overburden thickness,
m = the aquifer thickness,
γ_r = the specific weight of the overburden and aquifer (estimated to be 2.2 times the specific weight of water),
h = the potentiometric head above the top of the aquifer, and
γ_w = the specific weight of water.

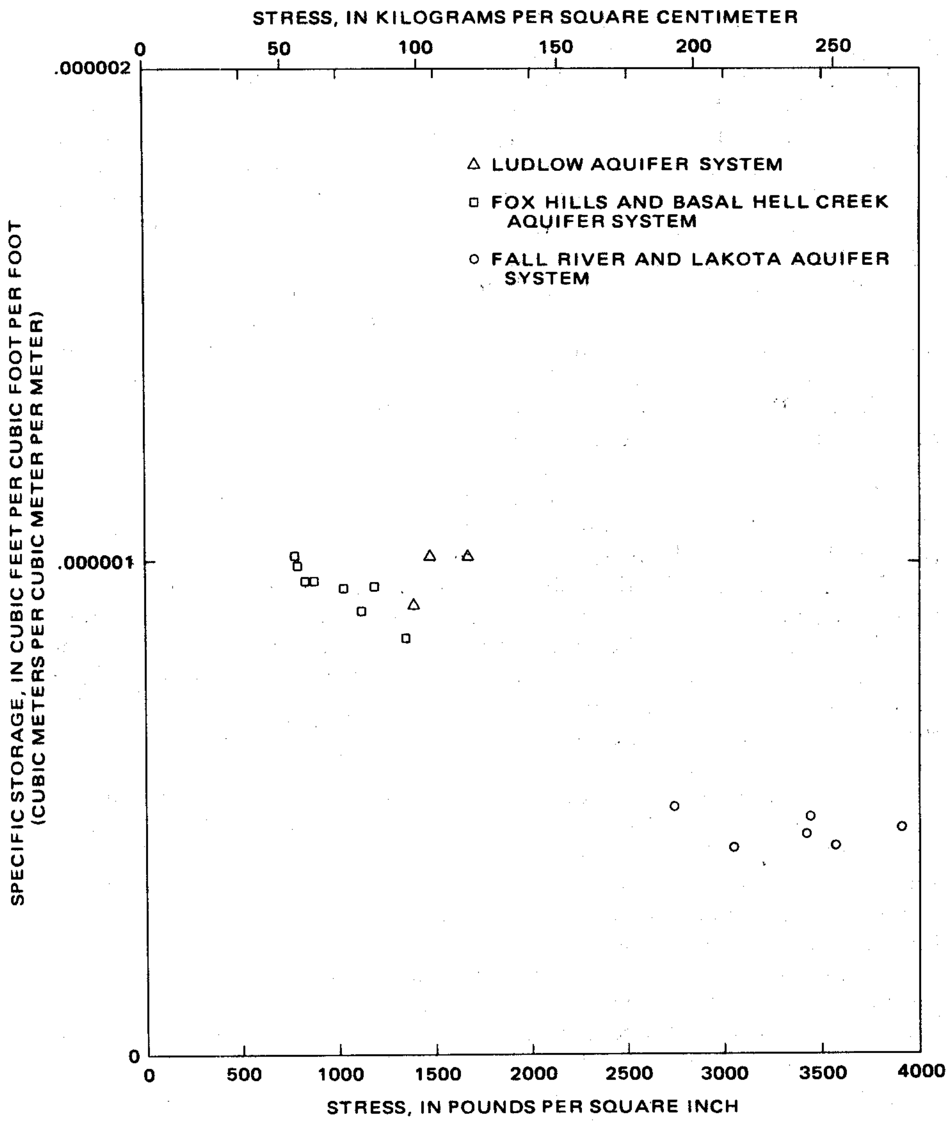


Figure 13.—Estimated vertical stress on aquifer skeleton and specific storage.

Calculated values for specific storage for three aquifers of varying depth from sonic logs are shown in figure 13. The variation of specific storage between the Fox Hills and basal Hell Creek aquifer system and the much deeper Fall River and Lakota aquifer system is very significant, but the difference between the Ludlow and the Fox Hills and basal Hell Creek aquifer systems may be due to uncertainty in the values used in the calculations. The storage coefficient for the aquifers may be estimated by multiplying the value for specific storage by the aquifer thickness. For example, if the Fox Hills and basal Hell Creek aquifer system had a thickness of about 350 ft (107 m) and the mean value for specific storage (8.6×10^{-7} cubic feet per cubic foot per foot) from the data plotted in figure 13, the value for S would be about 3×10^{-4}, nearly equal to the value obtained from a ground-water flow model at Bowman, N. Dak. (Croft, 1978, p. 45), and to the values obtained with equation (4).

Water in the Fox Hills and basal Hell Creek aquifer system is soft and is a sodium bicarbonate type (fig. 8). The water is anoxic and aferric. Water samples collected from the aquifer system had a median dissolved-solids concentration of 1,325 mg/L, a median boron concentration of 1.2 mg/L, and a median SAR of 71 (table 3). Because of the high SAR values, the water is not suitable for irrigation use. The water is, however, suitable for most domestic and livestock uses and for industrial purposes.

The median sulfate concentration (2.1 mg/L) is small, but the median chloride concentration (170 mg/L) is large (table 3). A geochemical study of the Fox Hills and basal Hell Creek aquifer system by Thorstenson and others (1979) indicates that chloride probably is entering the aquifer system from the underlying rocks. A brief discussion is presented in the following paragraph.

The average lateral particle velocity through the aquifer is defined by equation (1), and calculations show that the rate of flow equals 0.005 ft/d (0.0015 m/d) or about 2 ft/yr (0.61 m/yr). Water entering the aquifer system from the south has small chloride concentrations. The chloride concentration rapidly increases northward across the county (fig. 14). The lateral rate of flow, about 2 ft/yr (0.61 m/yr), indicates that any saline connate water entrapped at the time of deposition of the marine Fox Hills Sandstone, about 70,000,000 years ago, would have been flushed under the present hydraulic gradient in about 170,000 years. Because the head in the Fox Hills and basal Hell Creek aquifer system is higher than the head in the overlying aquifer systems, the source for the chloride probably is leakage from the underlying deposits.

Methane sharply increases in concentration from south to north in conjunction with reduction of sulfate by lignite in the aquifer matrix (Thorstenson and others, 1979). Methane concentrations are less than 10 mg/L south of Theodore Roosevelt National Park, but range from 15 to 37 mg/L north of the park (fig. 15). According to Hedberg (1974, fig. 1), kerogen material in the underlying shale formations of Late Cretaceous age is at sufficient depth to be converted to hydrocarbon gases. The possibility of thermogeneration of methane has not been explored sufficiently but may account for part of the methane in the water. However, the thermogeneration mechanism does not account for the large increase in methane and the accelerated rate of sulfate reduction. Methane generation could be related to bacterial sulfate reducti Bacterial activity would be greatest in shallow parts of the aquifer nearest Lake Sakakawea and waste methane production similarly might be expected to be greater there.

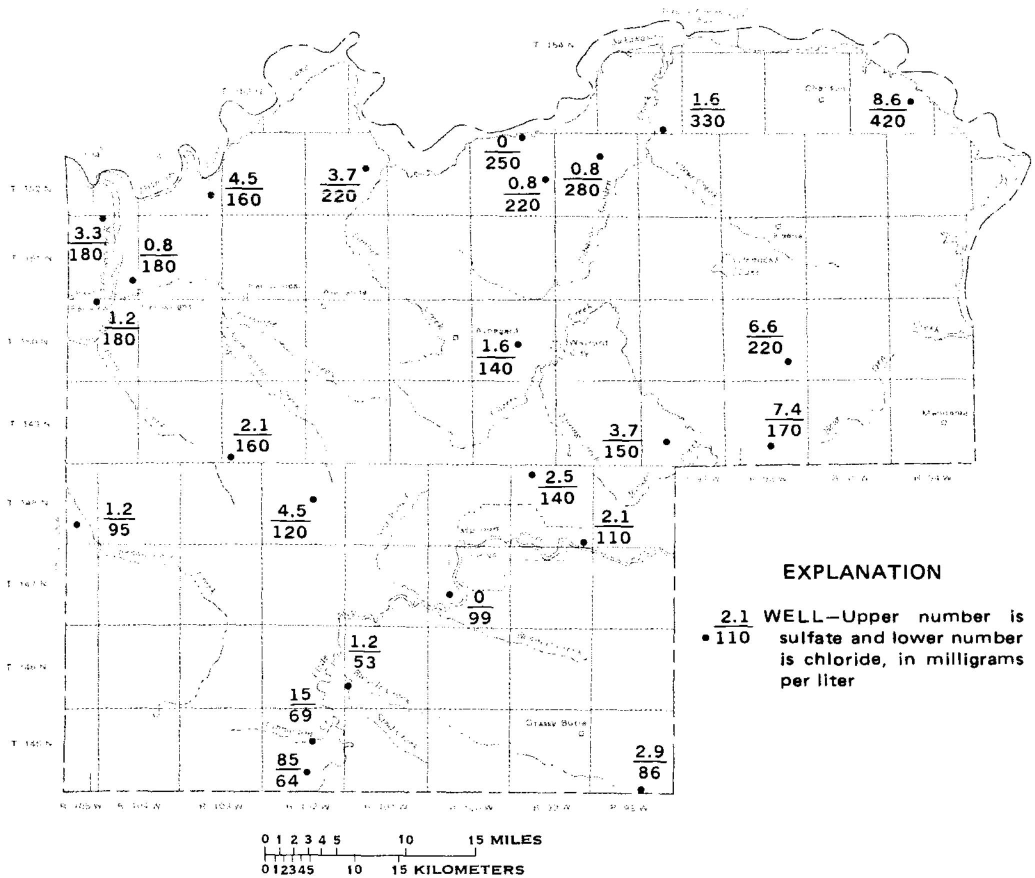


Figure 14.—Concentration of sulfate and chloride in the Fox Hills and basal Hell Creek aquifer system.

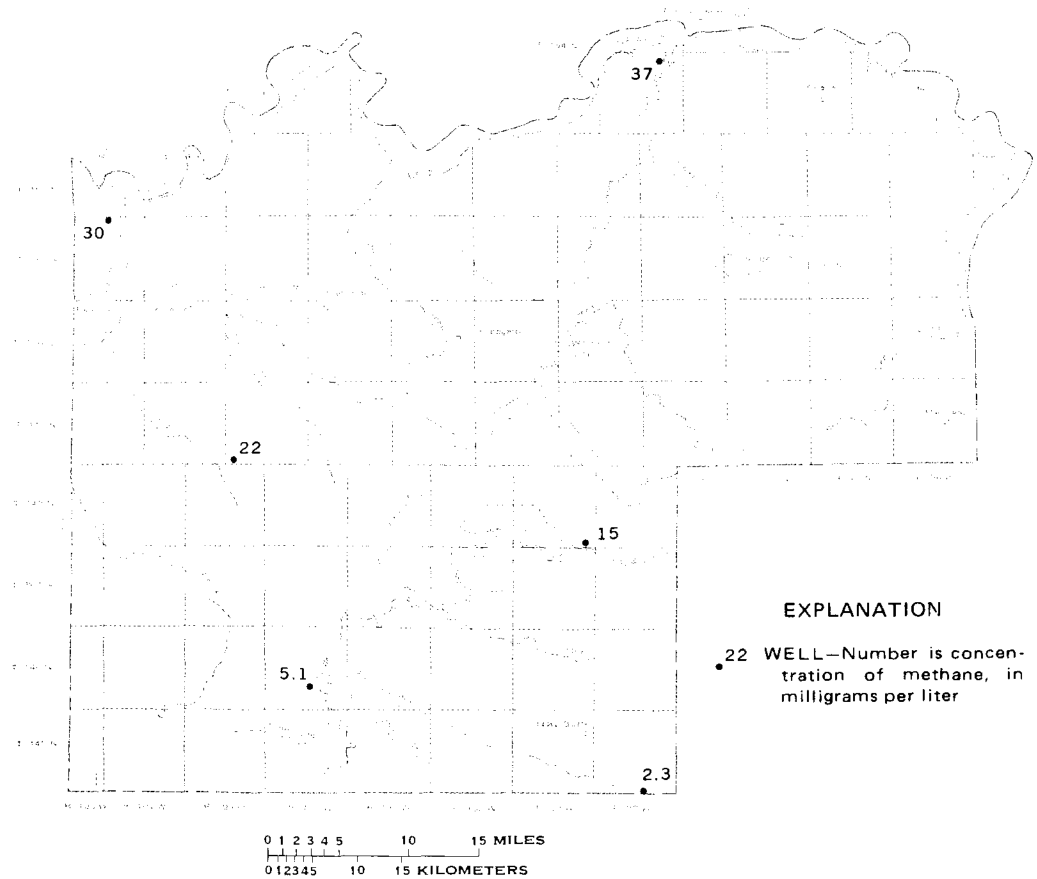


Figure 15.—Concentration of methane in the Fox Hills and basal Hell Creek aquifer system.

Aquifers of Tertiary Age

Ludlow Aquifer System

The Ludlow aquifer system underlies all of McKenzie County at depths of more than 500 ft (152 m). Beds equivalent to the Ludlow and overlying beds have been mapped as the Lebo, Tullock, and Cannonball Members of the Fort Union Formation in adjoining areas. Detailed paleontological data were not available to differentiate these members in this study.

The Ludlow aquifer system consists of fine- to medium-grained sandstone, siltstone, claystone, and lignite formed in meander belts, distributary channels, and fluvial deposits at the head of a delta. The aquifer system is considered to include the lower 600 ft (183 m) of the Fort Union Formation. About 75 ft (23 m) of claystone, which may be equivalent to the Lebo or the Cannonball Members, separates the Ludlow aquifer system from the overlying Tongue River aquifer system (pl. 2). For practical purposes, the Ludlow aquifer system is equivalent to the upper Hell Creek-lower Ludlow aquifer system of Anna (1981) and Croft (1978).

The contour map of the potentiometric surface of the Ludlow aquifer system (fig. 16) indicates two principal features — potentiometric highs occur near Grassy Butte and in the southwest corner of the county and potentiometric lows occur along the Little Missouri River and Lake Sakakawea. The head in the Ludlow aquifer system (fig. 16) generally is lower than the head in the underlying Fox Hills and basal Hell Creek aquifer system (fig. 11), indicating recharge is from the underlying deposits. The potentiometric lows are caused by discharge of flowing livestock and domestic wells. The contours also indicate seepage may be occurring upward into the valley of the Little Missouri River.

Porosity values obtained from sidewall cores of the aquifer system ranged from 26 to 37 percent and hydraulic conductivity (K) values ranged from 0.1 to 14 ft/d (0.03 to 4 m/d). The larger hydraulic conductivity values may be due to small fractures in the sandstone. Assuming an aquifer thickness of 600 ft (183 m), the value for the storage coefficient (S) is about $6x10^{-4}$ (fig. 13). Wells developed in the Ludlow aquifer system could yield as much as 25 gal/min (1.6 L/s).

Water in the Ludlow aquifer system is soft and is a sodium bicarbonate type (fig. 8). Water samples obtained from the aquifer system had a median dissolved-solids concentration of 1,750 mg/L (table 3). Chloride constituted about 9 percent of the anions and probably enters the aquifer system from the underlying rocks. The water is not suitable for irrigation or municipal use. It is, however, suitable for most domestic and livestock uses. The water from some wells is light brown due to dissolved organic compounds.

Tongue River Aquifer System

The Tongue River aquifer system underlies all of McKenzie County. The aquifer system is 140 to 500 ft (43 to 152 m) below land surface in most areas

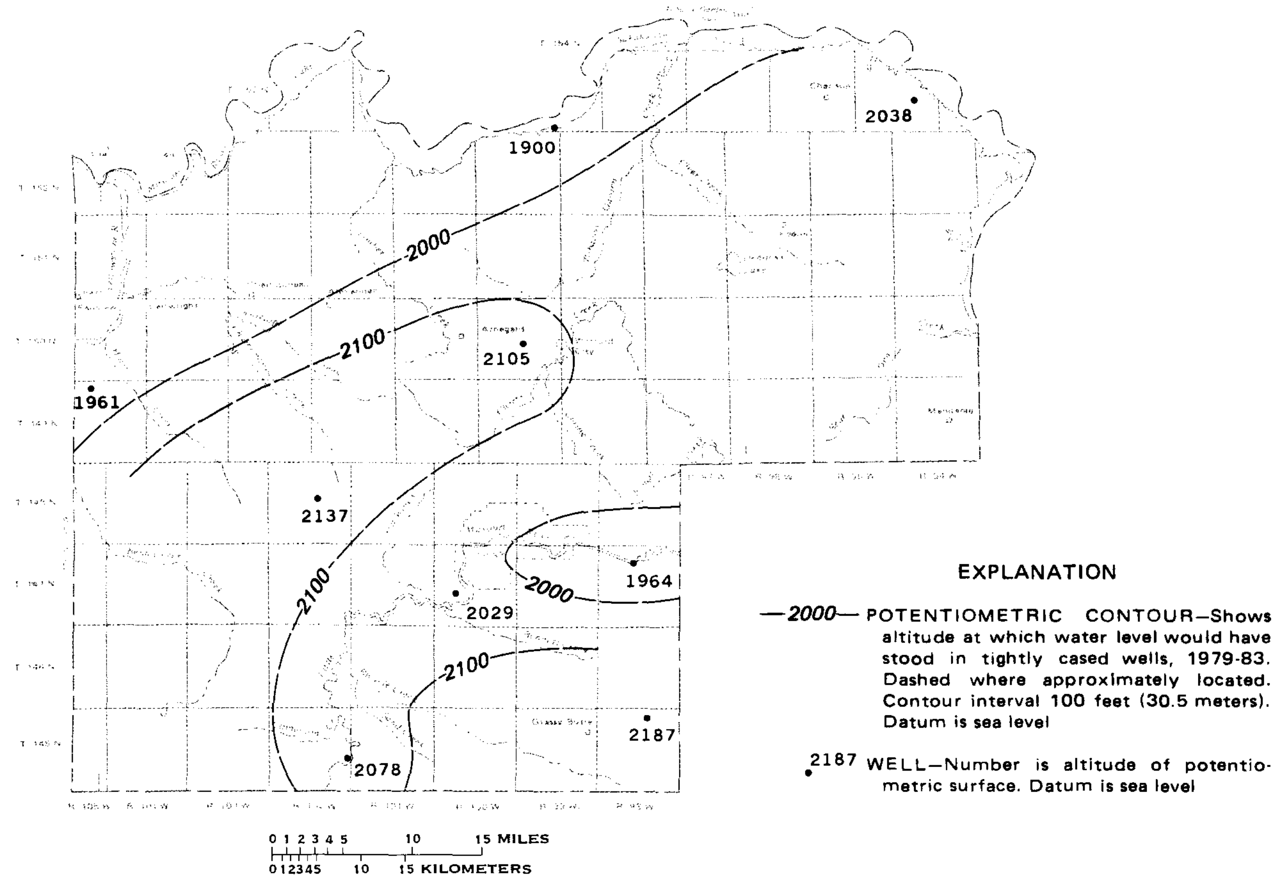


Figure 16.—Potentiometric surface of the Ludlow aquifer system, 1979-83.

and consists of fine- to medium-grained sandstone, siltstone, claystone, and lignite deposited as distributary-channel, mouth-bar, and delta-plain deposits. The coarsest and thickest deposits of sandstone generally are in the lower part of the Tongue River Member of the Fort Union Formation and are about 400 ft (122 m) thick in test hole 150-099-22BBA (pl. 2).

Most of the recharge to the Tongue River aquifer system is from precipitation and seepage from lakes and streams. Shallow wells in the overlying deposits of the Sentinel Butte Member generally have higher heads than wells in the Tongue River aquifer system, indicating that ground water is moving downward. The general movement of ground water is from south to north (fig. 17). The hydraulic gradient near the north unit of Theodore Roosevelt National Park is about 10 ft/mi (1.9 m/km). The head in the aquifer system generally is lower than in the underlying aquifer systems, indicating there is some recharge from the underlying rocks. Ground water discharges to the north, beyond the area of this investigation.

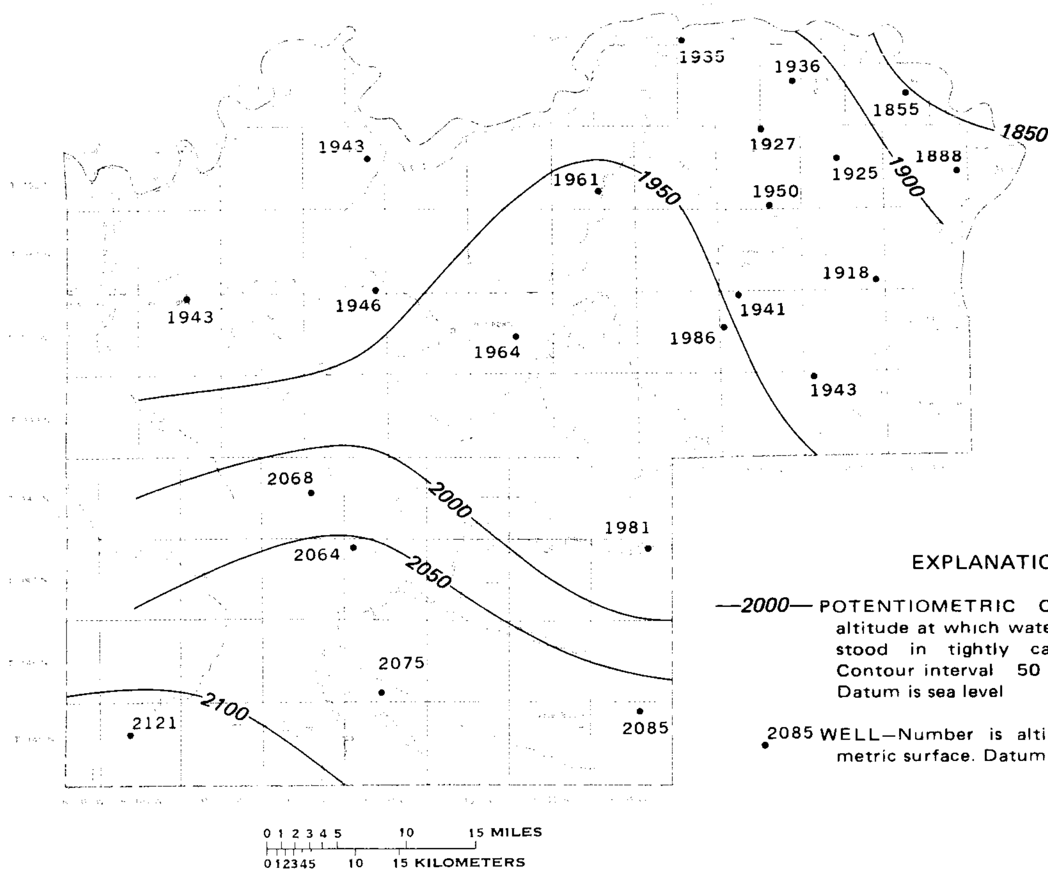
Porosity values obtained from sidewall cores of the Sentinel Butte and Tongue River Members ranged from 27 to 37 percent. Hydraulic conductivity (K) values from these samples were small and ranged from 0.03 to 58 ft/d (0.01 to 18 m/d). Most values greater than 5 or 6 ft/d (1.5 or 1.8 m/d) probably were due to small fractures in the samples. Wells will yield about 25 gal/min (1.6 L/s).

Water from the Tongue River aquifer system generally is soft and is a sodium bicarbonate type (fig. 8). Water samples obtained from the aquifer system had a median dissolved-solids concentration of 1,830 mg/L (table 3). Chloride constituted about 5 percent of the anions. The chloride concentration is larger than the chloride concentration in samples from the glacial-drift and alluvial aquifers (table 3) and five samples collected from the overlying Sentinel Butte Member. The larger concentration indicates that part of the chloride probably enters the aquifer from the underlying deposits. Water from the aquifer system is not usable for irrigation or municipal purposes. It is, however, suitable for most domestic and livestock uses. Much of the water is yellowish brown due to dissolved organic compounds.

Aquifers of Quaternary Age

Bennie Peer Aquifer

The Bennie Peer aquifer is a long narrow glaciofluvial deposit in the valleys of Bennie Peer and West and East Hay Draw Creeks from the Montana state line to the Little Missouri River. These valleys are near the southernmost extent of glacial ice in the county. The valleys were carved by glacial melt water and by the combined flow of the Yellowstone and Missouri Rivers. Backfill in the valleys, near section B-B′ (fig. 18), consists of about 70 ft (21 m) of outwash sand and gravel, 55 ft (17 m) of fine-grained lakebed deposits, and about 45 ft (14 m) of alluvium and colluvium. Backfill near the Little Missouri River is thicker and contains more fine-grained deposits. The aquifer is about 22 mi (35 km) long and less than a mile (1.6 km) in width.



EXPLANATION

—2000— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, 1983. Contour interval 50 feet (15.2 meters). Datum is sea level

• 2085 WELL—Number is altitude of potentiometric surface. Datum is sea level

Figure 17.—Potentiometric surface of the Tongue River aquifer system, 1983.

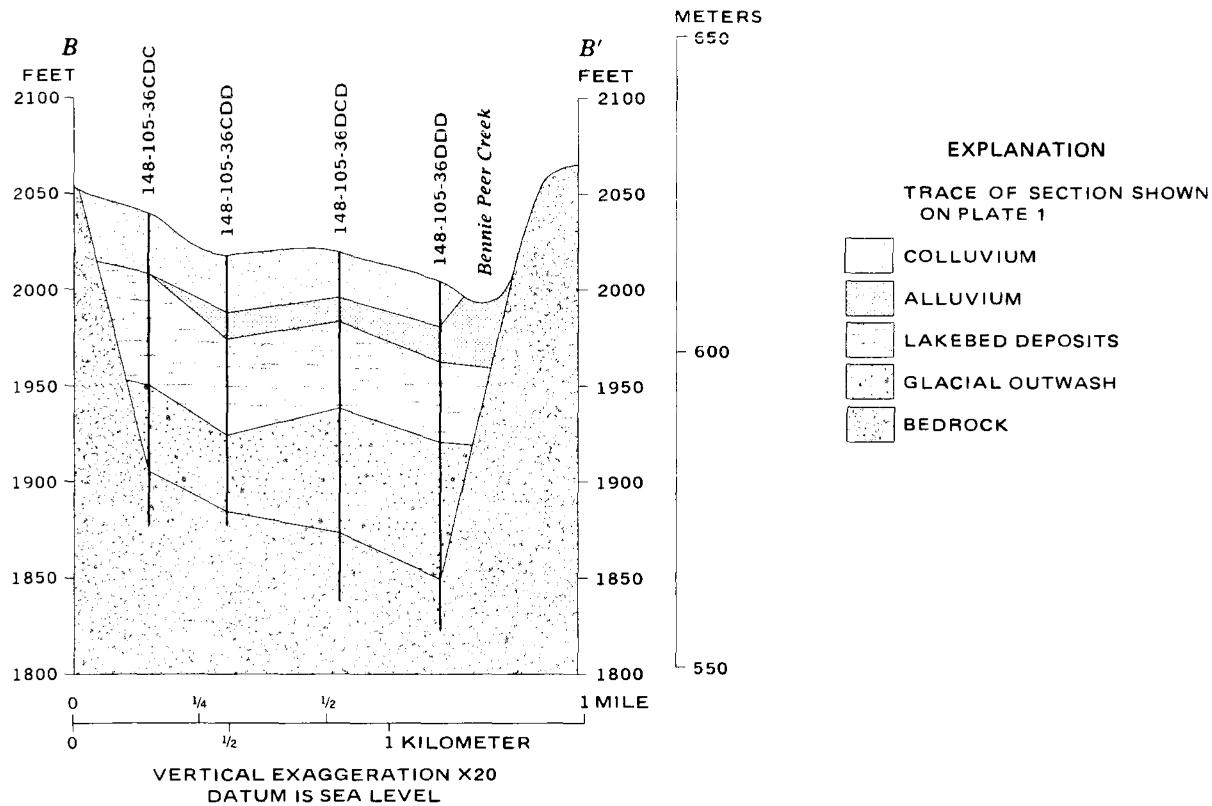


Figure 18.—Geologic section B-B′ through the Bennie Peer aquifer.

Values for transmissivity (T) were estimated for the sand and gravel deposits using the graph in figure 7. Transmissivity ranges from about 3,000 to 13,000 ft^2/d (250 to 1,200 m^2/d; pl. 1) in the central part of the aquifer where wells may yield in excess of 100 gal/min (6.3 L/s). Assuming a porosity of about 40 percent, a thickness of 100 ft (30 m), and a width of 0.7 mi (1.1 km), a 12-mi (19.3-km) stretch of the western part of the aquifer contains about 215,000 acre-ft (265 hm^3) of water in storage. About 108,000 acre-ft (133 hm^3) could be recovered by wells.

Water-level fluctuations in well 148-105-36CDC in the Bennie Peer aquifer are shown in figure 19. The water level rose from February to March 1980 and from October 1980 to February 1981 and from September 1981 to July 1982 due to recharge. The water level declined from March to October 1980 and February to September 1981 when discharge by evapotranspiration, springs, and seeps exceeded recharge by precipitation and inflow from the adjoining bedrock.

Eight water samples collected from the Bennie Peer aquifer contained large amounts of dissolved solids. The principal cation was sodium (fig. 8). Sulfate constituted about 60 percent of the anions and probably is dissolved from soluble sulfate minerals in the soil. Dissolved-solids concentrations ranged from 2,640 to 4,970 mg/L, and the median was 3,060 mg/L. Median boron concentration was 0.19 mg/L. The water is not usable for irrigation as it is classed C4-S4 (fig. 9). Due to the large sulfate and dissolved-solids concentrations, the water is suitable only for livestock use.

Charbonneau Aquifer

The Charbonneau aquifer is a long sinuous glaciofluvial deposit that underlies parts of Charbonneau and Timber Creeks from the Yellowstone River bottoms near Cartwright to Lake Sakakawea northeast of Alexander. The aquifer material fills an ice-marginal channel that was carved by the combined flow of the Yellowstone and Missouri Rivers. At test hole 151-102-14CCC, northeast of Charbonneau, the channel is backfilled with about 50 ft (15 m) of glacial outwash consisting of sand and gravel, more than 185 ft (56 m) of fine-grained lakebed deposits, and about 35 ft (11 m) of colluvium (fig. 20). At Cartwright most of the test holes penetrated more than 30 ft (9.1 m) of sand and gravel. The aquifer is about 24 mi (39 km) long and about 1 mi (1.6 km) in width.

Estimates of transmissivity (T) for the sand and gravel were made using figure 7. Wells that penetrate the outwash could yield more than 100 gal/min (6.3 L/s; pl. 1). At Cartwright, yields of more than 500 gal/min (31.5 L/s) are possible. Assuming a porosity of about 40 percent, a thickness of 50 ft (15 m), a width of 0.5 mi (0.8 km), and a length of 8 mi (13 km), the aquifer contains about 50,000 acre-ft (62 hm^3) of ground water in storage west of Charbonneau. Without additional recharge, about 25,000 acre-ft (31 hm^3) could be recoverable by wells. An additional 50,000 acre-ft (62 hm^3) of water probably is available east of Charbonneau, but this area was not explored as extensively.

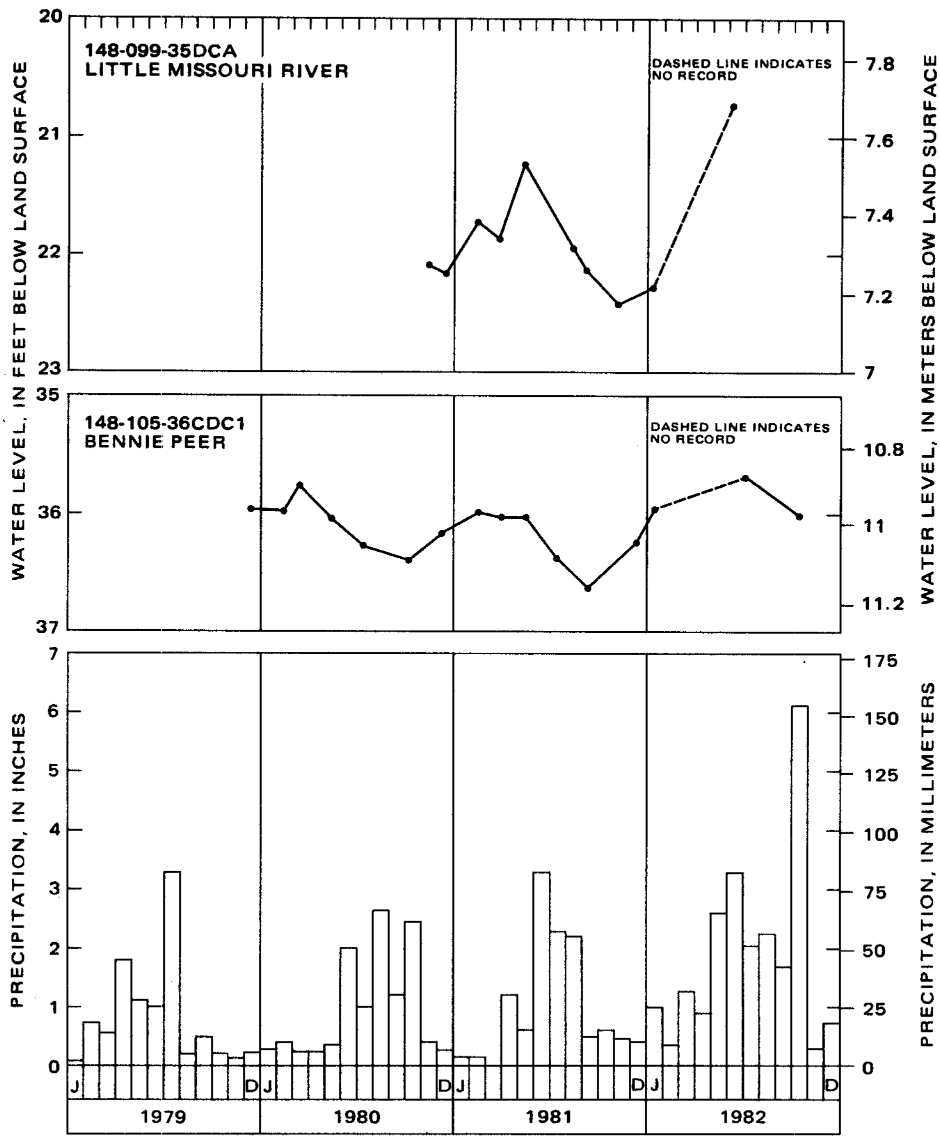


Figure 19.—Water-level fluctuations in the Bennie Peer and Little Missouri River aquifers and precipitation at Watford City, N. Dak.

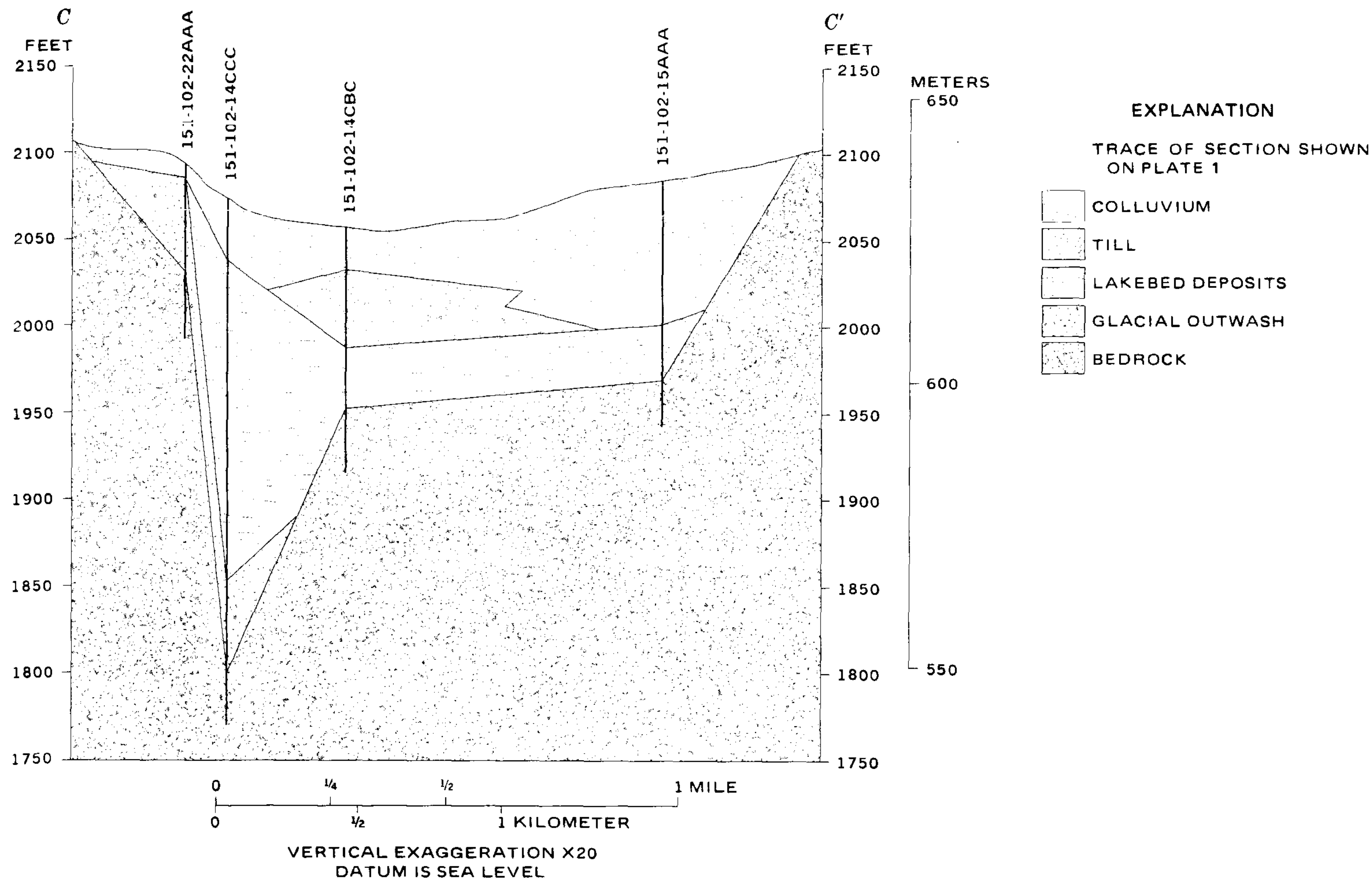


Figure 20.—Geologic section C-C′ through the Charbonneau aquifer.

The water level in well 152-101-24CBB1 (fig. 21) reflects the aquifer response to seasonal changes in recharge and discharge. From February to March 1980 the water level rose about 0.5 ft (0.15 m) from infiltration of melting snow, and declined about 0.5 ft (0.15 m) from July to October 1980 when discharge by springs, seeps, and evapotranspiration exceeded precipitation and inflow from adjoining bedrock.

Thirteen water samples collected from the Charbonneau aquifer contained moderate amounts of dissolved solids (table 3). Sodium was the principal cation and bicarbonate was the principal anion (fig. 8). Dissolved-solids concentrations ranged from 894 to 1,790 mg/L, and the median value was 1,100 mg/L. Boron had a median value of 0.06 mg/L. The water is classed C3-S1 to C4-S4 for irrigation purposes (fig. 9). Water from the aquifer is suitable for domestic and livestock supplies and from some parts of the aquifer is suitable for municipal and industrial supplies and for irrigation use.

Cherry Creek Aquifer

The Cherry Creek aquifer is a sinuous glaciofluvial deposit of sand and gravel that underlies Cherry Creek southeast of Watford City, N. Dak. The aquifer occupies a deep valley carved by glacial melt water that flowed southward into the rerouted Little Missouri River. Prior to glaciation, Cherry Creek flowed to the northwest (fig. 6). Locally, the sand and gravel is more than 100 ft (30.5 m) thick. The aquifer is less than a mile (1.6 km) wide and was accessible for test drilling only in the northern part. Based on the graph in figure 7, wells that penetrate the aquifer could yield more than 500 gal/min (31.5 L/s) in the vicinity of Highway 23, a few miles east of Watford City.

Water-level fluctuations in water-table well 150-098-23AAB in the Cherry Creek aquifer are shown in figure 21. The water level rose from October 1980 to February 1981 and from September 1981 to the summer of 1982. Declines were recorded from May to August 1980 and from February to November 1981 due to subsurface outflow, discharge by springs, and evapotranspiration exceeding precipitation and inflow from adjoining bedrock.

Four water samples collected from the aquifer contained moderate amounts of dissolved solids (table 3) and were a sodium bicarbonate type (fig. 8). Sodium and potassium constitute more than 90 percent of the cations. Dissolved-solids concentrations ranged from 1,570 to 3,520 mg/L and had a median value of 2,080 mg/L. The median value for boron was 0.12 mg/L. The water is classed C3-S4 or C4-S4 for irrigation purposes (fig. 9). Water in the Cherry Creek aquifer is suitable for domestic, livestock, municipal, and industrial supplies.

Little Missouri River Aquifer

The Little Missouri River aquifer is a long thin deposit consisting mainly of glacial outwash in the valley of the Little Missouri River. The deposit underlies the Crane Creek bench. The gorge was carved by melt water and is backfilled with as much as 176 ft (54 m) of sand and gravel (fig. 22) near

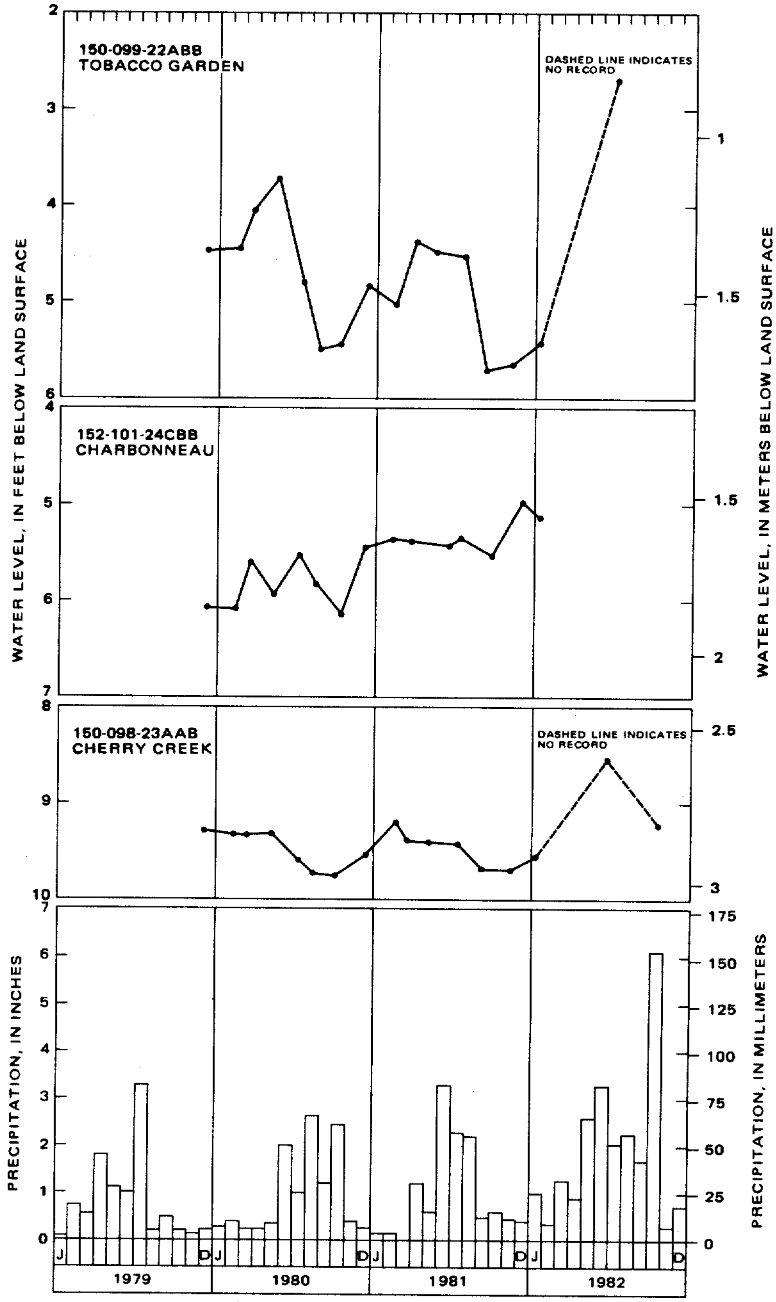


Figure 21.—Water-level fluctuations in Charbonneau, Cherry Creek, and Tobacco Garden aquifers and precipitation at Watford City, N. Dak.

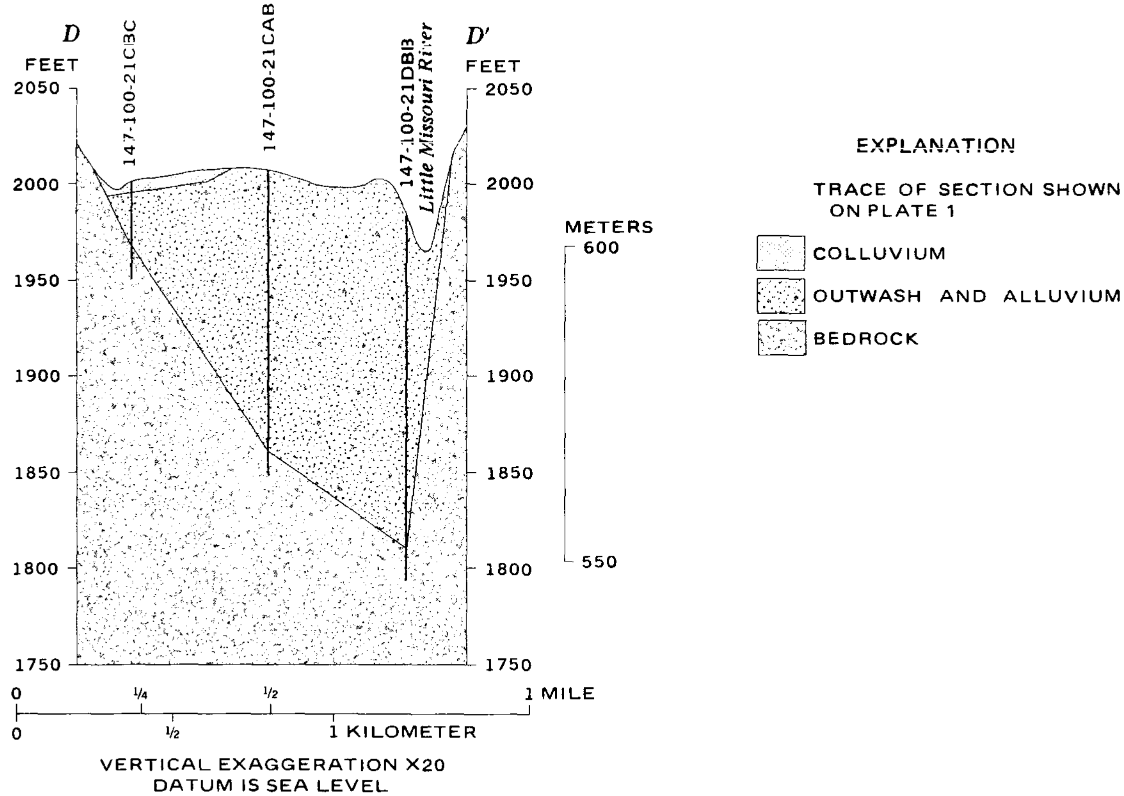


Figure 22.—Geologic section D-D' through the Little Missouri River aquifer.

Theodore Roosevelt National Park. The aquifer is about 40 mi (64 km) long and about three-fourths of a mile wide. Wells that penetrate the aquifer north of Cinnamon Creek could yield more than 100 gal/min (6.3 L/s), based on estimates using figure 7. Assuming a porosity of 35 percent, a thickness of 150 ft (46 m), a width of 0.75 mi (1.2 km), and a length of 20 mi (32 km), about 575,000 acre-ft (709 hm^3) of ground water is stored in the aquifer east of Red Wing Creek. About 288,000 acre-ft (355 hm^3) could be recoverable by wells.

Water-level fluctuations in well 148-099-35DCA in the Little Missouri River aquifer are shown in figure 19. The water level generally rose from December 1980 to May 1981 and from November 1981 to June 1982 due to snowmelt and precipitation. The water level declined from May to November 1981 due to discharge by evapotranspiration, seeps, and springs exceeding recharge by precipitation and inflow from adjoining bedrock.

Five water samples collected from the Little Missouri River aquifer contained large amounts of dissolved solids (table 3). Sodium constituted about 75 percent of the cations, and sulfate constituted about 55 percent of the anions (fig. 8). The sulfate is derived by leaching gypsum from the soil (table 5). Dissolved-solids concentrations ranged from 1,620 to 4,310 mg/L, and the median was 2,330 mg/L. The median value for boron was 0.09 mg/L. The water is classed C3-S3 to C4-S4 for irrigation purposes (fig. 9). Due to the large sulfate and dissolved-solids concentrations, the water is suitable mainly for livestock use.

Tobacco Garden Aquifer

The Tobacco Garden aquifer is a long sinuous bed of alluvial material deposited along the floor of the preglacial Little Missouri valley. The alluvial sand and gravel, as much as 85 ft (26 m) thick (figs. 23 and 24), is considered to be the same age as the Cartwright bench and generally is overlain by lakebed deposits, till, and colluvium. The aquifer extends from the confluence of Red Wing Creek with the Little Missouri River to Tobacco Garden Bay. The maximum width is about 3 mi (4.8 km).

Parts of the aquifer north of Watford City may yield more than 500 gal/min (31.5 L/s) to wells (pl. 1). Based on a porosity of about 40 percent, a width of about 1 mi (1.6 km), a thickness of 70 ft (21 m), and a length of 23 mi (37 km), about 410,000 acre-ft (506 hm^3) of ground water is stored in the aquifer north of Watford City. About 200,000 acre-ft (247 hm^3) could be recoverable by wells.

An aquifer test was made in May 1980 using irrigation well 150-098-06ADD1 owned by Mark Johnsrud as the pumped well and four observation wells (Thomas Johnson, North Dakota State Water Commission, written commun., 1980). Aquifer thickness ranges from 80 to 99 ft (24 to 30 m) at the test site. The pumped well is 136 ft (41.5 m) deep and screened from 101 to 136 ft (30.8 to 41.5 m). The well was pumped at 851 gal/min (53.7 L/s) for 4,500 minutes. The transmissivity at the test site was estimated to be between 7,000 to 19,900 ft^2/d (650 to 1,849 m^2/d; table 6), and the hydraulic

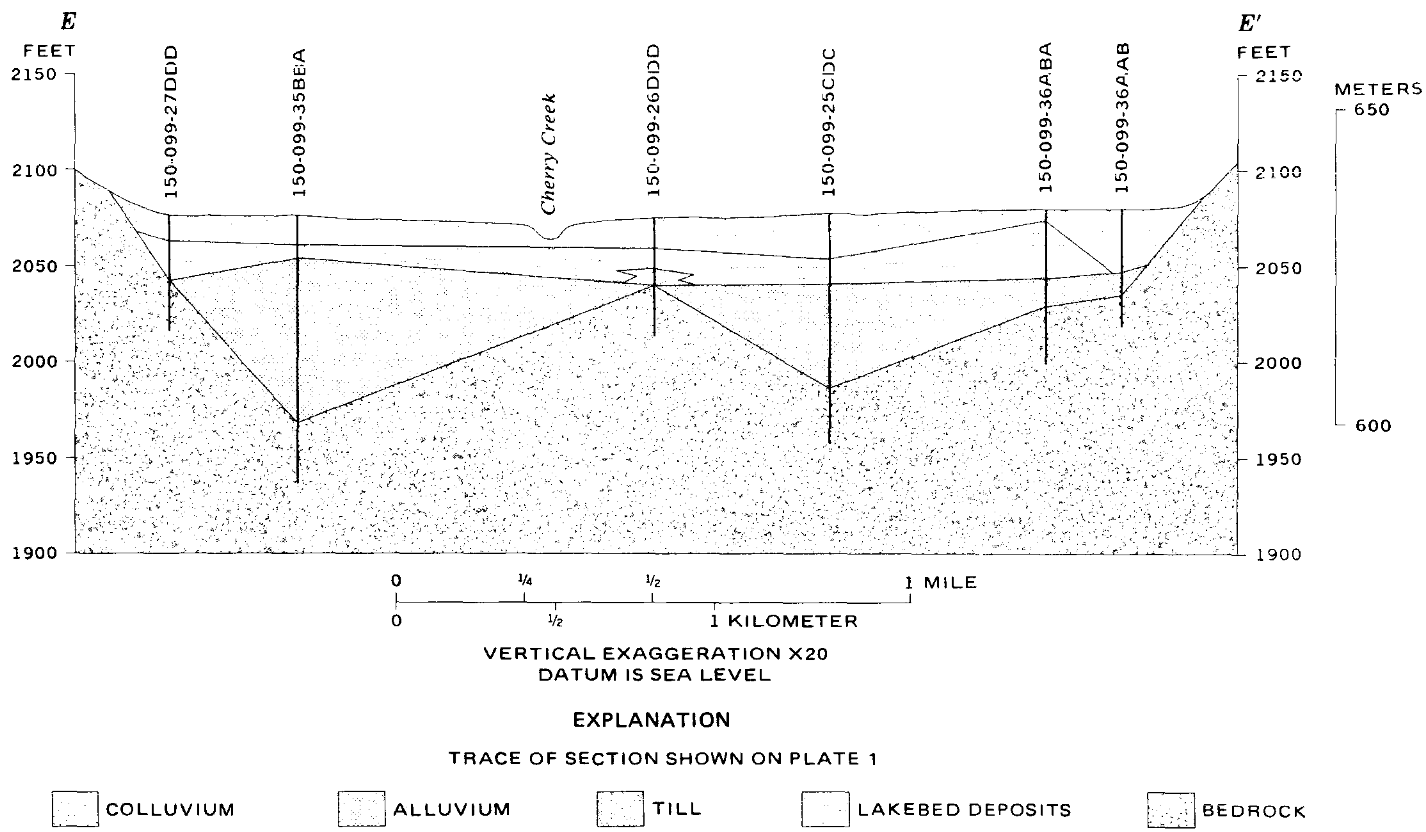


Figure 23.—Geologic section E-E′ through the Tobacco Garden aquifer.

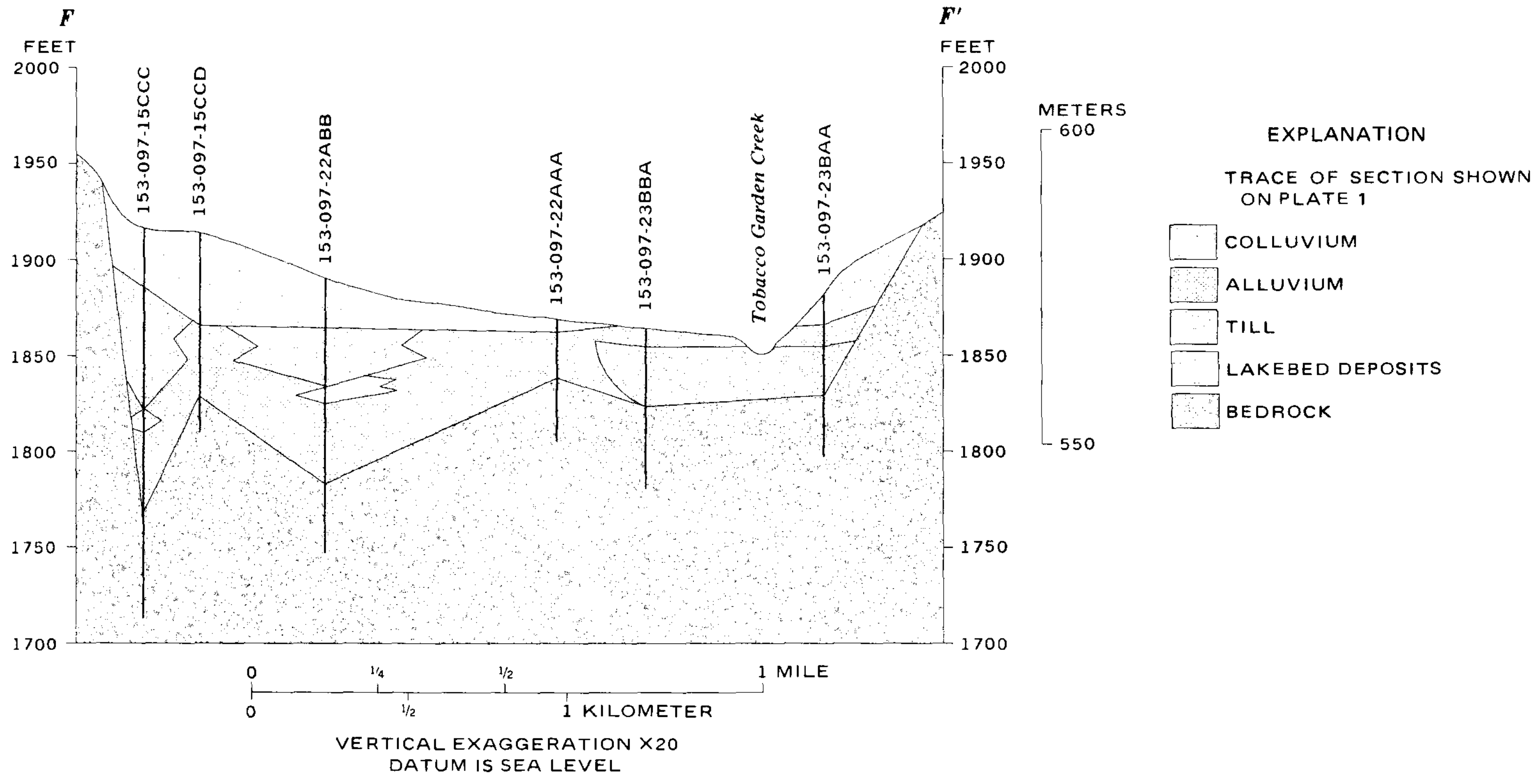


Figure 24.—Geologic section F-F′ through the Tobacco Garden aquifer.

conductivity was estimated to be about 500 ft/d (152 m/d). The estimated storage coefficient ranged from 0.0002 to 0.0006. Drawdown at the end of 4,500 minutes was 46.86 ft (14.3 m), and indicates a specific capacity of 18.2 (gal/min)/ft [3.8 (L/s)/m] of drawdown.

TABLE 6 — Results of aquifer test of the Tobacco Garden aquifer, May 1980

Well	Distance from pumped well (feet)	Aquifer thickness (feet)	Semilog plot method (Jacob, 1963)	Theis method (Wenzel, 1942)	
			Transmissivity (feet squared per day)		Storage coefficient
150-098-06ADD1 (pumped well)	—	—	9,850	—	—
150-098-06DAA1 (observation well)	50	95	11,850	11,650	0.0002
150-098-06ADD2 (observation well)	200	85	19,900	9,650	.0006
150-098-06DAA2 (observation well)	500	99	12,950	7,000	.0002
150-098-06ADA (observation well)	1,000	85+	16,700	12,650	.0006

Water-level fluctuations in well 150-099-22ABB in the Tobacco Garden aquifer are shown in figure 21. The water level rose from February to May 1980, from February to April 1981, and from September 1981 to July 1982 due to snowmelt and precipitation. The water level declined from May to August 1980 and from April to September 1981 when subsurface outflow and discharge from evapotranspiration exceeded recharge.

Fifty-two water samples collected from the Tobacco Garden aquifer contained moderate amounts of dissolved solids (table 3). Sodium constituted about 80 percent of the cations, and bicarbonate and carbonate about 60 percent of the anions (fig. 8). Dissolved-solids concentrations ranged from 467 to 3,070 mg/L, and the median value was 947 mg/L. The median value for boron was 0.20 mg/L. The median value for SAR was 10, and the water is classed C2-S1 to C4-S4 for irrigation purposes (fig. 9). The water generally is suitable for most domestic, livestock, municipal and industrial uses and for irrigation.

Yellowstone-Missouri Aquifer

The Yellowstone-Missouri aquifer is a thick blanket of glacial material deposited in the valleys of the Yellowstone and Missouri Rivers near East Fairview and Williston. The deposit underlies the Crane Creek bench. The valleys have been backfilled with as much as 92 ft (28 m) of outwash sand and gravel from mountain and continental glaciers and 20 to 45 ft (6 to 14 m) of finer alluvial material (fig. 25). The aquifer underlies about 55 mi^2 (142 km^2) in McKenzie County.

Wells penetrating the aquifer could yield more than 500 gal/min (31.5 L/s; pl. 1) in parts of the area. Assuming a porosity of 35 percent, a thickness of 100 ft (30 m), and a 55-mi^2 (142-km^2) area, about 1,400,000 acre-ft (1,726 hm^3) of water is stored in the aquifer. About 700,000 acre-ft (863 hm^3) could be recovered by wells, assuming there is no recharge from streams and precipitation.

An aquifer test was made in August 1967 (Roger Schmid, North Dakota State Water Commission, written commun., 1967) using well 150-104-20CCC1 as the pumped well and four observation wells. The aquifer has a thickness of about 80 ft (24 m) at the test site. The well was pumped at the rate of 1,210 gal/min (76.3 L/s) for 3,050 minutes. The test was analyzed by two methods and the results are summarized in table 7. The transmissivity ranged from

TABLE 7 — Results of aquifer test of the Yellowstone-Missouri aquifer, August 1967

Well	Distance from well depth (feet)	pumped well (feet)	Semilog plot method (Jacob, 1963)	Theis method (Wenzel, 1942)	
			Transmissivity (feet squared per day)		Storage coefficient
150-104-20CCC (pumped well)	91	—	12,300	—	—
#1 (observation well)	88	199	18,900	23,100	0.00075
#4 (observation well)	73	223	20,500	18,900	.0006
#4A (observation well)	41	230	15,500	10,900	.0027
150-104-29BBB #5 (observation well)	76	403	17,700	26,500	.0005

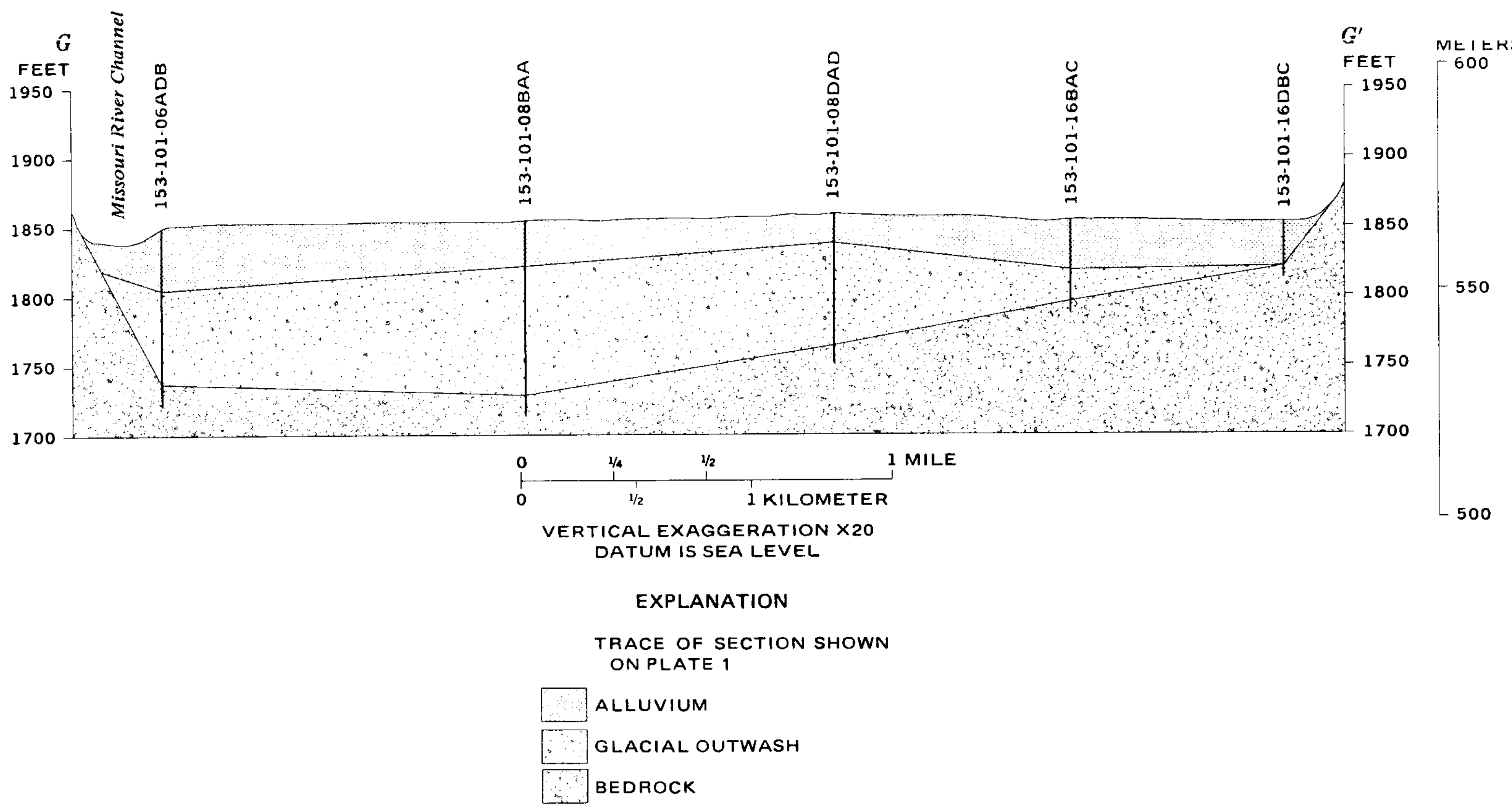


Figure 25.—Geologic section G-G' through the Yellowstone-Missouri aquifer.

10,900 ft^2/d to 26,500 ft^2/d (1,013 to 2,462 m^2/d). Transmissivity determined by a time-drawdown analysis at 3,000 minutes was 12,400 ft^2/d (1,152 m^2/d). Estimated hydraulic conductivity was about 200 ft/d (61 m/d). Values for storage coefficient ranged from 0.0027 to 0.0005. Drawdown at the end of the 3,050 minutes was 27.7 ft (8.4 m), indicating a specific capacity of 43.7 (gal/min)/ft [(9 L/s)/m] of drawdown.

Water-level fluctations in observation well 151-104-10CBB near East Fairview are shown in figure 26. Water levels in the aquifer respond to seasonal changes in recharge and discharge. The water level in the water-table well rises each spring and summer due principally to snowmelt, precipitation, and irrigation return infiltrating to the aquifer. The water level generally declines from July or August to February or March of each year when subsurface outflow and discharge from evapotranspiration exceeds recharge.

The water level in observation well 153-101-16BAC (fig. 26) responded to changes in recharge to and discharge from the aquifer near the Missouri River. The water level was high from December 1980 to February 1981 and December 1981 to February 1982 when ice on Lake Sakakawea created backwater and caused the river stage to rise during the winter months.

Fourteen water samples collected from the Yellowstone-Missouri aquifer generally contained moderate amounts of dissolved solids (table 3). Sodium constituted nearly 50 percent of the cations, and bicarbonate and carbonate about 55 percent of the anions (fig. 8). Dissolved-solids concentrations ranged from 472 to 3,660 mg/L, and the median was 1,100 mg/L. The median value for boron was 0.09 mg/L. The median value for SAR was 4 and the water is classified C3-S1 to C4-S4 for irrigation purposes (fig. 9). The water generally is suitable for most domestic, livestock, municipal, and industrial uses and for irrigation.

WATER USE

About 125 Mgal/d (5.5 m^3/d) of water was used in McKenzie County in 1980 (table 8). Most of the water (114.27 Mgal/d or 5 m^3/s) was obtained from the Yellowstone River in Montana and used for irrigation in the Yellowstone valley near Cartwright. Most of the ground water used for municipal supply (0.42 Mgal/d or 0.02 m^3/s) was pumped from the Tobacco Garden aquifer by Watford City. Alexander has one shallow well that supplies the town. The estimate of rural ground-water use (0.75 Mgal/d or 0.03m^3/s) made by Smith and Harkness (1980) may be low, because artesian flow from an estimated 150 wells tapping the Fox Hills and basal Hell Creek aquifer system and the Ludlow aquifer system probably was 2 to 3 Mgal/d (0.09 to 0.13 m^3/s). Conservation measures should be used to reduce the head decline in these aquifers, such as restricting the flow rate with either a valve or a small diameter pipe.

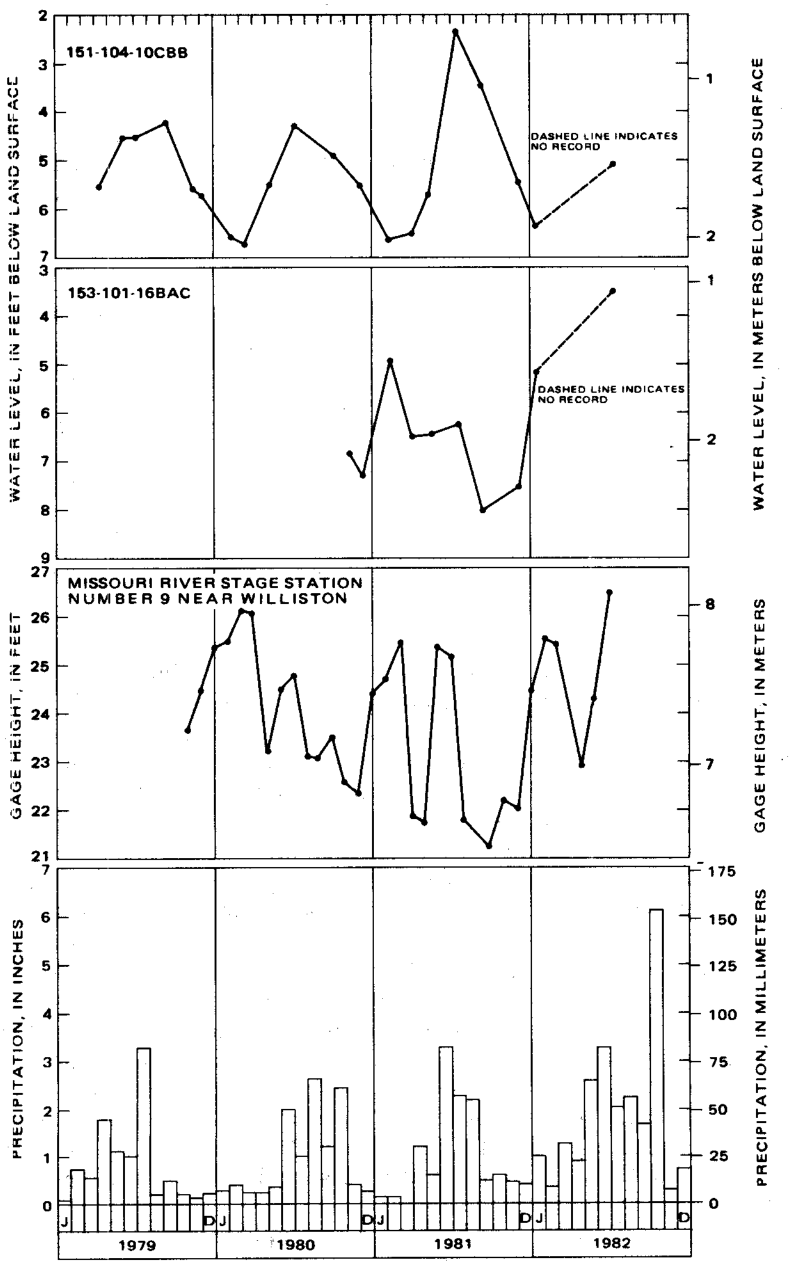


Figure 26.—Water-level fluctuations in the Yellowstone-Missouri aquifer, Missouri River gage height, and precipitation at Watford City, N. Dak.

TABLE 8 — Water use in McKenzie County, 1980

[Data from Smith and Harkness, 1980]

	Ground water (million gallons per day)	Surface water (million gallons per day)
Municipal	0.42	—
Irrigation	.83	8.86
(Imported)		114.27
Rural	.75	.29
Industrial	.03	.03
Totals	2.03	123.45

SUMMARY

Ground water for domestic and livestock use in McKenzie County is obtained from three aquifer systems in semiconsolidated rocks of Late Cretaceous and Tertiary age. Thickness, lithology, yield, and water quality are summarized in table 9. Rocks older than Late Cretaceous age extend to 15,000 ft (4,572 m) and generally contain brackish water that is unsuitable for most purposes. Ground water from six aquifers in unconsolidated rocks of Quaternary age occurs in various parts of the county.

The Fox Hills and basal Hell Creek aquifer system is used as a source for domestic, livestock, and industrial supplies. The aquifer matrix consists of fine- to medium-grained sandstone, siltstone, and claystone. The aquifer system generally is more than 1,500 ft (457 m) in depth except along the Little Missouri River valley and the shoreline of Lake Sakakawea. Recharge primarily is by subsurface inflow from adjacent areas to the south and leakage from underlying beds. The aquifer system discharges by outflow to the north and upward leakage into overlying aquifer systems. The transmissivity is 200 to 300 ft^2/d (18.6 to 27.9 m^2/d). The water generally is lower in dissolved solids than water from the overlying aquifers of Tertiary age. Many wells developed in the aquifer system in the valley of the Little Missouri River and adjacent to Lake Sakakawea flow at land surface.

The overlying Ludlow and Tongue River aquifer systems are relatively unused except for domestic and livestock supplies. They consist of interbedded fine- to medium-grained sandstone, siltstone, claystone, and lignite. The sandstone has a small hydraulic conductivity value. Much of the water is yellowish brown but suitable for many purposes. The Ludlow aquifer system

TABLE 9. — Summary of hydrologic properties and chemical characteristics of ground water, McKenzie County

System	Aquifer or aquifer system	Approximate thickness (feet)	Lithology	Estimated yield (gallons per minute)	Water Type	Median dissolved solids (milligrams per liter)	Suitable Uses
Quarternary	Bennie Peer	70	Glacial outwash, sand, and gravel.	100	Sodium sulfate.	3,060	Livestock.
	Charbonneau	50	Glacial outwash, sand, and gravel.	100	Sodium bicarbonate.	1,100	Domestic, livestock, municipal, industrial, and irrigation.
	Cherry Creek	100	Glacial outwash, sand, and gravel.	500	Sodium bicarbonate.	2,080	Domestic, livestock, municipal, and industrial.
	Little Missouri River	176	Glacial outwash, sand, and gravel.	100	Sodium sulfate.	2,330	Livestock.
	Tobacco Garden	85	Alluvium.	500	Sodium bicarbonate.	947	Domestic, livestock, municipal, industrial, and irrigation.
	Yellowstone-Missouri	100	Glacial outwash, sand, and gravel	500	Sodium bicarbonate.	1,100	Domestic, livestock, municipal, industrial, and irrigation.
	Tongue River	400	Sandstone, siltstone, claystone, and lignite.	25	Sodium bicarbonate.	1,830	Domestic and livestock.
Tertiary	Ludlow	600	Sandstone, siltstone, claystone, and lignite.	25	Sodium bicarbonate.	1,750	Domestic and livestock.
Cretaceous	Fox Hills and basal Hell Creek	400	Sandstone, siltstone, and claystone.	100	Sodium bicarbonate.	1,325	Domestic, livestock, and industrial.

probably is recharged from underlying deposits and discharges by seepage to the Little Missouri River and flowing wells tapping the aquifer system. The Tongue River aquifer system is recharged by precipitation and seepage from surface water and discharges north outside McKenzie County.

Six aquifers consisting of unconsolidated sand and gravel occur in McKenzie County. The sand and gravel is 50 to 176 ft (15 to 54 m) thick. Wells could yield 100 to more than 500 gal/min (6.3 to 32 L/s). The aquifers in Quaternary deposits are recharged by precipitation and discharge to surface water. The water from four aquifers generally is a sodium bicarbonate type. Median dissolved-solids concentrations ranged from 1,100 to 2,330 mg/L. The water in the Charbonneau, Tobacco Garden, and Yellowstone-Missouri aquifers is suitable for irrigation use.

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DEFINITIONS OF SELECTED TERMS

Alluvial — deposited by a stream or running water.

Anticline — a fold, the core of which contains stratigraphically older rocks.

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

Aquifer system — a series of interconnected aquifers.

Area of influence — the area underlain by the cone of depression caused by a discharging well.

Artesian — artesian is synonymous with confined. Artesian water and artesian water body are equivalent, respectively, to confined ground water and confined water body. The water level in an artesian well stands above the top of the aquifer it taps.

Bedrock — consolidated or semiconsolidated rock underlying glacial and alluvial deposits of Pleistocene and(or) Holocene age.

Cone of depression — the conical low produced in a water table or potentiometric surface by a discharging well.

Confined — as used in this report, the term confined refers to an aquifer in which the water is under artesian pressure. See artesian.

Drawdown — decline of the water level in a well or aquifer caused by pumping or artesian flow.

Ground water — water in the zone of saturation.

Hardness — the adjectives hard and soft are inexact, and the following classification is used in this report:

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

Hydraulic conductivity (K) — a measure of the capacity of a rock to transmit water — usually described as the rate of flow in cubic feet per day through 1 square foot of the aquifer under unit hydraulic gradient at existing kinematic viscosity.

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

Infiltration — the movement of water from the land surface toward the water table.

Inflow — the movement of ground water into an area in response to the hydraulic gradient.

Percolation — movement of water through the interstices of a rock or soil.

Poisson's ratio — the ratio of the lateral unit strain to the longitudinal unit strain in a body that has been stressed longitudinally within its elastic limit.

Porosity θ — the ratio of void spaces within a porous media to the total volume of the sample.

Potentiometric surface — as related to an aquifer, it is defined by the level to which water will rise in tightly cased wells. The potentiometric surface is reported in feet above sea level.

Recharge — the addition of water to the zone of saturation.

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

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

where ion concentrations are expressed in milliequivalents per liter. 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 (SC) — the rate of discharge of water from a well, divided by the drawdown of the water level within the well.

Specific conductance — electrical conductance, or conductivity, is the ability of a substance to conduct an electrical current. The electric conductivity of water is related to the concentration of ions in the water. Distilled water normally will have a conductance of about 1.0 micromhos per centimeter, whereas sea water may have a conductance of about 50,000 micromhos per centimeter. Standard laboratory measurements report the conductivity of water in micromhos per centimeter at 25°C.

Specific yield — the ratio of 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 (S) — the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head.

Surface runoff — that part of the runoff which travels over the soil surface to the nearest stream channel.

Transmissivity (T) — the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. It is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow paths.

Unconfined (water table) — as used in this report, the term unconfined refers to an aquifer in which the water is under atmospheric pressure.

Underflow — the flow of water through the soil or a subsurface stratum.

Zone, saturated — that part of the water-bearing material in which all voids are ideally filled with water under pressure greater than atmospheric.