GROUND-WATER RESOURCES

OF

BILLINGS, GOLDEN VALLEY, AND SLOPE COUNTIES, NORTH DAKOTA

by

Lawrence O. Anna

U.S. Geological Survey

COUNTY GROUND-WATER STUDIES 29 — PART III

North Dakota State Water Commission

Vernon Fahy, *State Engineer*

BULLETIN 76 — PART III

North Dakota Geological Survey

Lee Gerhard, *State Geologist*

Prepared by the U.S. Geological Survey
in cooperation with the North Dakota State
Water Commission, North Dakota Geological
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Bismarck, North Dakota

CONTENTS

Page

ABSTRACT 1
INTRODUCTION 1
  Purpose and objectives of the investigation 2
  Geography 2
  Acknowledgements 4
  Location-numbering system 4
  Previous investigations 6
AVAILABILITY AND QUALITY OF GROUND WATER 6
  General concepts 6
  Geologic setting 8
  Aquifers of Paleozoic and Mesozoic age 11
  Aquifers of Late Cretaceous age 11
    Fox Hills-lower Hell Creek aquifer system 11
  Aquifers of Late Cretaceous and Tertiary age 22
    Upper Hell Creek-lower Ludlow aquifer system 22
  Aquifers of Tertiary age 27
    Aquifers in the upper part of the Ludlow and Tongue River Members of the Fort Union Formation 27
    Aquifers in the Sentinel Butte Member of the Fort Union Formation 33
    Aquifers in the Golden Valley and White River Formations 34
  Aquifers of Quaternary age 36
    Alluvial aquifers 36
HYDROGEOLOGY OF STRIPPABLE LIGNITE DEPOSITS 40
EFFECTS OF FLOWING WELLS 43
SURFACE WATER 43
WATER UTILIZATION 45
  Domestic and livestock use 45
  Public supplies 46
    Beach 46
    Golva 46
    Marmarth 47
    Medora 47
  Irrigation 47
  Industrial 47
SUMMARY 48
SELECTED REFERENCES 50
DEFINITIONS OF TERMS 54

ILLUSTRATIONS

Plate — Page

1. Hydrogeologic sections, Billings, Golden Valley, and Slope Counties, North Dakota ....(in pocket)

Figure

1. Map showing physiographic divisions in North Dakota and location of study area 3
2. Diagram showing location-numbering system 5
3. Diagram showing irrigation classifications 10
4. Bedrock geologic map 13
5. Map showing structure contours of base of Fox Hills Sandstone 14
6. Map showing transmissivity and net thickness of sandstone of the Fox Hills-lower Hell Creek aquifer system 16
7. Map showing potentiometric contours of the Fox Hills-lower Hell Creek aquifer system, 1976 19
8. Trilinear diagram showing major constituents in selected water samples from the Fox Hills-lower Hell Creek aquifer system, the Little Missouri River, and Little Beaver Creek..21
9. Map showing potentiometric contours of the upper Hell Creek-lower Ludlow aquifer system, 1976-77...25
10. Trilinear diagram showing major constituents in selected water samples from the upper Hell Creek-lower Ludlow aquifer system 26
11. Map showing structure contours of the top of the Harmon lignite bed 28
12. Map showing potentiometric contours of aquifers in the lower part of the Tongue River Member of the Fort Union Formation, 1977 30
13. Trilinear diagram showing major constituents in selected water samples from aquifers in the lower part of the Tongue River Member of the Fort Union Formation 32
14. Trilinear diagram showing major constituents in selected water samples from aquifers in the Sentinel Butte Member of the Fort Union Formation and from the Green River 35

Page

15. Generalized geologic section C-C′ through the flood plain of the Little Missouri River 37
16. Hydrograph showing water-level fluctuations in the Little Missouri River valley aquifer, gage height of Little Missouri River at Marmarth, and precipitation at Medora, 1977 38
17. Graph showing low-flow measurements August 1976, and dissolved-solids concentrations November 1976, in the Little Missouri River 39
18. Map showing strippable lignite deposits 41

TABLES

Table

1. Major chemical constituents in water, their sources, effects upon usability, and recommended concentration limits 9
2. Billings, Golden Valley, and Slope Counties stratigraphic column 12
3. Summary of aquifer tests, Fox Hills-lower Hell Creek aquifer system 18
4. Summary of aquifer tests, upper Hell Creek-lower Ludlow aquifer system 24
5. Flowing-well measurements 44
6. Generalized geologic section and water-yielding characteristics of geologic units in Billings, Golden Valley, and Slope Counties, North Dakota 49

SELECTED FACTORS FOR CONVERTING INCH-POUND UNITS TO THE INTERNATIONAL SYSTEM (SI) OF METRIC UNITS

A dual system of measurements — inch-pound units and the International System (SI) of metric units — is given in this report. 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 units
Acre	0.4047	hectare (ha)
Acre-foot	.001233	cubic hectometer (hm^3)
Cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)
Foot	.3048	meter (m)
Foot per day (ft/d)	.3048	meter per day (m/d)
Foot per mile (ft/mi)	.18943	meter per kilometer (m/km)
Foot squared per day (ft^2/d)	.0929	meter squared per day (m^2/d)
Gallon	3.785	liter (L)
Gallon per day (gal/d)	3.785	liter per day (L/d)
Gallon per minute (gal/min)	.06309	liter per second (L/s)
Gallon per minute per foot [(gal/min)/ft]	.2070	liter per second per meter [(L/s)/m]
Inch	25.4	millimeter (mm)
Mile	1.609	kilometer (km)
Million gallons (Mgal)	3,785	cubic meter (m^3)
	.003785	cubic hectometer (hm^3)
Square mile (mi^2)	2.590	square kilometer (km^2)

GROUND-WATER RESOURCES OF BILLINGS, GOLDEN VALLEY, AND SLOPE COUNTIES, NORTH DAKOTA

By Lawrence O. Anna

ABSTRACT

Billings, Golden Valley, and Slope Counties, in west-central North Dakota, are underlain by at least 15,000 feet (4,570 meters) of sedimentary rocks. Rocks within the upper 2,200 feet (670 meters) contain aquifers that bear relatively fresh water. These upper rocks, which are Late Cretaceous and Tertiary in age, consist of interbedded sandstone, siltstone, claystone, and lignite.

The major aquifers in the study area are the Fox Hills-lower Hell Creek aquifer system, the upper Hell Creek-lower Ludlow aquifer system, aquifers in the upper Ludlow-Tongue River Members, and aquifers in the Sentinel Butte Member. The Fox Hills-lower Hell Creek aquifer system has a mean transmissivity of 313 feet squared per day (29.1 meters squared per day) from drawdown tests and 80 feet squared per day (7.4 meters squared per day) from flow and recovery tests, and may yield as much as 300 gallons per minute (19 liters per second) of sodium bicarbonate type water to wells at selected locations. The upper Hell Creek-lower Ludlow aquifer system may yield as much as 150 gallons per minute (9.5 liters per second) of sodium bicarbonate type water to wells. Aquifers in the upper part of the Ludlow and Tongue River Members may yield as much as 250 gallons per minute (16 liters per second). The quality of the water varies with depth. Aquifers in the Sentinel Butte Member yield as much as 50 gallons per minute (3 liters per second). The quality of the water varies with depth and aquifer lithology.

Withdrawals of water from flowing wells along the valley of the Little Missouri River have created a cone of depression and major deflections in the potentiometric surface of the Fox Hills-lower Hell Creek and upper Hell Creek-lower Ludlow aquifer systems.

Aquifers in alluvial deposits consist of thin beds of sand and gravel and generally yield less than 50 gallons per minute (3.2 liters per second).

Water for public, domestic, and livestock use is obtained from ground-water supplies. The most dependable supplies of relatively good quality water are obtained from the Fox Hills-lower Hell Creek aquifer system.

INTRODUCTION

This investigation was made cooperatively by the U.S. Geological Survey, North Dakota State Water Commission, North Dakota Geological Survey, U.S. Forest Service (Surface Environmental and Mining program), U.S. Park Service, and Billings, Golden Valley, and Slope Counties Water Management

Districts. The results of the investigation will be published in three parts. Part I is an interpretive report describing the surface geology of the study area, part II (Anna, 1980) is a compilation of the ground-water basic data, and part III, this report, is an interpretation describing the ground-water resources. Part II makes available geologic and hydrologic data collected during the investigation and functions as a reference to the other reports. All data referred to in this report are from part II (Anna, 1980), unless otherwise referenced.

Purpose and Objectives of the Investigation

The purpose of this investigation was to determine the quantity and quality of ground water available in Billings, Golden Valley, and Slope Counties for municipal, domestic, livestock, industrial, and irrigation uses. The specific objectives were to: (1) determine the location, extent, and nature of the major aquifers and confining beds; (2) evaluate the occurrence and movement of ground water, including sources of recharge and discharge; (3) estimate the quantities of water stored in the alluvial aquifers; (4) estimate the potential yields to wells tapping the major aquifers; and (5) determine the chemical quality of the ground water.

Geography

Billings, Golden Valley, and Slope Counties, which are located in southwestern North Dakota (fig. 1), have a combined area of 3,379 mi^2 (8,752 km^2). Billings County has an area of 1,139 mi^2 (2,950 km^2), Golden Valley County has an area of 1,014 mi^2 (2,626 km^2), and Slope County has an area of 1,226 mi^2 (3,175 km^2). The counties lie within the unglaciated section of the Great Plains Province (fig. 1).

The three counties are located in the Missouri River drainage basin. The Little Missouri River, the main drainage, is north flowing, and most of its major tributaries are east-west flowing. A drainage divide trending north-south through the eastern part of the study area forms the headwaters of the Heart (via the Green River), Knife, and Cannonball Rivers, which flow eastward and discharge into the Missouri River.

The topography of the area ranges from rolling uplands in the eastern and western parts of the study area to highly dissected erosional badlands in the central part. The Little Missouri River and its major tributaries carved the badlands, a spectacular display of steep-sided buttes and narrow valleys with as much as 500 feet (152 m) of relief.

Maximum relief in the study area is about 1,430 feet (436 m); the highest point being 3,506 feet (1,069 m) above NGVD of 1929 at White Butte (the highest point in North Dakota) in central Slope County and the lowest point being approximately 2,080 feet (634 m) above NGVD of 1929 where the Little Missouri River leaves northwestern Billings County.

The climate is semiarid and continental, characterized by long cold winters and short warm summers. According to the U.S. Environmental Data Service

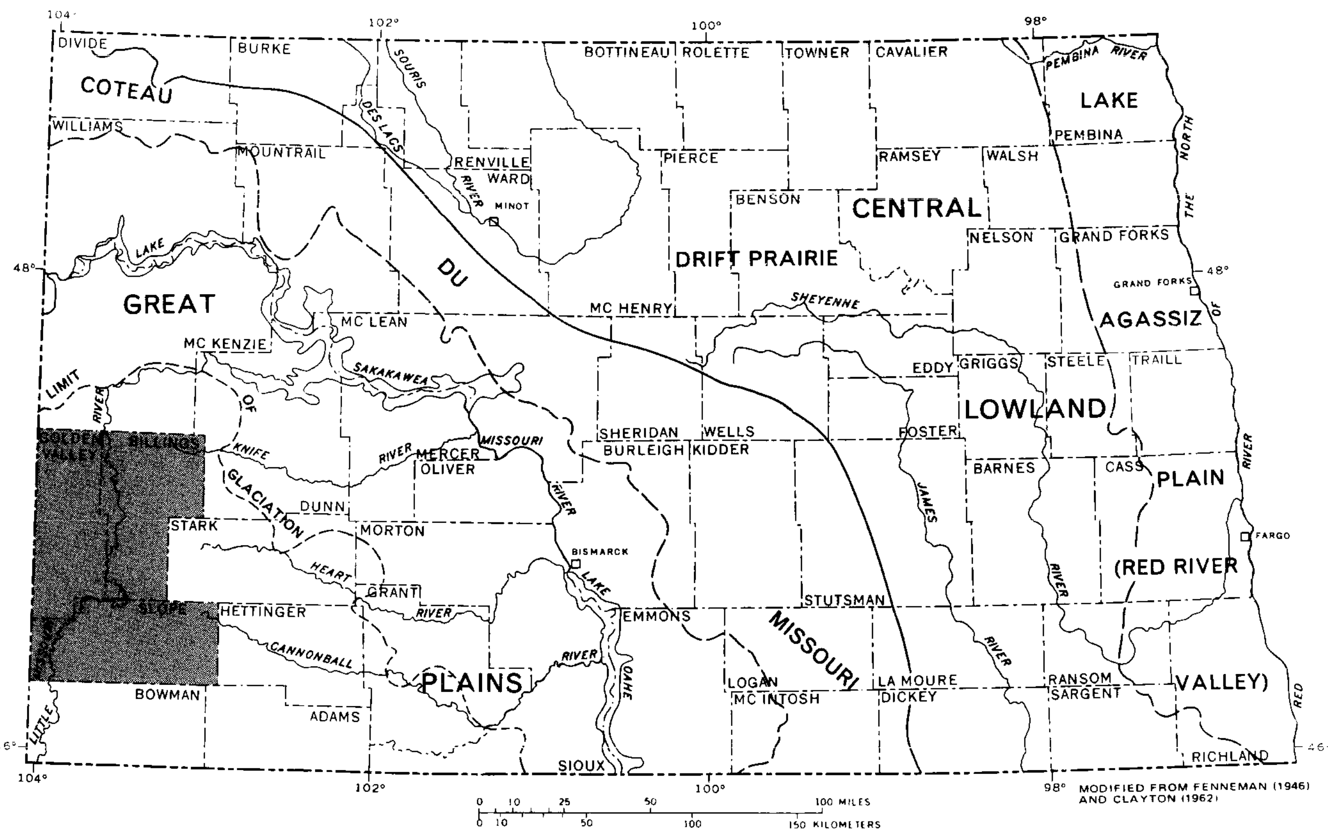


FIGURE 1.—Physiographic divisions in North Dakota and location of study area.

(1973) the mean annual temperature at Marmarth is 42.7°F (5.95°C) — ranging from 70.4°F (21.3°C) in July to 13.9°F (−10.1°C) in January. The mean annual temperature at Amidon is 42.3°F (5.72°C) — ranging from 69.5°F (20.8°C) in July to 13.8°F (−10.1°C) in January. Temperatures of 90°F (32.2°C) or above occur on an average of 20 days per year. The long-term average length of the growing season (above 32°F or 0.0°C) is 121 days. Mean annual precipitation varies from 14.97 inches (380 mm) at Marmarth to 16.41 inches (417 mm) at Amidon. June usually has the most precipitation and December the least. Seventy-five percent of the precipitation falls in the 6-month period April through September.

In 1970 the population of the three counties was 5,293 (U.S. Bureau of the Census, 1971). Beach (Golden Valley County), the largest community in the three-county area, had a population of 1,408.

Dryland farming, stock raising, and petroleum production are the three main industries. The principal crops are wheat, hay, oats, and rye. Livestock production is mainly cattle with some sheep and hogs. U.S. National Grasslands, where only livestock grazing is permitted, occupy 24 percent of the three-county area. Several oil fields are located in Slope and Billings Counties, and recently (1977) there has been a sharp increase in oil exploration.

There are no commercial lignite operations at the present time (1978) in the three counties; however, there are numerous potential strippable deposits (Pollard and others, 1972). The deposit near Beach (Golden Valley County) probably will be mined in the near future with a gasification or generating plant, or both, constructed nearby.

Uranium exploration has increased greatly after being dormant since the 1950's. Most of the uranium is concentrated in shallow lignite deposits but it occasionally is found in shallow sandstones. *In situ* leaching of the uranium is a proposed method of mining the uranium ore found in sandstone.

Acknowledgements

The collection of data for this report was made possible by the cooperation of those residents and officials of Billings, Golden Valley, and Slope Counties who furnished information on wells and permitted the use of their land for drilling test holes, making hydrologic measurements, and sampling of ground water. Particular recognition is due the following personnel of the North Dakota State Water Commission: L. D. Smith and G. L. Sunderland for logging test holes, providing lithologic descriptions of cuttings, and contributing to the understanding of the local stratigraphy; and M. O. Lindvig for scheduling of drilling activities. Recognition also is given to C. G. Carlson of the North Dakota Geological Survey for his contribution of surface geological mapping.

Location-Numbering System

The location-numbering system used in this report is based on the public land classification system used by the U.S. Bureau of Land Management. The system is illustrated in figure 2. The first numeral denotes the township north of

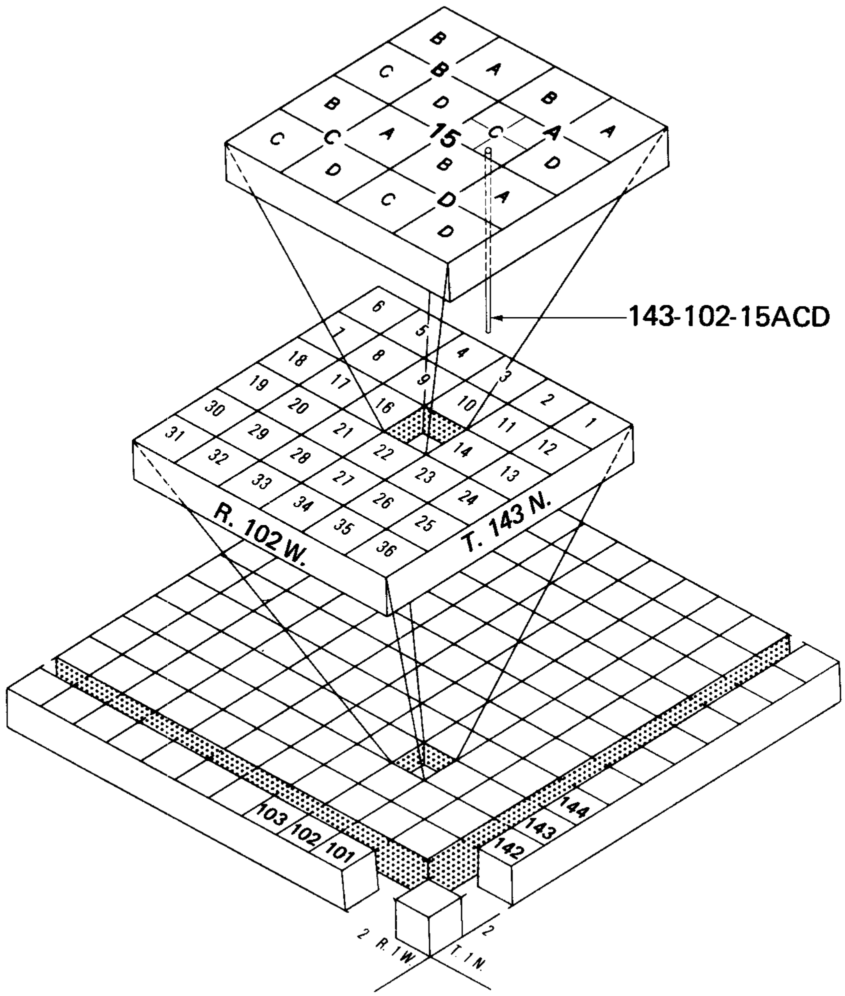


FIGURE 2.—Location-numbering system.

line, the second numeral the range west of the fifth principal meridian, and the third numeral indicates the section in which the well, test hole, or spring 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 143-102-15ACD is in the SE¼SW¼NE¼ sec. 15, T. 143 N., R. 102 W. Consecutive terminal numbers are added if more than one well, test hole, or spring is recorded within a 10-acre (4-ha) tract. This numbering system also is used for the location of stream-gaging stations and other specific locations.

Previous Investigations

The earliest geologic investigations of southwestern North Dakota were made by Lloyd and Hares (1915), Stanton (1920), and Hares (1928). Studies describing regional stratigraphy that include the tri-county area were made by Brown (1952), Denson and Gill (1965), Pipiringos and others (1965), and Gill and Cobban (1973). Frye (1969) and Feldman (1972) described in detail the stratigraphy of the Hell Creek and Fox Hills Formations, respectively, in western North Dakota. Short articles or maps on the geology, structure, and stratigraphy for all or part of the study area were prepared by Fisher (1954), Hanson (1953), and Bergstrom (1956).

Recent geologic studies have been spurred by increasing energy developments in the area. Pollard and others (1972) described the locations, tonnage, overburdens, and characteristics of lignite deposits. Royce (1967, 1970), Jacob (1975, 1976), Cvancara (1976), and Moore (1976) described in detail the stratigraphy of Upper Cretaceous and Tertiary sediments in western North Dakota.

The first comprehensive report on ground-water resources that includes the three-county area was by Simpson (1929). Other geohydrologic studies include reports by Hamilton (1970), describing ground-water flow in the badlands area; Croft (1974A), describing the well installation at Painted Canyon Overlook; M. G. Croft, L. O. Anna, and D. W. Fisher (written commun., 1977) describing the shallow aquifer systems of the Fort Union coal region; and Don Thorstenson, D. W. Fisher, and M. G. Croft (written commun., 1977) describing in detail the geochemistry of the Fox Hills-lower Hell Creek aquifer system of western North Dakota.

Tables of well schedules for various counties including the study area were compiled during the 1930's as part of a Works Progress Administration project. Also, data from selected shallow observation wells were collected by the U.S. Geological Survey at that time.

AVAILABILITY AND QUALITY OF GROUND WATER

General Concepts

All ground water is derived from precipitation. After precipitation falls on the earth's surface, part runs off into streams, part is returned to the atmosphere by evaporation, and the remainder infiltrates the soil. A large quantity of the water that enters the soil is held temporarily and then is returned to the atmosphere by evaporation or by transpiration. After soil and plant requirements have been satisfied, the excess water, if any, percolates downward until it reaches the water table, at which time it becomes available to wells.

Ground water moves by the influence of gravity from areas of recharge to areas of discharge along paths normal to the hydraulic gradient. Ground-water movement generally is 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, well-sorted sand, and fractured rock generally are highly conductive. Poorly sorted sand is less conductive, and fine-grained materials such as silt, clay, and shale usually have low conductivities and restrict ground-water movement.

The water level in an aquifer fluctuates in response to recharge to and discharge from the aquifer, usually indicating a change in the amount of water stored in the aquifer. Changes in atmospheric pressure and surface loading, however, cause small fluctuations in confined aquifers. Aquifers exposed at land surface are usually recharged each spring and early summer by direct infiltration of precipitation. Recharge to these aquifers in the study area usually is sufficient to replace losses caused by natural processes and by pumping of wells. Aquifers that are confined by deposits of fine-grained materials are recharged by lateral movement downgradient from a recharge area exposed at the surface and by leakage through the fine-grained material. Recharge rates in confined aquifers may increase as water levels in the aquifers are reduced by pumping, but water levels may decline for several years before sufficient recharge is induced to balance the rate of withdrawal. In some places this balance may never be achieved without curtailment of withdrawals.

In parts of Billings, Golden Valley, and Slope Counties, surface-water sources, such as the Little Missouri River and its major tributaries, are in hydraulic connection with the aquifers. The aquifers may either receive recharge from or discharge into them, depending on head relationships, which generally vary both in time and space.

The ground water in Billings, Golden Valley, and Slope Counties contains varying degrees of dissolved mineral matter. Rain begins to dissolve mineral matter in the air as it falls and continues to dissolve minerals as it percolates through the soil. The amount and kind of dissolved mineral matter in water depends upon the solubility and types of sediments encountered, temperature, pressure, length of time the water is in contact with the minerals, and the amount of carbon dioxide and soil acids in the water. Ground water that has been in storage 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 suitability of water for various uses is determined largely by the kind and amount of dissolved minerals. The chemical constituents and physical properties most likely to be of concern are: iron, sulfate, nitrate, fluoride, percent sodium, dissolved solids, trace elements, hardness, temperature, odor, specific conductance and sodium-adsorption ratio (SAR). The sources of the major chemical constituents, their effects on usability, and the limits recommended by the Environmental Protection Agency (National Academy of Sciences-National Academy of Engineering, 1972) are given in table 1.

The concentration of dissolved solids is a measure of the mineralization of the water. The dissolved-solids concentration is important because it may limit the use of water for many purposes. In general, the suitability of water decreases with an increase in dissolved solids.

Hardness does not seriously affect the use of water for most purposes, but it does decrease the effectiveness of soap. Hardness removal by a softening process increases the water's suitability for domestic, laundry, and industrial purposes. The classifications of hardness used in this report are listed below:

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

Two indices of the suitability of water for irrigation are SAR and specific conductance. SAR is related to the sodium hazard, and specific conductance is related to the salinity hazard. The hazards increase as the numerical values of the indices increase. Figure 3 shows 16 classifications of water for irrigation as determined by SAR and specific conductance. For further information the reader is referred to "Diagnosis and Improvement of Saline and Alkali Soils" (U.S. Salinity Laboratory Staff, 1954).

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

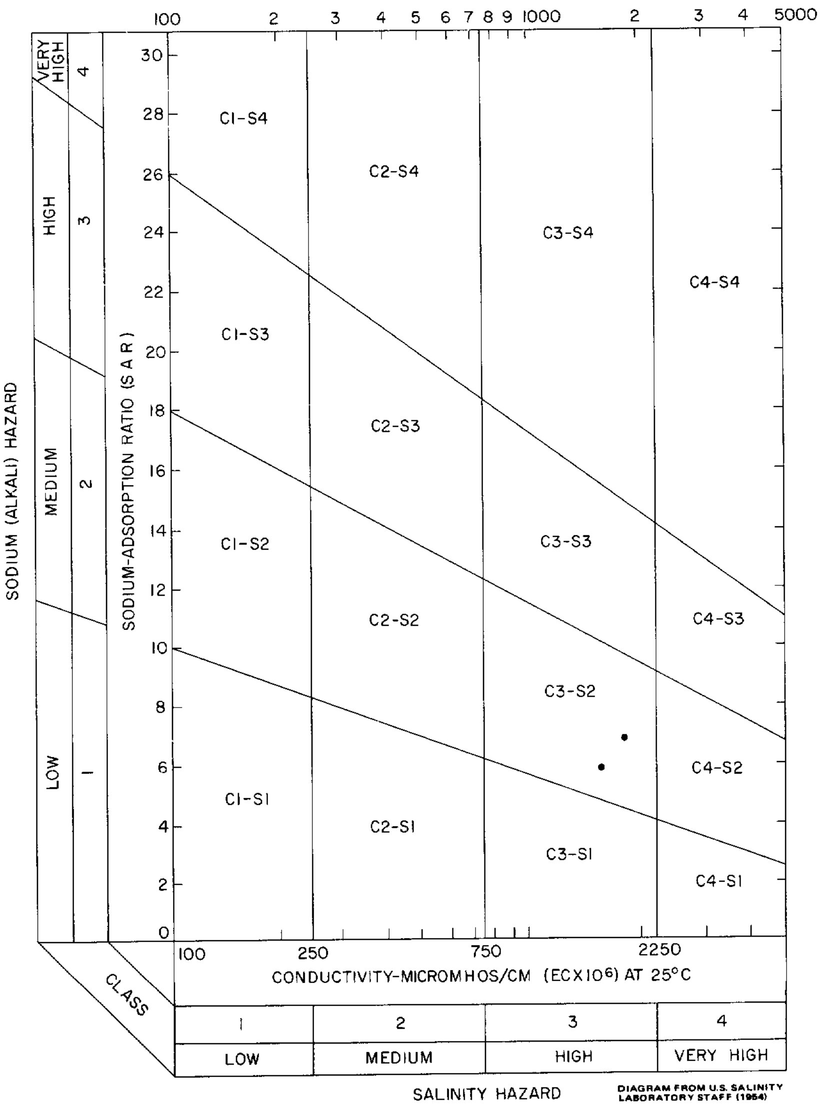
Geologic Setting

Billings, Golden Valley, and Slope Counties lie on the southwest flank of the Williston basin, a broad structural depression underlying parts of North Dakota, South Dakota, Montana, Manitoba, and Saskatchewan. The trace of the basin's synclinal axis trends north-south immediately east of the study area. The regional dip in the study area is to the northeast toward the center of the basin at about 20 ft/mi (3.8 m/km). The Cedar Creek anticline, a major oil producing structure, trends northwest-southeast in the extreme southwest part of the study area. The trace of its axis extends from approximately Glendive, Mont., to Buffalo, S. Dak.; through the southwest corner of Bowman County, N. Dak. The northeast flank of the anticline extends into the southwest corner of Slope County.

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	National Academy of Sciences — National Academy of Engineering (1972) recommended limits for drinking water
Silica (SiO_2)	Feldspars, ferromagnesian, and clay minerals.	In presence of calcium and magnesium, silica forms a scale that retards heat transfer in boilers and on steam turbines.	
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. High concentrations of magnesium have a laxative effect.	
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, dolomite, magnesite, and clay minerals.		
Sodium (Na)	Feldspars, clay minerals, evaporites, and cation exchange with calcium and magnesium on clay minerals.	More than 50 mg/L (milligrams per liter) sodium and potassium with suspended matter causes foaming, which accelerates scale formation and corrosion in boilers.	
Potassium (K)	Feldspars, feldspathoids, some micas, and minerals.		
Bicarbonate (HCO_3)	Limestone, dolomite, and anaerobic processes.	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 or weathering of sulfide minerals in lignite.	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 maximum limits depend on average of maximum daily temperatures. Maximum limits range from 1.4 mg/L at 32°C to 2.4 mg/L at 10°C.
Nitrate (NO_3)	Nitrogenous fertilizers, animal excrement, legumes, and plant debris.	More than 100 mg/L may cause a bitter taste and may cause physiological distress. Concentrations greatly in excess of 45 mg/L have been reported to cause methemoglobinemia in infants.	45 mg/L
Iron (Fe)	Natural sources: Amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, carbonates, and clay minerals. Man-made sources: well casings, pump parts, and storage tanks.	If more than 100 ug/L (micrograms per liter) iron is present, it will precipitate when exposed to air causing turbidity, staining plumbing fixtures, laundry, and cooking utensils, and imparting tastes and colors to food and drinks. More than 200 ug/L iron is objectionable for most industrial uses. High concentrations of manganese cause difficulty in water-quality control.	300 ug/L
Manganese (Mn)			50 ug/L
Boron (B)	Tourmaline, biotite, and amphiboles.	Many plants are damaged by concentrations of 2,000 ug/L.	
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.	Because of the wide range of mineralization, it is not possible to establish a limiting value.



EXPLANATION

• LITTLE MISSOURI RIVER AQUIFER

FIGURE 3.—Irrigation classifications.

In the Rocky Mountain region, during Late Cretaceous and early Tertiary time, east-west compressional stresses (Stone, 1969) deformed and warped the rocks into northwest and northeast compressional features as shown by drainage, vegetation, and fracture lineaments.

The study area is underlain by sedimentary rocks that are Cambrian to Quaternary in age (table 2), and have a combined thickness of at least 15,000 feet (4,570 m). The formations of Paleozoic and Mesozoic age below the Pierre Shale are approximately 10,000 feet (3,050 m) thick and consist mainly of limestone, dolomite, sandstone, shale, and evaporate deposits. The Pierre Shale is as much as 2,200 feet (670 m) thick and consists of dark-gray to black shale. The formations overlying the Pierre (fig. 4) consist mainly of semiconsolidated siltstone, claystone, and lignite. These formations range in thickness from 0 to approximately 2,200 feet (0 to 670 m). The following section describes the availability and quality of ground water in the formations.

Aquifers of Paleozoic and Mesozoic Age

Aquifers of Paleozoic and Mesozoic age in formations below the Pierre Shale lie at depths that presently are uneconomical for drilling of water wells (6,000 to 15,000 feet or 1,830 to 4,570 m); however, industrial use of the water from the aquifers may occur in the future. Currently, the aquifers (the Madison Group in particular) are being studied geologically and hydrologically as to their water-yielding and water-quality characteristics in parts of Wyoming, Montana, North Dakota, and South Dakota (U.S. Geol. Survey, 1975). Potential yields from aquifers in the Madison Group may vary from 20 to 9,000 gal/min (1.3 to 570 L/s). Generally, dissolved-solids concentrations in water from the Madison Group in North Dakota are high, ranging from 6,000 to 400,000 mg/L.

Aquifers of Late Cretaceous Age

Fox Hills-Lower Hell Creek Aquifer System

The Fox Hills Sandstone, a barrier-bar deltaic deposit (Waage, 1968), and the overlying lower part of the Hell Creek Formation, a deltaic sequence of subaerial topset beds (Frye, 1969), probably form one of the most extensive aquifer systems in the contiguous United States. The Fox Hills Sandstone and Hell Creek Formation underlie all of Billings, Golden Valley, and Slope Counties (fig. 4).

Structure contours of the base of the Fox Hills Sandstone (fig. 5) indicate that the formations dip northeastward about 60 ft/mi (12 m/km) in southwest Slope County. The dip rapidly decreases to about 25 ft/mi (4.7 m/km) near the center of study area and further decreases to approximately 10 ft/mi (1.9 m/km) in northeast Billings County — this area being near the southwest flank of a broad structural saddle adjacent to the southern end of the Nesson anticline in Dunn County (North Dakota Geological Society, 1959). Minor folding has occurred but the folding has had no significant influence on ground-water movement.

TABLE 2.—Billings, Golden Valley, and Slope Counties

stratigraphic column

Era	Period	Group	Formation or Member	Aquifer
Cenozoic	Quaternary			Alluvium
	Tertiary		White River Formation Golden Valley Formation	
			Fort Union Formation: Sentinel Butte Member	Sentinel Butte
			Fort Union Formation: Tongue River Member	Tongue River and upper Ludlow
			Fort Union Formation: Ludlow Member (upper part) and Lebo Shale Member equivalent	
			Fort Union Formation: Cannonball Member	Lower Ludlow and upper Hell Creek
			Fort Union Formation: Ludlow Member (lower part)	
Mesozoic	Upper Cretaceous		Hell Creek Formation	Fox Hills and lower Hell Creek
		Montana Group	Fox Hills Sandstone	
			Pierre Shale	
		Colorado Group	Niobrara Formation Carlile Shale Greenhorn Limestone Belle Fourche Shale	
	Lower Cretaceous		Mowry Shale Newcastle Sandstone Skull Creek Shale	Dakota
		Inyan Kara Group	Fall River Sandstone Fuson Shale Lakota Formation	
	Jurassic		Morrison Formation Swift Formation Rierdon Formation Piper Formation Nesson Formation	Undifferentiated Paleozoic and Mesozoic aquifers
	Triassic		Spearfish Formation	
Paleozoic	Permian		Minnekahta Limestone Opeche Formation	
	Pennsylvanian		Minnelusa Formation	
	Mississippian	Big Snowy Group	Heath Formation Otter Formation Kibbey Formation	
		Madison Group	Charles Formation Mission Canyon Limestone Lodgepole Limestone	
			Bakken Formation	
	Devonian		Three Forks Formation Birdbear Formation Duperow Formation Souris River Formation Dawson Bay Formation Prairie Formation Winnipegosis Formation	
	Silurian		Interlake Formation	
	Ordovician	Bighorn Group	Stony Mountain Formation Red River Formation	
			Winnipeg Formation	
	Cambrian		Deadwood Formation	

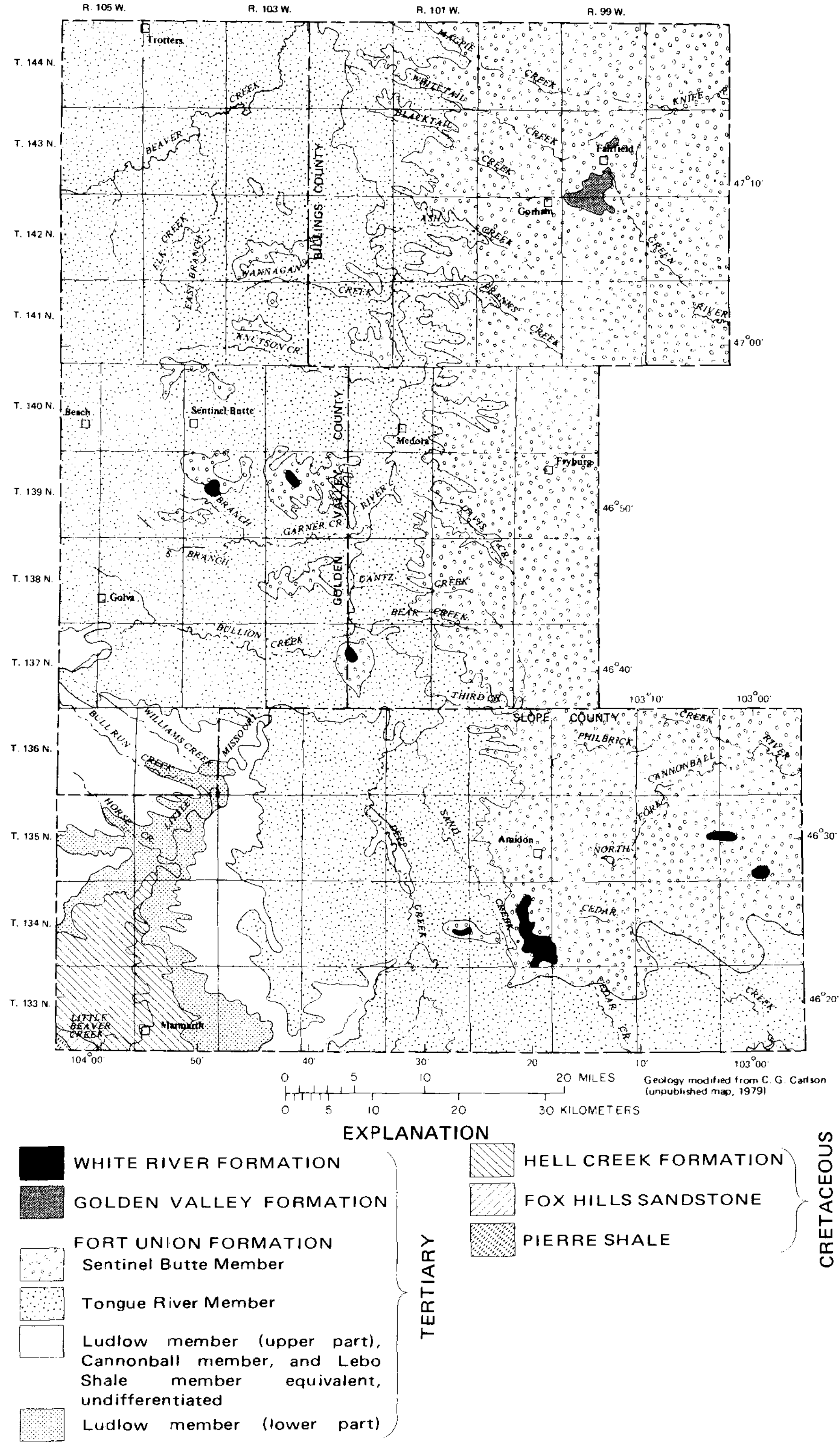
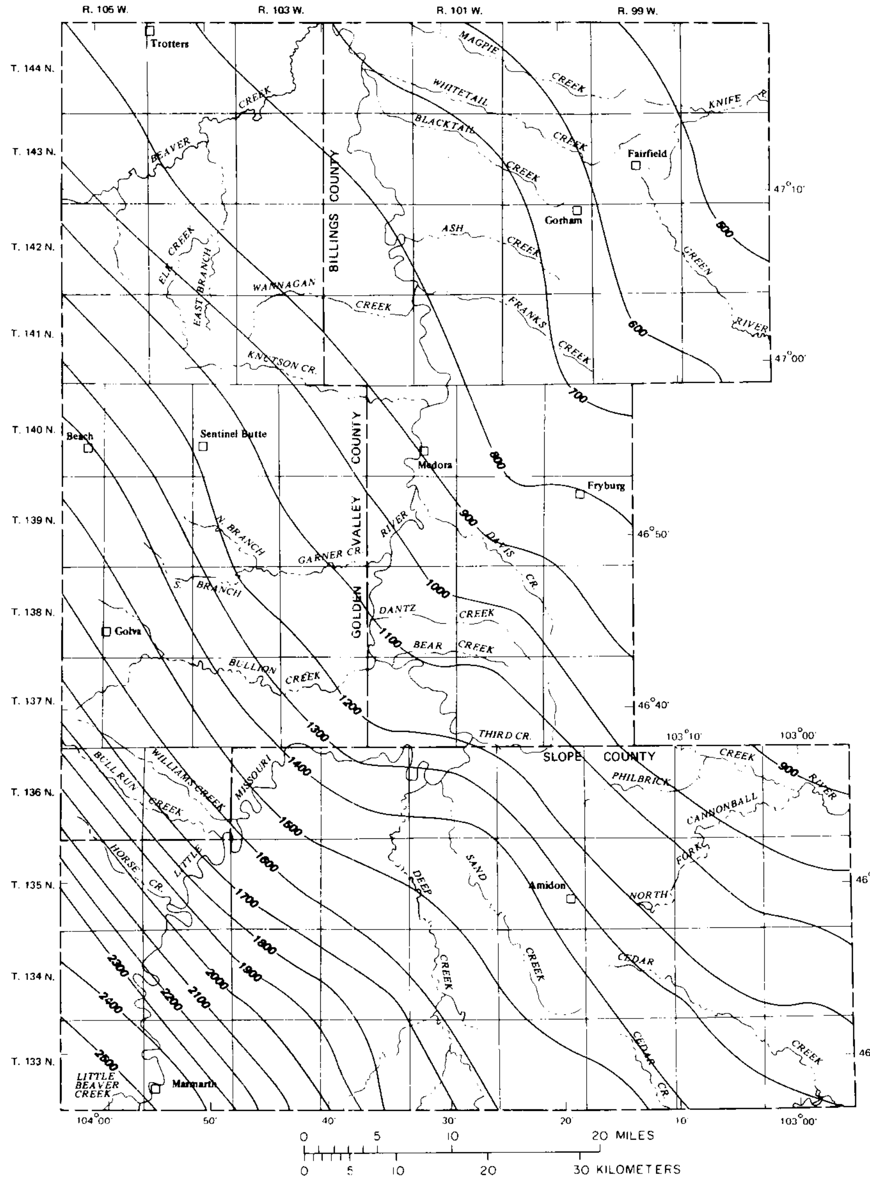


FIGURE 4.—Bedrock geologic map.



EXPLANATION

——1000—— STRUCTURE CONTOUR—Shows altitude of base of Fox Hills Sandstone. Contour interval 100 feet (30.5 meters). Datum is National Geodetic Vertical Datum of 1929

FIGURE 5.—Structure contours of base of Fox Hills Sandstone.

Contours of net sandstone thickness of the Fox Hills-Hell Creek aquifer system show northwest-southeast and northeast-southwest lineaments that possibly influenced sedimentation (fig. 6). The contours also show a trough — termed the Medora trough — of low net sand thickness trending northwest-southeast near the central part of the study area. Because aquifer permeability is influenced by sedimentation patterns, the Medora trough may have an effect on ground-water movement, especially under stressed conditions. Other studies show that this area has several geologic and hydrologic anomalies. Rahbein (1977) showed that a channel sand in the Tongue River Member of the Fort Union Formation parallels the trough, and Thorstenson (written commun., 1976) indicated that a geochemical "transition zone" in the Fox Hills-Hell Creek aquifer system parallels the trough.

The Fox Hills and lower part of the Hell Creek consist of interbedded very find to medium sandstone, siltstone, and claystone, and a few thin beds of carbonaceous and lignitic shale. The sandstone generally consists of about 28 percent silt and clay, the percentage increasing slightly from southwest to northeast. The Fox Hills can be subdivided into three subsurface units: (1) the lower unit consisting of siltstone and very fine to fine sandstone; (2) a middle unit consisting mostly of silty claystone; and (3) an upper unit consisting generally of very fine to medium-grained sandstone. The lower part of the Hell Creek consists of very fine to medium sandstone and interbedded claystone. The claystone and silty claystone of the upper part of the Hell Creek form a major confining bed throughout most of the study area; however, some sandstone does occur in the upper part of the Hell Creek in western Slope County.

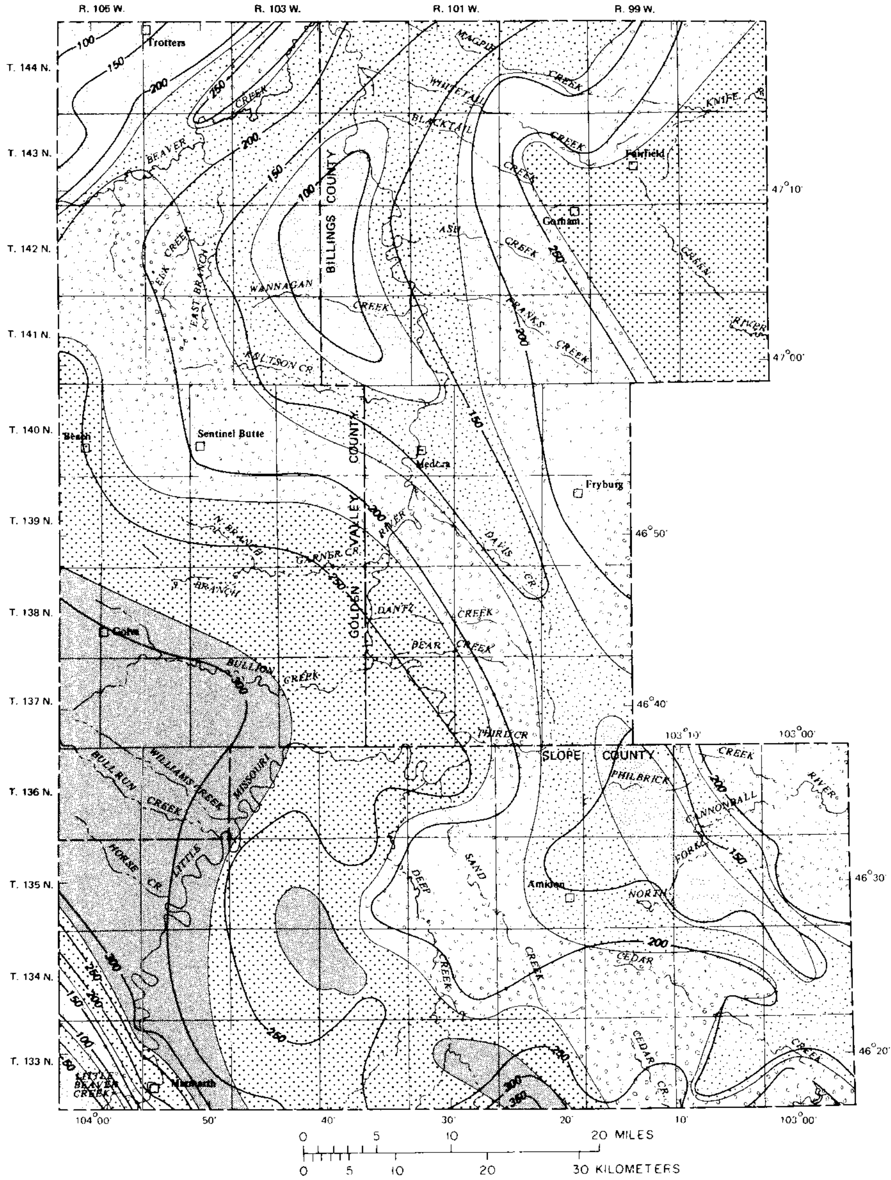
The Fox Hills Sandstone is about 80 feet (24 m) thick in southwest Slope County and increases northeasterly (pl. 1) to an average of about 210 feet (64 m) in northeastern Billings County. The Hell Creek Formation, however, is approximately 450 feet (137 m) thick in western Slope County and thins northeasterly (pl. 1) to less than 250 feet (76 m).

The net sandstone thickness of the Fox Hills-lower Hell Creek aquifer system (fig. 6) ranges from approximately 90 feet (27 m) in northwest Golden Valley County and southwest Slope County (due to erosion) to 355 feet (108 m) in south-central Slope County.

Depth to the top of the aquifer system ranges from 0 feet (0 m) at the outcrop to 1,900 feet (580 m) below land surface in northeast Billings County. In the valley of the Little Missouri River in Billings County the depth is about 1,000 feet (305 m) below land surface.

Porosity values for the aquifer system were obtained in the laboratory from sidewall cores that had greater than 70 percent sand-size grains. The values ranged from 31.6 to 40.2 percent, and had a mean of 35.3 percent.

Hydraulic conductivity values for the Fox Hills-lower Hell Creek aquifer system were determined from drawdown tests and from laboratory analyses of sidewall cores. Three drawdown tests indicated a mean conductivity of 1.6 ft/d (0.49 m/d), and 10 sidewall cores indicated that horizontal conductivities ranged from 0.4 to 7.1 ft/d (0.1 to 2.2 m/d) and had a mean of 2.2 ft/d (0.7 m/d). Conductivity values calculated from geophysical logs, using a method described



EXPLANATION

ESTIMATED TRANSMISSIVITY, IN FEET SQUARED PER DAY (METERS SQUARED PER DAY)

- MORE THAN 500 (46.4)
- 401 to 500 (37.3 to 46.4)
- 301 to 400 (28 to 37.3)
- 201 to 300 (18.7 to 28)
- LESS THAN 200 (18.7)

——200—— LINE OF EQUAL NET THICKNESS OF SANDSTONE OF THE FOX HILLS-LOWER HELL CREEK AQUIFER SYSTEM—Interval feet (15.2 meters)

FIGURE 6.—Transmissivity and net thickness of sandstone of the Fox Hills-lower Hell Creek aquifer system.

by Croft (1971), of two wells that had accurate temperature data were 0.8 to 6.7 ft/d (0.2 to 2.0 m/d). Croft's method, however, can produce large variations in conductivity with only slight variations of temperature and resistivity.

Transmissivity values determined from drawdown tests (table 3) ranged from 135 to 600 ft^2/d (12.5 to 55.7 m^2/d) and had a mean of 313 ft^2/d (29.1 m^2/d); values determined from flow and recovery tests ranged from 11 to 215 ft^2/d (1.0 to 20 m^2/d) and had a mean of 80 ft^2/d (7.4 m^2/d). The lower values for the flow and recovery tests possibly are due to partial penetration of most of the wells.

The transmissivity of the aquifer system ranges from more than 500 ft^2/d (46 m^2/d) in the western third of Slope County and southwest Golden Valley County to less than 200 ft^2/d (19 m^2/d) in the Medora trough area in west-central Billings County, northwest and east-central Golden Valley County, and eastern Slope County (fig. 6). The transmissivity pattern not only parallels regional lineaments but is normal to the direction of the Pierre sea regression. (See Gill and Cobban, 1973.)

Potential yields from the Fox Hills-lower Hell Creek aquifer system will vary depending on the thickness of the sandstone penetrated and the hydraulic conductivity. Potential yields in gallons per minute may be estimated by dividing the transmissivity at any point by 270, then multiplying by the amount of available drawdown in feet (Johnson Division, Universal Oil Products Company, 1966). Properly completed and developed wells may yield as much as 300 gal/min (19 L/s). Flowing wells, however, generally will not yield more than 150 gal/min (9.5 L/s).

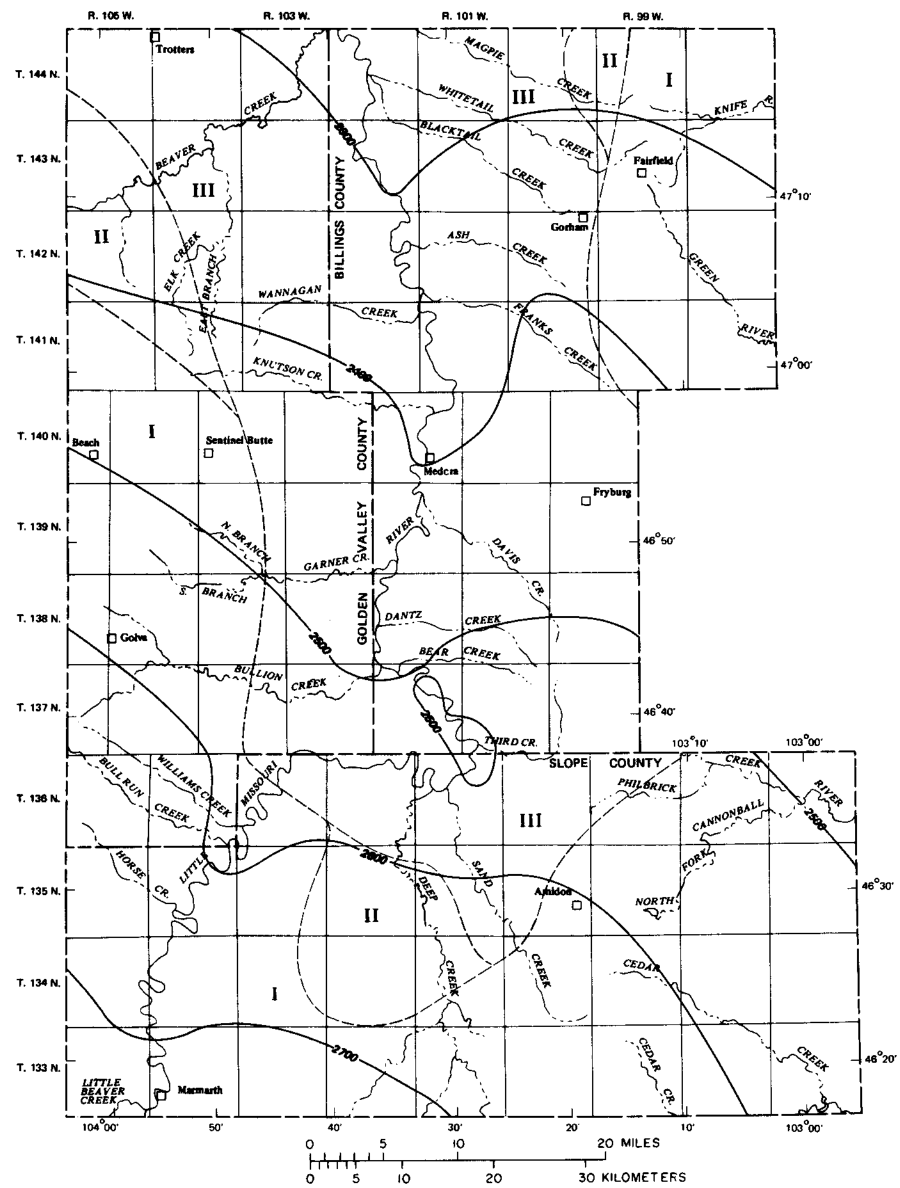
Potentiometric contours indicate that ground-water movement in the study area generally is from southwest to northeast (fig. 7) with a hydraulic gradient of about 6 ft/mi (1 m/km).

In the Fox Hills-lower Hell Creek aquifer system there are three zones of potential leakage of ground water. (1) In the southwestern part of Golden Valley County, the eastern part of Billings County, and parts of Slope County (zone I) heads in the overlying aquifer system are higher than those in the Fox Hills-lower Hell Creek aquifer system, creating a potential for water to leak downward from the overlying aquifer system. (2) In two small locations near the periphery of the study area and one locale in central Slope County (zone II), the head in the Fox Hills-lower Hell Creek aquifer system is at approximately the same altitude as the head in the overlying aquifer system; therefore, there is no potential to leak upward or downward. (3) In the central part of the study area (zone III) heads in the Fox Hills-lower Hell Creek aquifer system are higher than the heads in the overlying aquifer system, creating a potential for water to leak upward. Generally the head differential in zone III is about 100 feet (30.5 m) near the valley of the Little Missouri River and 10 to 50 feet (3 to 15 m) east and west of the valley.

Withdrawals of water from flowing wells have created a cone of depression along the Little Missouri River in north-central Slope and southern Billings Counties (fig. 7). Withdrawals also have deflected the potentiometric surface all along the Little Missouri River (see section on effects of flowing wells).

TABLE 3.—Summary of aquifer tests, Fox Hills-lower Hell Creek aquifer system

Location	Method of aquifer test	Transmissivity (ft^2/d)	Discharge (gal/min)	Specific capacity [(gal/min)/ft]	Storage coefficient
133-105-30CCC	Drawdown	—	—	3.5	—
134-104-24DDD	Drawdown	600	10	2.2	—
135-102-03CDB	Recovery	33	3.0	—	—
136-100-31DDC	Drawdown	205	7.4	.9	3.0×10^{-4}
136-102-20BBD	Recovery	59	3.6	—	—
136-104-12BAA	Recovery	54	3.5	—	—
137-101-29CCA	Recovery	120	2.6	—	—
138-102-34DDA	Recovery	42	4.8	—	—
140-101-35DAD	Recovery	74	74	.40	—
140-102-18DCC	Flow	204	4.8	.90	—
140-102-22DBD	Recovery	215	—	—	—
140-106-25CBB1	Recovery	—	210	1.2	—
141-101-03AAB	Flow	21	2.0	.5	—
141-101-21CAC	Recovery	18	4.6	—	—
142-101-33DBA	Recovery	11	—	—	—
144-100-24BBD1	Drawdown	135	7	.70	4.2×10^{-4}
144-102-24DDD	Flow	105	2.3	1.8	—



EXPLANATION

—2600— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, 1976. Contour interval 100 feet (30.5 meters). Datum is National Geodetic Vertical Datum of 1929

I ZONE OF POTENTIAL GROUND-WATER LEAKAGE—I, potential downward leakage; II, no potential leakage; and III, potential upward leakage

----------- ZONE BOUNDARY

FIGURE 7.—Potentiometric contours of the Fox Hills-lower Hell Creek aquifer system, 1976.

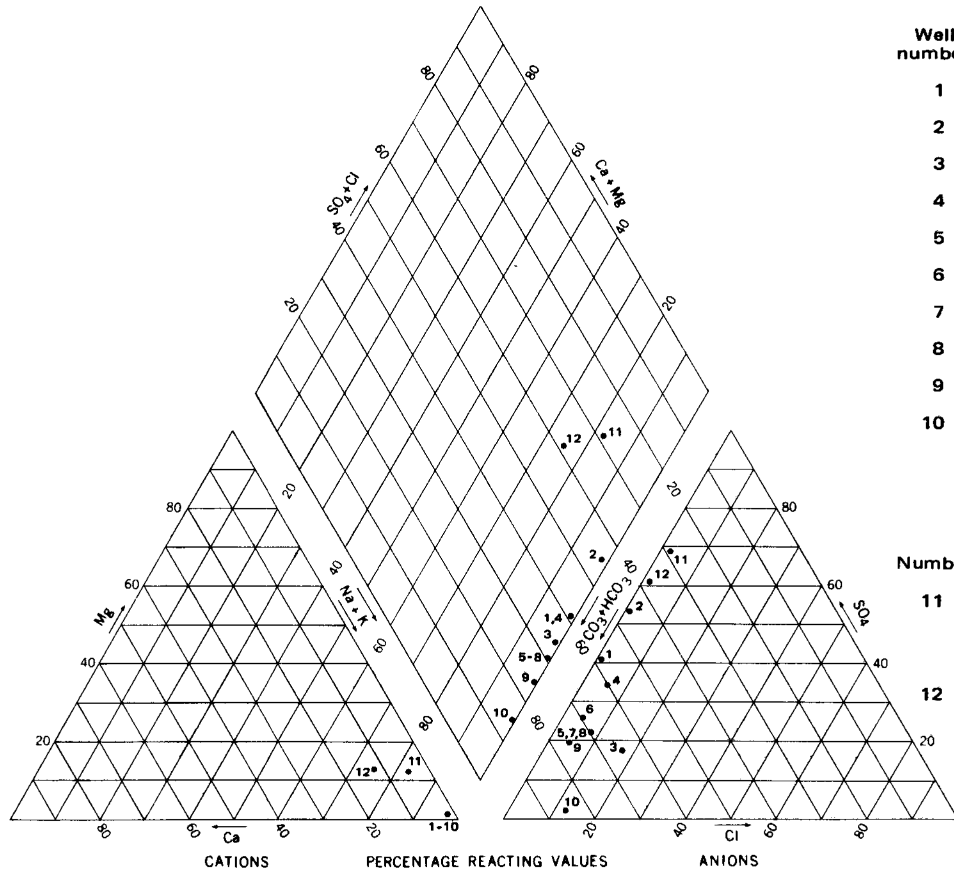
Most of the water in the Fox Hills-lower Hell Creek aquifer system is a sodium bicarbonate type that generally has less dissolved constituents than water in the overlying aquifers. Major chemical constituents in selected surface-water and ground-water samples are plotted on a trilinear diagram in figure 8. The wells are numbered downgradient from the outcrop. As the water moves downward through overlying beds and downgradient through the aquifer, the calcium in solution, picked up in the soil zone, exchanges with sodium. Water from well number 1, which is less than 1.0 mile (1.6 km) down dip from the outcrop, had sodium (at 99 percent) as the major cation. An increase of bicarbonate plus carbonate ions (from 742 to 967 mg/L) and a corresponding reduction in sulfate (from 420 to 29 mg/L) occurs downgradient; chloride also increases downgradient (from 5.5 to 77 mg/L).

D. L. Thorstenson (written commun., 1976) concluded that sulfate reduction appeared to be the only reasonable reaction to account for the disappearance of sulfate in the aquifer. He postulated that the removal of sulfate was by bacterial reduction of dissolved sulfate, and oxidation of organic carbon was the energy source for the bacteria (Kuznetsov and others, 1963). Another possibility for the reduction of sulfate stated by Thorstenson is that water in underlying formations that is high in sodium, chloride, and methane may leak into the Fox Hills-lower Hell Creek aquifer system. The methane reduces the sulfate and the chloride and bicarbonate increase accordingly. However, carbon sources other than methane, that could reduce the sulfate, may be available from underlying and(or) overlying formations.

Locally, water from the Fox Hills-lower Hell Creek aquifer system is discharging into streams near the outcrop during low flow. Relatively high calcium and magnesium concentrations in the surface-water samples probably are the result of ground-water discharge. Higher sulfate/lower bicarbonate is a typical anion combination for ground water discharging to the streams near the recharge area.

Dissolved-solids concentrations in 41 samples from the Fox Hills-lower Hell Creek aquifer system ranged from 887 to 1,720 mg/L and had a mean of 1,160 mg/L. The water was soft; 76 samples contained 0 to 110 mg/L hardness, and had a mean of 11 mg/L. Fluoride concentrations ranged from 0.2 to 7.4 mg/L and generally increased from south to north. Boron concentrations in 36 samples ranged from 0.28 to 1.8 mg/L and iodine in four samples ranged from 0.0 to 0.34 mg/L; both increased from southwest to northeast. Sulfur as sulfide was 0.2 and 0.41 mg/L in samples from two wells; however, all water samples collected from the aquifer system had a rotten egg odor from hydrogen sulfide. Sodium-adsorption ratios ranged from 24 to 200, indicating the sodium hazard generally was too high to be classified for irrigation purposes.

For wells more than 800 feet (244 m) deep the water at the well head had a mean temperature of 63°F (17°C); however, the actual temperature of the water in the aquifer determined from temperature logs generally was about 80°F (26.7°C) or 17°F (9°C) higher.



Well number	Well location	Well depth (feet)	Dissolved solids (mg/L)
1	133-106-34BAA	104	1,290
2	133-106-13ADB2	229	1,560
3	134-104-24DDD1	1,300	1,070
4	136-104-12BAA	987	1,020
5	136-100-31DDC1	1,725	1,230
6	138-102-34DDA	988	992
7	140-106-25CBB1	1,259	1,430
8	140-102-26BCA	1,080	1,060
9	143-105-33BAB	1,177	1,180
10	144-100-24BBD1	2,160	1,070

Number	Date	Discharge (ft^3/s)	Dissolved solids (mg/L)
	Little Missouri River at Marmarth		
11	10/02/74	4.6	2,060
	Little Beaver Creek near Marmarth		
12	9/04/75	2.1	1,200

FIGURE 8.—Major constituents in selected water samples from the Fox Hills-lower Hell Creek aquifer system, the Little Missouri River, and Little Beaver Creek.

Aquifers of Late Cretaceous and Tertiary Age

Upper Hell Creek-Lower Ludlow Aquifer System

The upper part of the Hell Creek Formation and the lower part of the Ludlow Member of the Fort Union Formation form an extensive regional aquifer system that underlies all of Billings and Golden Valley Counties and most of Slope County. The units crop out in southwestern Slope County (fig. 4). Although a structure map was not constructed for the upper Hell Creek and lower Ludlow aquifer system, the regional dip is thought to approximate that of the Fox Hills-lower Hell Creek aquifer system (fig. 5).

The upper part of the Hell Creek Formation generally consists of a confining bed composed of claystone and silty claystone, equivalent to the Bacon Creek Member of Frye (1969). In western Slope County, however, very fine to medium sandstone occurs above the confining bed. This sandstone forms the upper Hell Creek part of the aquifer system. The sandstone either pinches out north of Slope County or has been eroded; therefore, only sandstone in the lower part of the Ludlow Member constitutes the aquifer system over most of the study area.

The lower part of the Ludlow Member consists of lignite, brownish-gray carbonaceous claystone and siltstone, gray siltstone, and gray very fine to fine sandstone. The sandstone, however, consists of about 30 percent silt and clay. The upper contact of the lower part of the Ludlow Member is arbitrarily placed at the top of the T-cross lignite bed (C. G. Carlson, oral commun., 1977), which is the base of the Lebo Shale Member equivalent in the western part of the study area and the base of the marine Cannonball Member in the remainder of the study area (table 2). The Lebo Shale Member equivalent and the Cannonball Member, which are thought to be time-stratigraphic equivalents, form a major confining bed throughout the region (pl. 1).

Where the upper part of the Hell Creek Formation forms part of the aquifer system its maximum thickness is about 80 feet (24 m). The thickness of the lower part of the Ludlow Member ranges from 0 to 500 feet (0 to 152 m) and commonly is 300 feet (91 m); generally, the unit is thinnest near the Cedar Creek anticline and thickens to the northeast.

The net sandstone thickness in the upper Hell Creek-lower Ludlow aquifer system is less than the net sandstone thickness in the Fox Hills-lower Hell Creek aquifer system due to the increase of siltstone and claystone, especially near the upper part of the aquifer system. Generally the sandstone near the base of the lower part of the Ludlow Member stores most of the water in the aquifer system.

Depth to the top of the aquifer system ranges from 0 feet (0 m) at the outcrop to about 1,400 feet (427 m) below land surface in the upland areas of northeast Billings County. In the valley of the Little Missouri River the depth ranges from 0 feet (0 m) north of Marmarth to about 700 feet (210 m) at the north edge of Billings County.

Porosity values for the aquifer system obtained in the laboratory from two sidewall cores that had greater than 70 percent sand-sized grains were 33.0 and

34.9 percent. Hydraulic conductivity values obtained in the laboratory from two sidewall cores that had greater than 70 percent sand-sized grains were 0.6 and 0.8 ft/d (0.18 and 0.24 m/d). The low hydraulic conductivity values for the upper Hell Creek-lower Ludlow aquifer system apparently are due to poor sorting and the large percent of silt.

Transmissivity values determined from recovery tests on flowing wells ranged from 1.5 to 160 ft^2/d (0.14 to 15 m^2/d) and had a mean of 77 ft^2/d (7.2 m^2/d; table 4). The low values are due to partial penetration of the wells, low net sandstone thickness, and the overall low hydraulic conductivity of the aquifer system.

Potential yields from properly completed and developed wells may be as much as 150 gal/min (9.5 L/s). Flowing wells, however, generally will not yield more than 30 gal/min (1.9 L/s).

A map of the potentiometric surface (fig. 9) indicates that ground-water movement generally is from south to north and hydraulic gradients vary from about 17 ft/mi (3.2 m/km) in central Golden Valley County, to 6 ft/mi (0.8 m/km) in northern Golden Valley County, and 4 ft/mi (1.1 m/km) east of the Little Missouri River.

Withdrawals of water from flowing wells along the Little Missouri River in western Billings County have created major deflections in the potentiometric surface. Head declines in the upper Hell Creek-lower Ludlow aquifer system are greater than those in the Fox Hills-lower Hell Creek aquifer system due to the lower hydraulic conductivity.

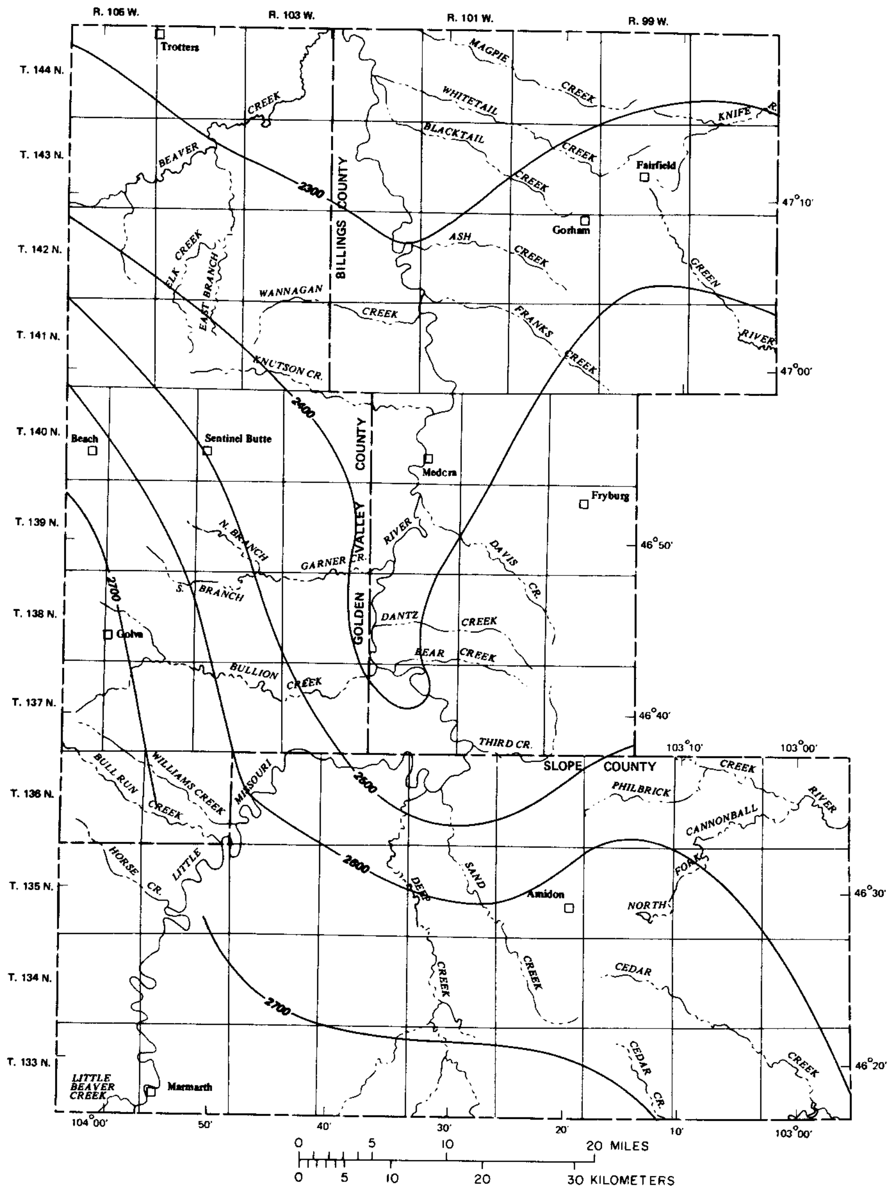
Most of the water in the upper Hell Creek-lower Ludlow aquifer system is soft and is a sodium bicarbonate type. The water generally is more mineralized than water in the underlying Fox Hills-lower Hell Creek aquifer system, yet, on the average, less mineralized and less variable than water in the overlying aquifers.

Major chemical constituents in water samples from selected wells finished in the upper Hell Creek-lower Ludlow aquifer system are shown in figure 10. The wells are numbered downgradient from the outcrop. Sodium constituted more than 97 percent of the cations, ranging from 400 to 610 mg/L; bicarbonate plus carbonate constituted more than 60 percent of the anions, ranging from 666 to 1,524 mg/L. Generally, sulfate constituted less than 30 percent of the anions, ranging from 0.8 to 260 mg/L, and generally decreasing downgradient. The sulfate reduction process downgradient is thought to be similar to that in the Fox Hills-lower Hell Creek aquifer system — reduction by anaerobic bacteria or methane entering the aquifer system from underlying formations. The method of reduction by bacteria seems more probable than reduction by methane because of the abundance of lignite in the Ludlow Member that would provide organic carbon as energy for the bacteria.

Dissolved-solids concentrations in 19 samples ranged from 940 to 2,490 mg/L, and had a mean of 1,390 mg/L. Fifty samples contained 2 to 130 mg/L hardness; the mean was 15 mg/L. Chloride concentrations in 50 samples ranged from 1.5 to 56 mg/L and had a mean of 10 mg/L. Boron concentrations in 19 samples ranged from 0.05 to 1.6 mg/L and fluoride concentrations in 48 samples

TABLE 4. — Summary of aquifer tests, upper Hell Creek-lower Ludlow aquifer system

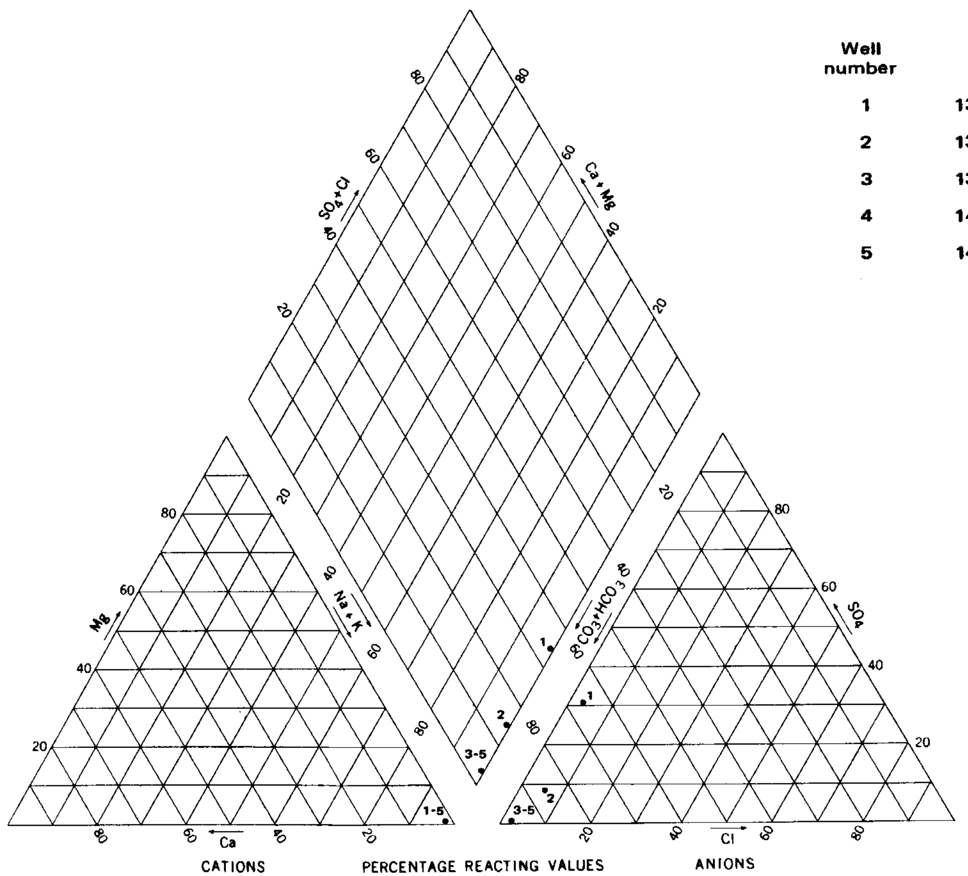
Location	Method of aquifer test	Transmissivity (ft^2/d)	Discharge (gal/min)	Specific capacity [(gal/min)/ft]
135-102-19DAA	Recovery	110	1.9	0.3
137-101-19BBD	Recovery	1.5	.5	.01
137-103-01ACA	Recovery	117	1.6	.1
139-102-33AAA	Recovery	70	6.7	.2
139-102-33CBB	Recovery	160	6.0	.3
144-102-16BBB	Recovery	3.3	—	—



EXPLANATION

—— 2300 —— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, 1977. Contour interval 100 feet (30.5 meters). Datum is National Geodetic Vertical Datum of 1929

FIGURE 9.—Potentiometric contours of the upper Hell Creek-lower Ludlow aquifer system, 1976-77.



Well number	Well location	Well depth (feet)	Dissolved solids (mg/L)
1	136-105-26ACA	570	1,080
2	137-101-32CCB	585	1,020
3	138-100-07AAA1	980	1,290
4	142-100-25DDA	1,374	1,330
5	144-100-24BBD2	1,624	1,470

FIGURE 10.—Major constituents in selected water samples from the upper Hell Creek-lower Ludlow aquifer system.

ranged from 0.4 to 10 mg/L, both generally increasing downgradient. Iron concentrations in 19 samples ranged from 0.02 to 0.77 mg/L, and had a mean of 0.24 mg/L. Sodium-adsorption ratios of 50 samples ranged from 31 to 145, and had a mean of 68.

Aquifers of Tertiary Age

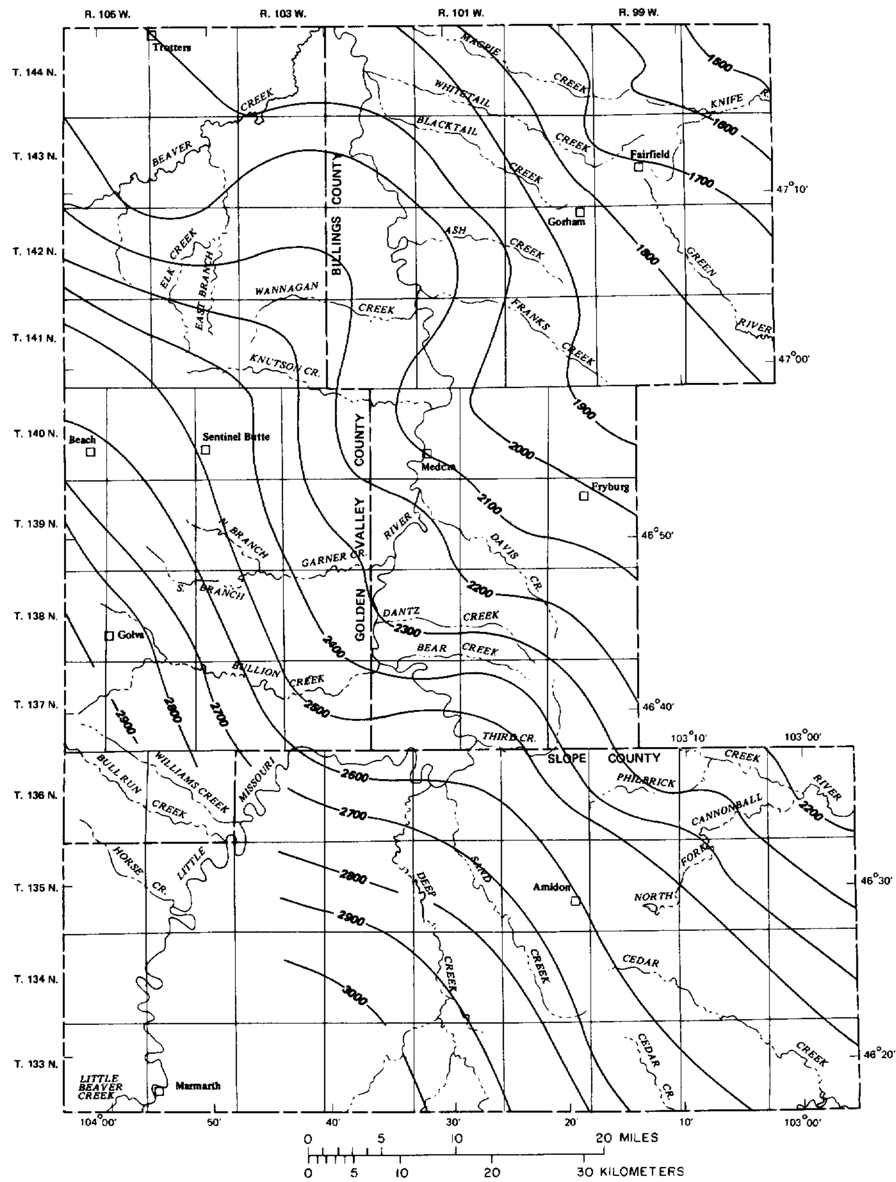
Aquifers in the Upper Part of the Ludlow and Tongue River Members of the Fort Union Formation

The upper part of the Ludlow Member is part of a high-constructive delta deposit consisting of very fine to medium channel fill and sheet sandstone. The Tongue River Member is also part of a high-constructive delta system consisting of very fine to medium channel fill and distributary type sandstone (M. G. Croft, L. O. Anna, and D. W. Fisher, written commun., 1977). Other reports (Trapp and Croft, 1975; Croft, 1978) combine the two formations into one aquifer system. The term aquifer system as used in the definitions of terms section of this report, however, does not apply to aquifers in the two members. It is not known if the upper part of the Ludlow Member is in hydraulic connection with the lower part of the Tongue River Member to form one aquifer system. Most of the data presented in this report were collected from aquifers in the lower part of the Tongue River Member. The upper part of the Tongue River Member is essentially a confining unit consisting mostly of silt, clay, lignite, and thin lenticular sandstone.

The members crop out as structural and topographic expressions over most of the western half of the three counties (fig. 4). A structure-contour map of the top of the Harmon lignite bed, which is near the base of the Tongue River Member, indicates an average dip of approximately 23 ft/mi (4.4 m/km) to the northeast (fig. 11). The dip decreases slightly near the Medora trough in central Billings, northeast Slope, and northwest Golden Valley Counties. The more northwesterly strike of the members in northeast Billings County probably is due to the influence of the Nesson anticline in Dunn County.

The upper part of the Ludlow Member consists of interbedded moderately sorted gray very fine to medium sandstone, gray siltstone, claystone, silty claystone, and thick discontinuous lignite. The Tongue River Member consists of interbedded poor to moderately sorted gray very fine to medium sandstone, siltstone, silty claystone, thick areally extensive lignite beds near the base that thin near the Medora trough and thinner discontinuous lignite beds in the middle and upper parts.

Geophysical logs show a distinct depositional pattern of the two members. The upper part of the Ludlow Member overlies the Cannonball Member in the eastern part of the study area and overlies the Lebo Shale Member equivalent in the western part (pl. 1). Sandstone beds generally are confined to the middle part. The sandstone beds are overlain by interbedded silt, silty claystone, and claystone. In most places, the lower part of the Tongue River Member is characterized by thick beds of siltstone and sandstone near the base and thick



EXPLANATION

——2000—— STRUCTURE CONTOUR—Shows altitude of top of Harmon lignite bed (lower Tongue River Member). Contour interval 100 feet (30.5 meters). Datum is National Geodetic Vertical Datum of 1929

FIGURE 11.—Structure contours of the top of the Harmon lignite bed.

lignite beds (Harmon and Hanson beds) about 150 feet (46 m) above the upper Ludlow-Tongue River contact. In northeast Billings County the lignite beds are only a few feet above the contact and the sandstone-siltstone beds occur above the lignites.

The thickness of the upper part of the Ludlow Member ranges from 0 feet (0 m) at the outcrop to about 350 feet (107 m) and has a mean of 200 feet (61 m). The thickness of the Tongue River Member ranges from 0.0 feet (0.0 m) to about 650 feet (198 m), increasing from southwest to northeast. Aquifers in the two members generally consist of sandstone and, to a lesser degree, of lignite beds. The mean net aquifer thickness in the two members is about 250 feet (76 m).

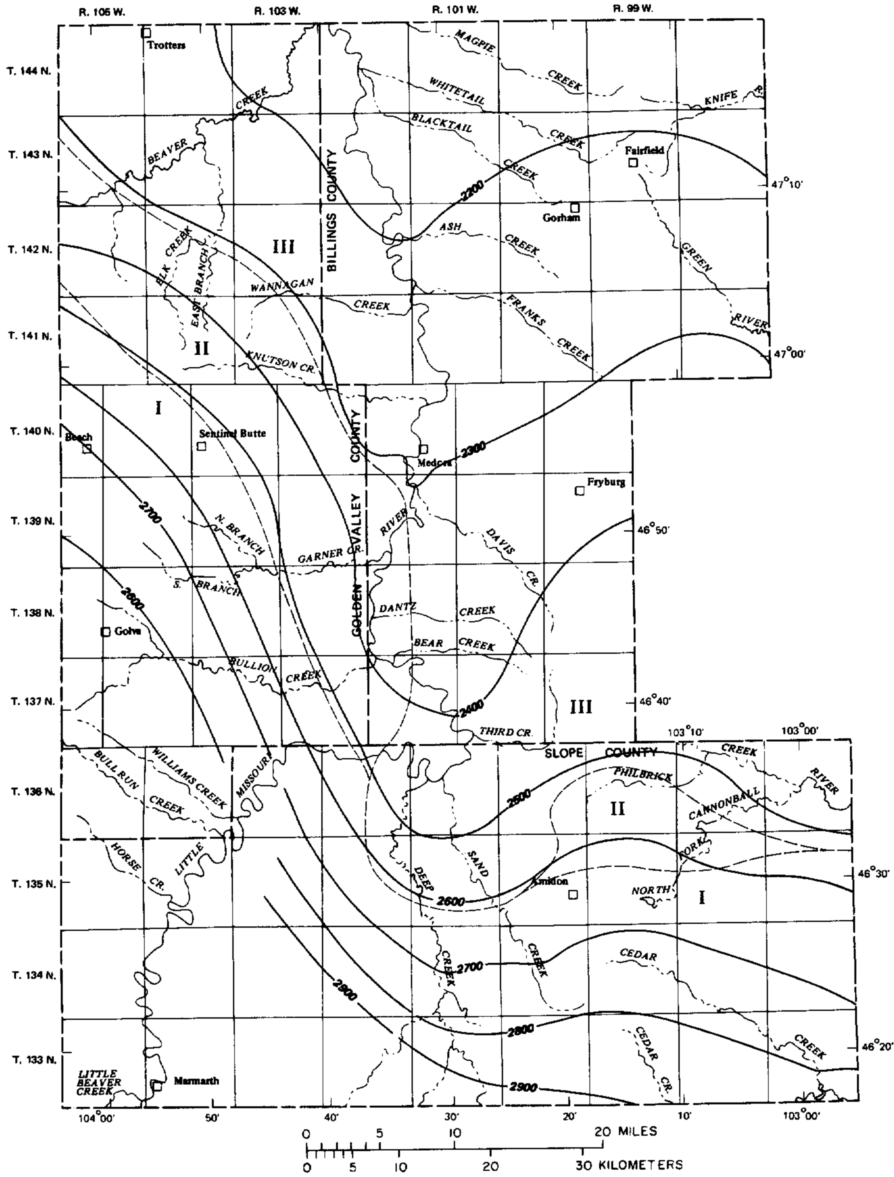
Specific-capacity values determined from three drawdown tests on aquifers in the lower part of the Tongue River Member were 1.5, 2.0, and 4.0 (gal/min)/ft [0.3, 0.4, and 0.8 (L/s)/m]. Transmissivity values determined from two of the drawdown tests were 520 and 530 ft^2/d (48 and 49 m^2/d), and one value determined from a recovery test on a flowing well was 220 ft^2/d (20 m^2/d). Generally, thicker more permeable sandstone, and the corresponding higher transmissivity values, occur in the southern half of the study area.

Properly completed and developed wells in aquifers in the upper part of the Ludlow and Tongue River Members may yield as much as 250 gal/min (16 L/s), although yields from flowing wells generally will be less than 10 gal/min (0.6 L/s).

A map of the potentiometric surface was constructed for Billings, Golden Valley, and Slope Counties using only wells tapping aquifers in the lower part of the Tongue River Member (fig. 12). The map indicates that ground-water movement in the western half of the study area generally is from southwest to northeast with an average hydraulic gradient of 14 ft/mi (2.7 m/km); and in the eastern half the movement generally is from south to north with an average hydraulic gradient of 10 ft/mi (1.9 m/km).

In aquifers in the lower part of the Tongue River Member there are three zones of potential leakage of ground water (fig. 12). (1) In southern Slope and western Golden Valley Counties (zone I) heads in aquifers are higher than heads in the underlying aquifer system, creating a potential for water to leak downward into the underlying aquifer system. (2) In a narrow band near the center of the study area (zone II) — paralleling the Medora trough — heads in the two aquifers are at approximately the same altitude. Therefore, the water has no potential to leak upward or downward and the flow is lateral. (3) In the northern one-third of the study area (zone III) heads in the underlying aquifer system are higher than heads in aquifers in the lower part of the Tongue River Member, creating a potential for water to leak upward from the underlying aquifer system.

Heads generally decrease with depth in the Tongue River Member, and indicate a potential for water to leak downward. Generally recharge to the aquifers in the upper part of the Ludlow and Tongue River Members occurs in zone I. Modern carbon in the water from well 140-106-25CBB3 at Beach, determined from Carbon 14 analysis, is relatively high at 17.2 percent. This suggests that recharge at the well site is local and relatively rapid (D. W. Fisher, written commun., 1977). Recharge to the ground-water basin (aquifer) may be controlled by topography as the potentiometric-surface divide in the aquifers in



EXPLANATION

——— 2400 ——— POTENTIOMETRIC CONTOUR—Shows altitude at which water level would have stood in tightly cased wells, 1977. Contour interval 100 feet (30.5 meters). Datum is National Geodetic Vertical Datum of 1929

I ZONE OF POTENTIAL GROUND-WATER LEAKAGE—I, potential downward leakage; II, no potential leakage; and III, potential upward leakage

- - - - - - - - - - ZONE BOUNDARY

FIGURE 12.—Potentiometric contours of aquifers in the lower part of the Tongue River Member of the Fort Union Formation, 1977.

eastern Billings and Slope Counties coincides with the surface-drainage divide of the Little Missouri River basin and the Knife, Green, and Cannonball River basins.

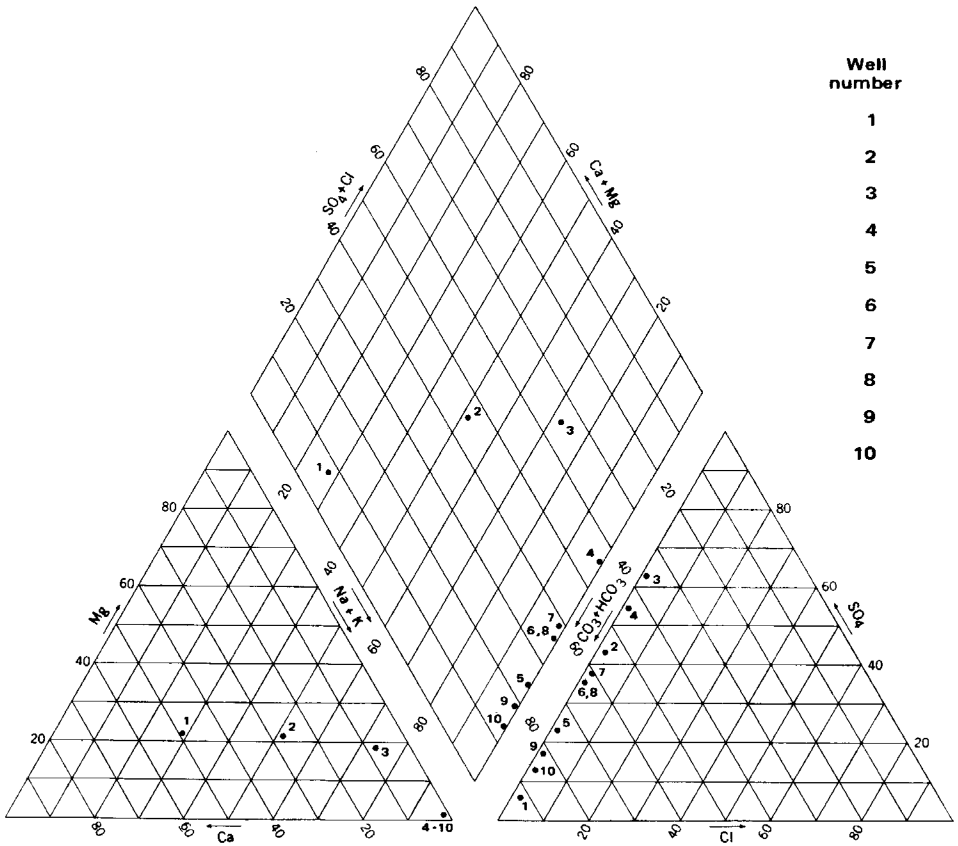
Locally water from the aquifers discharges into streams as base flow or from flowing wells. Only minor deflections in the potentiometric surface along the Little Missouri River have occurred compared to those in underlying aquifers because there are fewer flowing wells, lower pressures, and smaller yields.

Chemical analyses of water samples indicate that the water quality in aquifers in the lower part of the Tongue River Member is variable and depends mostly on depth, to a lesser degree on proximity to lignites, and least on distance from outcrop.

A trilinear diagram (fig. 13) shows the major constituents in water from 10 wells in the aquifers. The wells are listed according to increased depth. The diagram indicates that sodium generally is the major cation in the water. In wells greater than 200 feet (61 m) deep, sodium constituted more than 96 percent of the total cations (340 to 580 mg/L and a mean of 440 mg/L). In wells less than 200 feet (61 m) deep, sodium was less than 73 percent of the total cations (40 to 510 mg/L and a mean of 250 mg/L). Generally, the percentage of calcium decreased with increasing depth. In wells greater than 200 feet (61 m) deep, calcium ranged from 2.0 to 6.6 mg/L and had a mean of 3.4 mg/L. In wells less than 200 feet (61 m) deep, calcium ranged from 57 to 100 mg/L and had a mean of 73 mg/L.

In wells greater than 200 feet (61 m) deep, bicarbonate comprised from 50 to 86 percent of the total anions (508 to 976 mg/L and a mean of 700 mg/L), and sulfate comprised from 12 to 49 percent of the total anions (120 to 660 mg/L and a mean of 300 mg/L). However, in water from wells less than 200 feet (61 m) deep, bicarbonate constituted from 36 to 91 percent of the total anions (351 to 686 mg/L and a mean of 560 mg/L) and sulfate constituted 7.9 to 63 percent of the total anions (24 to 930 mg/L and a mean of 440). Dissolved-solids concentrations in the samples were variable, ranging from 270 to 1,880 mg/L; the mean was 1,100 mg/L.

For all wells sampled in aquifers in the lower part of the Tongue River Member, the most consistent values were from wells over 200 feet (61 m) deep. Generally, the water from wells less than 200 feet (61 m) deep was very hard. Hardness ranged from 20 to 760 mg/L and had a mean of 280 mg/L. Water from wells more than 200 feet deep generally was soft; hardness ranged from 4 to 420 mg/L and had a mean of 38 mg/L. Chloride concentrations generally were less than 1 percent of the total anions, ranging from 0.5 to 79 mg/L. There was no apparent correlation of chloride concentrations with depth or distance from the outcrop. Boron and fluoride concentrations ranged from 0.1 to 2.2 mg/L and 0.1 to 6.5 mg/L, respectively, and fluoride increased slightly downgradient. Dissolved nitrate concentrations were low, ranging from 0.2 to 26 mg/L, and two samples had dissolved nitrogen of 36 and 36.3 mg/L. Iron plus manganese concentrations ranged from 0.009 to 5.6 mg/L and had no apparent correlation with depth. Values from seven water samples would plot on the low-sodium-hazard scale for irrigation (fig. 3); other values would be in the high-hazard scale or completely off scale.



Well number	Well location	Well depth (feet)	Dissolved solids (mg/L)
1	133-101-09CDD	64	270
2	140-106-25CBB3	110	1,060
3	134-103-28BDA	168	1,880
4	139-103-32DBB	285	1,590
5	138-101-02BAC	343	923
6	137-101-34ABA1	355	985
7	140-102-16DAA	364	1,140
8	143-103-14DBC	446	1,230
9	141-100-34CBC	508	1,010
10	136-099-26DAD	534	1,150

FIGURE 13.—Major constituents in selected water samples from aquifers in the lower part of the Tongue River Member of the Fort Union Formation.

Aquifers in the Sentinel Butte Member of the Fort Union Formation

The Sentinel Butte Member is thought to be the landward part of a delta plain overlying the Tongue River Member. The vertical arrangement of the formations indicates a progradation of a large deltaic complex into the Cannonball sea (Jacob, 1976). The member crops out in the upland areas east of the Little Missouri River and as buttes west of the Little Missouri River; some of the buttes are capped by the White River Formation (fig. 4). Analyses of pollen in the clays and lignites in the member indicate that it is of late Paleocene age (R. H. Tschudy, written commun., 1976), and is equivalent to the upper part of the Tongue River Member in northeast Wyoming and southeast Montana.

The Sentinel Butte Member consists of thin lignite, gray claystone, silty claystone, and gray to yellowish-gray fine to medium channel sandstone. The contact with the underlying Tongue River Member is generally placed at the top of the H-T Butte lignite bed. The Sentinel Butte is conformably overlain by the Golden Valley Formation or unconformably overlain by the White River formation.

On the upland areas in the southeast part of the study area the Sentinel Butte Member is relatively thin, and has a mean thickness of less than 100 feet (30.5 m). However, in the northeastern part the member thickens considerably, ranging from 300 to 450 feet (91 to 137 m).

Aquifers in the Sentinel Butte Member consist of poorly consolidated discontinuous channel sandstone and fractured lignite. Most of the wells that tap aquifers in the Sentinel Butte Member are completed in sandstone and are generally less than 100 feet (30.5 m) deep. However, in the Green River drainage basin, several miles east of Highway 85, and in extreme northeast Slope County thick shallow lignites are often tapped as aquifers.

In topographically high areas — paralleling the drainage divide of the Little Missouri River basin and the Green and Knife River basins — the member is characterized by perched aquifers, especially in northern Billings County. Downward percolating water is perched by lignite and sandstone beds and travels horizontally until it reaches the surface as springs. Underlying aquifers may not be recharged from perched aquifers and can be dry. As an example, well 144-100-24BAC2 was screened in sandstone from 260 to 270 feet (79 to 82 m) below land surface and was dry, yet overlying sandstone, claystone, and lignite beds were water saturated. Geophysical logs of this well indicate that the interstices of the dry aquifer are filled with gas, possibly carbon dioxide and(or) nitrogen.

In topographically low areas few springs exist and water percolates downward recharging the underlying aquifers — including the aquifers in the upper part of the Ludlow and Tongue River Members.

Since specific hydrologic data were not collected for aquifers in the Sentinel Butte Member, mean hydraulic conductivities were obtained from the groundwater report for Dunn County (Klausing, 1978), which borders Billings County on the east. The mean conductivity value for sandstone aquifers in Dunn County was 0.4 ft/d (0.1 m/d) and mean values for lignite aquifers, determined from two pump tests, ranged from 94 to 1,200 ft/d (29 to 366 m/d).

Individual wells in sandstone aquifers will yield 5 to 50 gal/min (0.3 to 3 L/s). Individual wells in lignite aquifers may yield 1 to 200 gal/min (0.06 to 13 L/s).

Water in aquifers in the Sentinel Butte Member is extremely variable in concentration of dissolved solids, cations, and anions. Generally, the water quality is dependent on depth (the water generally has a vertical flow path) and aquifer lithology.

Based on few data, a trilinear diagram (fig. 14) shows the major constituents in water from wells. In wells less than 100 feet (30.5 m) deep, calcium plus magnesium constituted more than 74 percent of the cations, ranging from 79 to 940 mg/L and had a mean of 370 mg/L. In wells greater than 100 feet (30.5 m) deep, sodium constituted more than 58 percent of the total cations, ranging from 100 to 1,100 mg/L and had a mean of 580 mg/L. Therefore, it seems reasonable to assume that at a depth of about 100 feet (30.5 m) much of the cation exchange of sodium for calcium in the water has taken place.

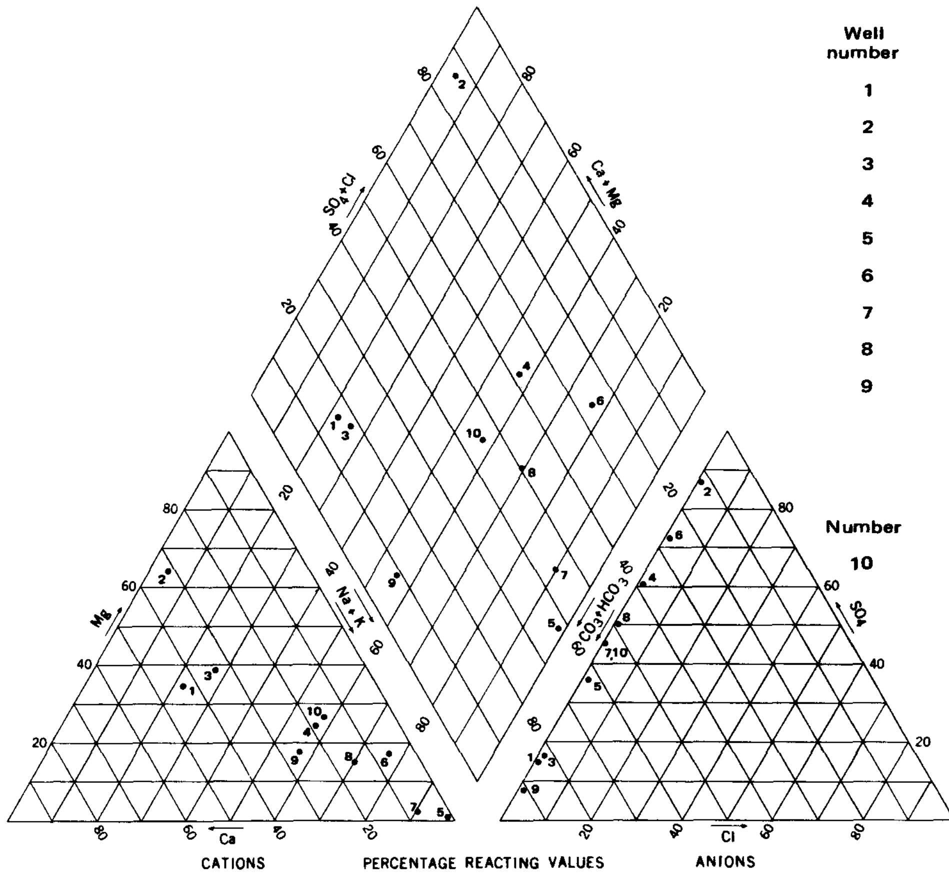
Sulfate and bicarbonate plus carbonate concentrations apparently are related to the proximity of lignite deposits in the area. The iron sulfide in the lignite combines with bicarbonate and carbon dioxide to form iron oxides and release sulfate. Sulfate concentrations ranged from 30 to 2,700 mg/L and bicarbonate plus carbonate concentrations ranged from 318 to 1,248 mg/L.

Dissolved-solids concentrations in nine samples ranged from 367 to 4,210 mg/L. Generally the water was very hard, ranging from 240 to 3,200 mg/L in wells less than 100 feet (30.5 m) deep and 12 to 990 mg/L in wells 100 feet (30.5 m) or deeper. Chloride concentrations were low, ranging from 0.9 to 18 mg/L. Boron and fluoride concentrations ranged from 0 to 1.3 mg/L and 0.2 to 1.6 mg/L, respectively. Dissolved nitrate generally was low and had a mean of 2.8 mg/L; however, there was one anomaly of 35 mg/L from well 135-098-32DAD1. Iron plus manganese concentrations ranged from 0.6 to 7.35 mg/L. Water from wells less than 100 feet (30.5 m) deep had a mean of 0.09 mg/L iron plus manganese and water from wells 100 feet (30.5 m) or deeper had a mean of 2.8 mg/L. Values from three water samples would plot in the low-sodium medium-salinity zone for irrigation purposes (fig. 3); six values would plot in either the very high-hazard zone or were too high to be classified.

Aquifers in the Golden Valley and White River Formations

The Golden Valley Formation crops out in two small areas in northeast Billings County (fig. 4) and reaches a maximum known thickness of about 100 feet (30.5 m). The formation consists of light-purplish-gray claystone, tan sandy claystone, and a tan micaceous crossbedded sandstone (C. G. Carlson, oral commun., 1977). There are no major aquifers in the formation.

The White River Formation forms the rimrock of scattered high buttes and underlies a relatively small area (fig. 4). The formation consists of conglomerate, arkose, tuffaceous sandstone, siltstone, and claystone (C. G. Carlson, oral commun., 1977). Its maximum thickness is 250 feet (76 m). There are no major aquifers in the formation.



Well number	Well location	Well depth (feet)	Dissolved solids (mg/L)
1	142-099-10DDD	54	367
2	135-098-32DAD1	62	4,210
3	142-099-03DCC	80	444
4	144-099-30AAB	100	2,870
5	144-100-13DBD	105	1,990
6	142-100-01BDC	115	4,110
7	136-098-33CCD	120	1,660
8	135-101-16CBA	167	1,380
9	134-101-35BCC	184	413

Green River near New Hradec

Number	Date	Discharge (ft^3/s)	Dissolved solids (mg/L)
10	10/17/74	0.52	702

FIGURE 14.—Major constituents in selected water samples from aquifers in the Sentinel Butte Member of the Fort Union Formation and from the Green River.

Aquifers of Quaternary Age

Alluvial Aquifers

Alluvial deposits containing aquifers of potential importance occur in the Little Missouri River valley and Beaver and Deep Creek valleys. They occupy about 4 percent of the total surface area in Billings, Golden Valley, and Slope Counties.

The alluvium consists of sand, gravel, silt, and clay. The sand, silt, and clay were derived from local Fort Union Formation deposits and the gravel was derived from terrace deposits — similar lithologically to the Flaxville Formation of Miocene and Pliocene age in eastern Montana. Generally, all the alluvial deposits in the three-county area have similar characteristics; the upper few feet consist of silty clay that contains local patches of sand and becomes sandier near the stream channel. The lower part of the deposits generally consists of about 10 to 15 feet (3.0 to 4.6 m) of gravel that is underlain by bedrock (fig. 15).

The alluvial aquifers obtain recharge from precipitation that infiltrates surface soils from high streamflow (fig. 16), as underlow from the alluvium of small ephemeral streams on the flanks of the valleys, and from floods that inundate the flood plain and saturate the underlying aquifers.

The Little Missouri River valley aquifer generally is less than 1 mile (1.6 km) wide and has an areal extent of about 65 mi^2 (168 km^2). Based on a mean thickness of 12 feet (3.7 m), and an estimated specific yield of 15 percent, a maximum of 74,000 acre-feet (91 hm^3) of water is available to wells from ground-water storage. Potential yields to properly constructed wells generally would be less than 50 gal/min (3.2 L/s).

Low-flow measurements were made on the Little Missouri River in August 1976 (fig. 17) from Marmarth to the McKenzie County line. The measurements indicate that there is frequent interchange of ground water and surface water north of Medora. Stream discharge increases sharply along the reach from 140-102-27ABB to 140-102-01ACC (fig. 17). This reach is located in zone III for aquifers in the lower part of the Tongue River Member (fig. 12), that was identified previously as the zone where water has the potential to leak upward into the lower part of the Tongue River Member. The decrease in discharge in the reach between 140-102-01ACC and 142-102-12CDC probably is due to the water infiltrating into the alluvium. Apparently infiltration from bedrock into the alluvium is negligible. Thick lignites that subcrop beneath the alluvium in the area also may affect aquifer discharge into the stream.

Water samples were collected for chemical analyses from the Little Missouri River at the same locations that the low-flow measurements were made but at a different time (November 1976). The analyses indicate a significant increase in dissolved solids at the same location as the significant increase in discharge of the river (fig. 17). Dissolved solids ranged from 1,900 mg/L to 2,750 mg/L; however, the percentages of cations and anions remained constant (sodium 74 percent, calcium 13 percent, magnesium 13 percent, sulfate 71 percent, bicarbonate 27 percent, chloride 2 percent).

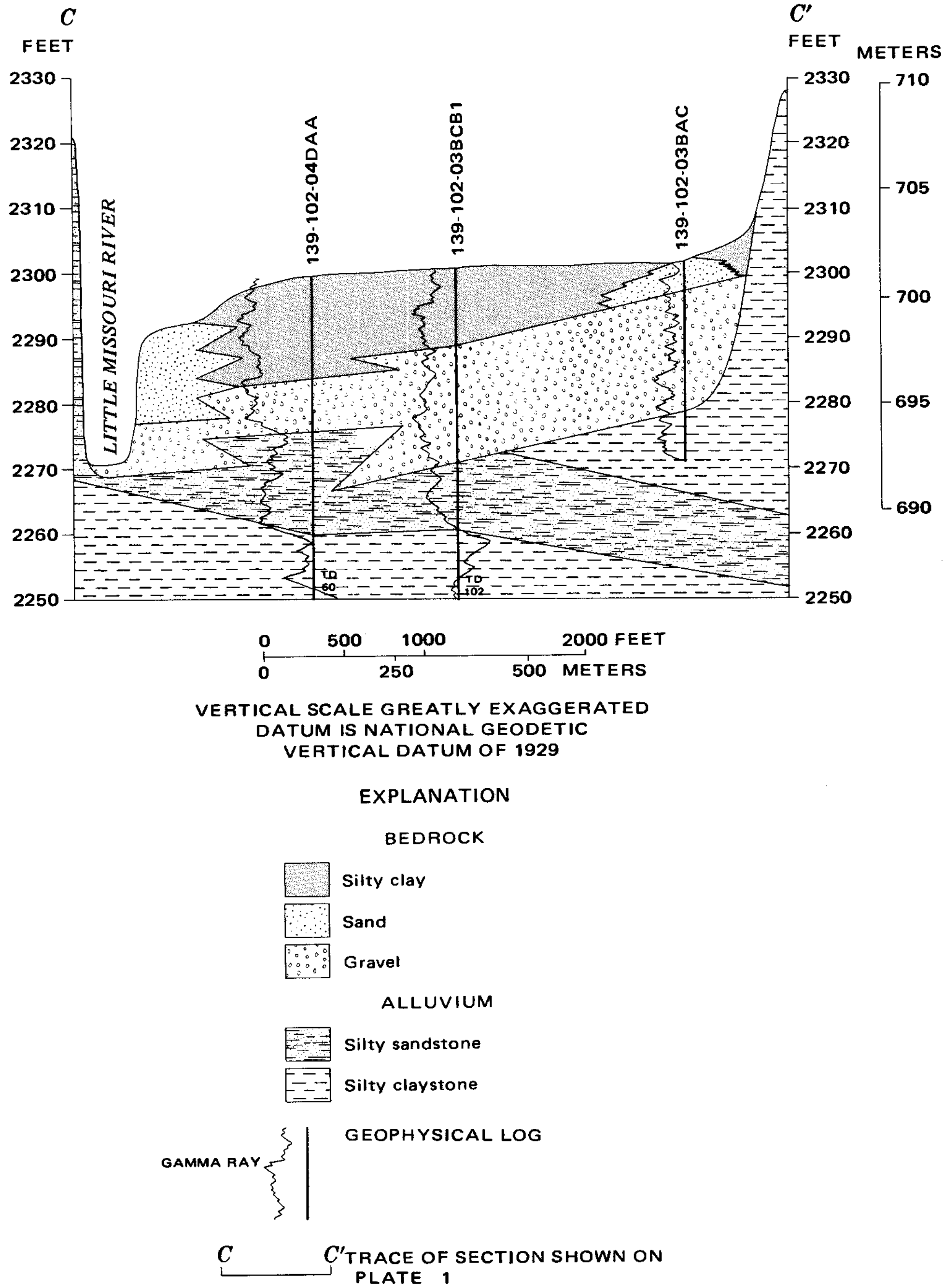


FIGURE 15.—Generalized geologic section C-C′ through the flood plain of the Little Missouri River.

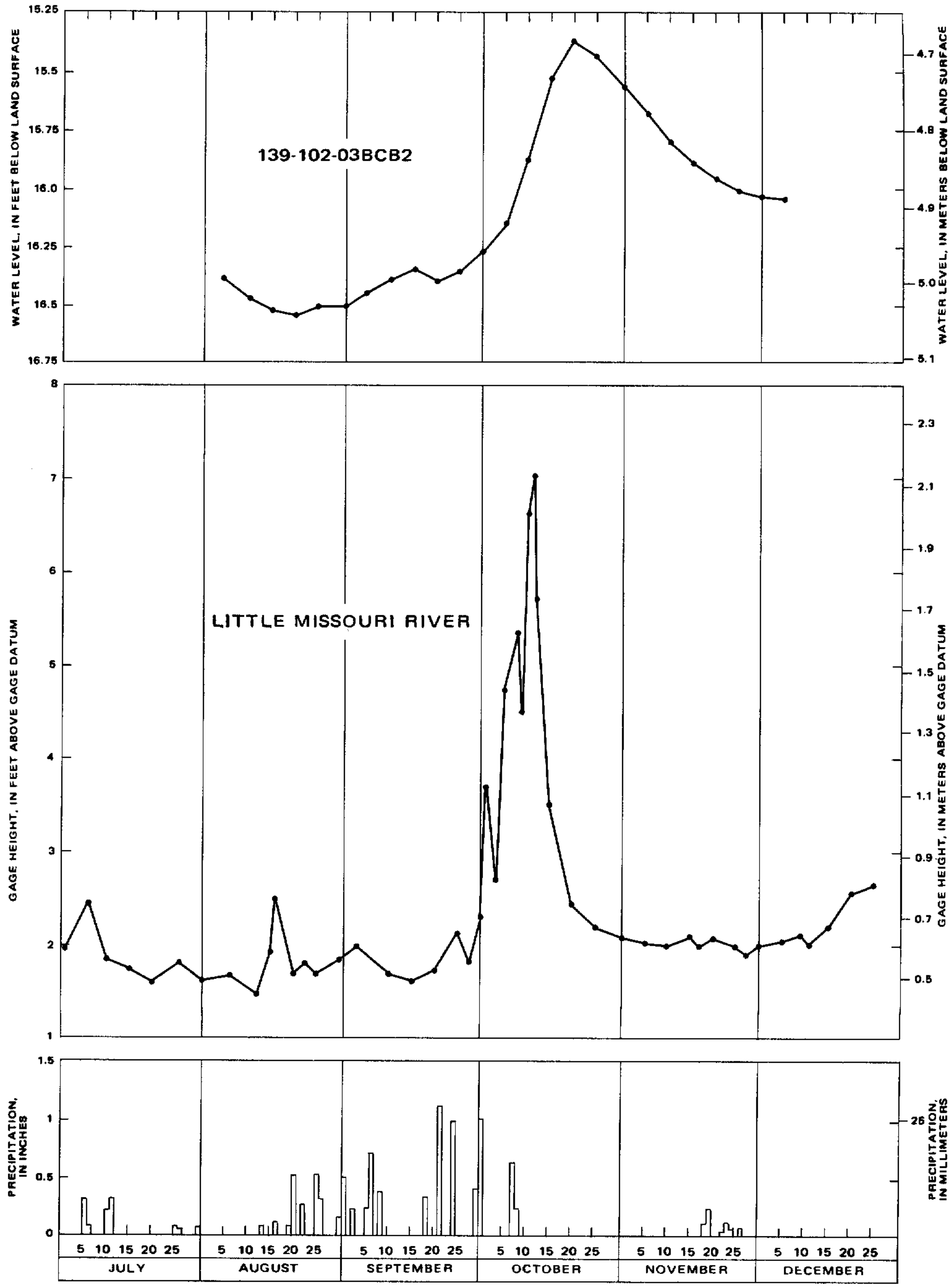


FIGURE 16.—Water-level fluctuations in the Little Missouri River valley aquifer, gage height of Little Missouri River at Marmarth, and precipitation at Medora, 1977.

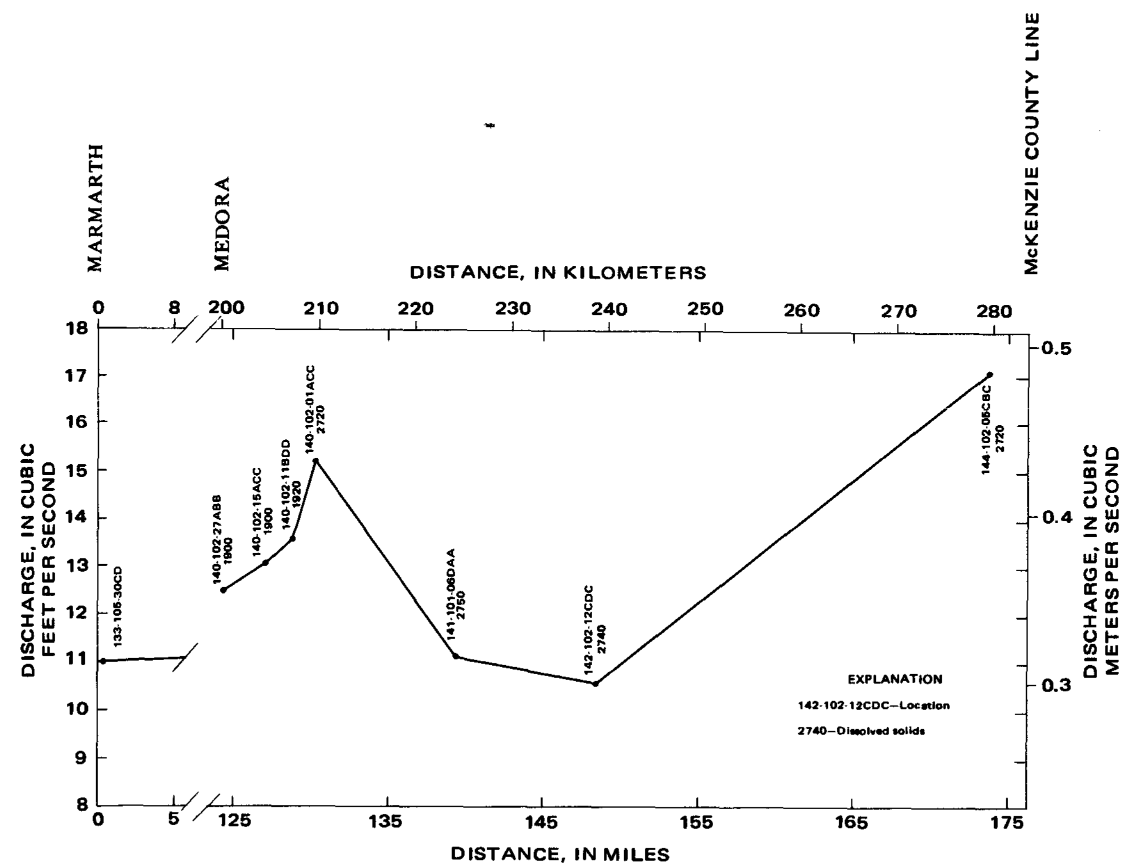


FIGURE 17.—Low-flow measurements August 1976, and dissolved-solids concentrations November 1976, in the Little Missouri River.

Three water samples collected from the Little Missouri River valley aquifer indicate the water generally is a sodium sulfate-bicarbonate type. Dissolved constituents in water from the aquifer at 143-102-09BCC2 were similar to those in samples from the underlying aquifers in the Tongue River Member, indicating that ground water from the aquifers in the Tongue River Member may be leaking into the alluvium at least in that area. The irrigation classifications of the water samples were C3-S2 (fig. 3) to off scale.

Beaver Creek valley aquifer generally is less than 0.5 mile (0.8 km) wide and has an areal extent of about 12 mi^2 (31 km^2). Based on a mean thickness of 12 feet (3.7 m), and an estimated specific yield of 15 percent, about 14,000 acre-feet (17 hm^3) of water is available to wells from ground-water storage. Potential yields to properly constructed wells generally would be less than 50 gal/min (3.2 L/s).

Deep Creek valley aquifer generally is less than 0.5 mile (0.8 km) wide and has an areal extent of about 3.6 mi^2 (9.3 km^2). Based on a mean thickness of 12 feet (3.7 m), and an estimated specific yield of 15 percent, about 4,000 acre-feet (5 hm^3) of water is available to wells from ground-water storage. Potential yields to properly constructed wells generally would be less than 50 gal/min (3.2 L/s).

HYDROGEOLOGY OF STRIPPABLE LIGNITE DEPOSITS

Most of the data presented in this section are from a regional study of the effects of strip mining on ground-water resources in western North Dakota (W. F. Horak, written commun., 1977). Figure 18 shows the locations of strippable lignite deposits in Billings, Golden Valley, and Slope Counties (Pollard and others, 1972). The hydrogeology of the Beach, Bowman, and New England deposits is described below. The Dickinson deposit occurs in Billings, Dunn, and Stark Counties. The deposit was evaluated hydrogeologically in Dunn and Stark Counties (W. F. Horak, written commun., 1977), but has not been evaluated in Billings County. Currently, there are no commercial mining operations in the three-county area.

The Beach deposit is in west-central Golden Valley County and central Wibaux County, Montana. Most of the strippable deposit lies within the drainage basin of Beaver Creek and its tributaries. The strippable deposit is the Harmon lignite bed ("C" bed of May, 1954) in the lower part of the Tongue River Member. Locally the bed dips 40 to 60 ft/mi (7.6 to 11.4 m/km) to the northeast. The bed has a maximum thickness of 40 feet (12 m) and a mean thickness of 18 feet (5.5 m).

Where drilled, the lignite was completely saturated. The poteniometric surface has a gradient of 13 ft/mi (2.5 m/km) to the north in the southern part of the strippable area. The contours of the potentiometric surface gradually shift to the northeast — paralleling Little Beaver Creek — and the gradient increases to about 20 ft/mi (3.8 m/km) in the northern part.

Chemical quality of ground water in the Beach deposit is quite variable. Calcium and magnesium are the dominant cations near the outcrop in Wibaux County, Montana, with sodium becoming the dominant cation down dip. Sulfate and bicarbonate are the major anions with higher sulfate concentrations near the

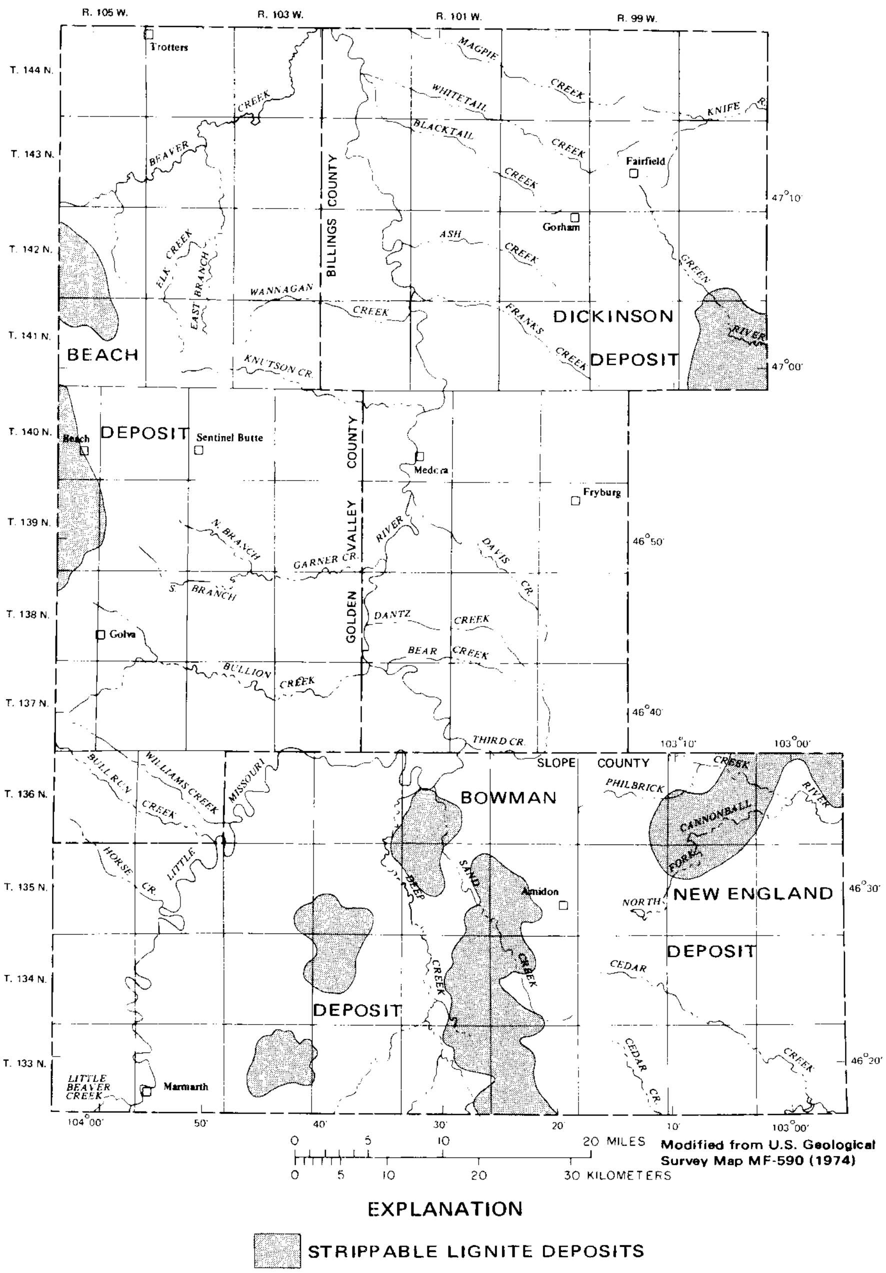


FIGURE 18.--Strippable lignite deposits.

outcrop. Water quality near the outcrop is influenced mainly by oxygenated water reacting with the sediments, resulting in an average pH of around 6.0.

The Bowman deposit occurs in central Slope County and north-central Bowman County. The strippable area is parallel to and west of U.S. Highway 85 (fig. 18). The major strippable deposit is the Harmon lignite bed in the lower part of the Tongue River Member. The local structure shows that the Harmon bed dips to the northeast at about 30 ft/mi (5.7 m/km). The bed has a mean thickness of 24 feet (7.3 m) and a maximum thickness of 40 feet (12 m). Other potential strippable deposits include the Hansen bed 10 to 60 feet (3 to 18 m) below the Harmon bed; however, the Hansen bed has not been evaluated hydrologically.

The Harmon lignite bed is completely saturated in most areas, and has a potentiometric surface 16 to 94 feet (4.9 to 29 m) above the top of the bed. Data indicate that the potentiometric surface is greatly influenced by the dissected topography and ground-water movement is from topographic highs to topographic lows. Ground water discharges from the lignite bed into local drainages, which are Sand Creek in the central part of the area and Deep Creek in the west. Also, in higher topographic areas, some of the ground water leaks downward through the lignite and recharges the sandstone aquifers in the lower part of the Tongue River Member.

Chemical analyses of water from the lignite indicate that sodium constitutes 53 to 99 percent of the total cations; the remainder is calcium and magnesium. Sulfate ranges from 8 to 84 percent of the total anions and bicarbonate plus carbonate ranges from 15 to 90 percent. Dissolved solids in the samples ranged from 336 to 3,150 mg/L.

Part of the New England deposit occurs in northeast Slope County, north of Highway 21 and east of U.S. Highway 85 (fig. 18). The strippable lignite deposits are in the upper part of the Tongue River and lower part of the Sentinel Butte members. Interbedded siltstone and claystone occur above and between the lignite beds and discontinuous sandstone lenses underlie the lignite. There are at least three lignite beds greater than 4 feet (1.2 m) thick within 200 feet (61 m) of the land surface. One of these is the H-T Butte lignite bed, which marks the top of the Tongue River Member. A structure-contour map on one of the beds shows a dip of 25 to 120 ft/mi (4.7 to 23 m/km) to the northwest (W. F. Horak, written commun., 1977).

Wells penetrating the H-T Butte lignite were used to evaluate the hydrology of all the lignite aquifers in the New England area, since a number of wells in the upper lignite beds were dry. In the lowlands of the Cannonball River, the major drainage of the area, ground water locally has an upward flow potential. Near topographic highs, however, head differentials indicate the water has a downward flow potential towards the aquifers in the lower part of the Tongue River Member.

Water quality in the H-T Butte lignite is less variable than that in other strippable lignites in other areas. Less permeable overburdens allow more time for ionic exchanges and reactions to take place, allowing more time for chemical equilibrium of the water to take place. Sodium constitutes 85 to 99 percent of the total cations, and bicarbonate-carbonate and sulfate constitute 31 to 80 percent and 11 to 68 percent, respectively, of the total anions. Dissolved-solids concentrations in samples ranged from 948 to 2,600 mg/L, and had a mean of 1,600 mg/L. The pH of the water averaged more than 8.0.

EFFECTS OF FLOWING WELLS

Head declines attributed to flowing wells have occurred in the major bedrock aquifer systems along the valleys of the Little Missouri River and its tributaries.

In 1967-69 T. M. Hamilton (written commun., 1969) made head measurements on more than 70 flowing wells. In 1975-76 head measurements were made on 39 flowing wells (table 5), including 17 of those measured by Hamilton. The 1975-76 measurements were made using a pressure gage and measuring only those wells that had proper completion, documented depths, and proper plumbing so that a pressure gage could be fitted securely. From 1967 to 1976 the mean head decline was 4.0 percent per year.

Many flowing wells that originally had low heads have ceased to flow because of the lowering of static pressure in each aquifer or aquifer system. Heads will continue to decline as long as the amount of water being withdrawn from the aquifers is greater than the recharge.

Conservation measures should be initiated to reduce the head declines in the aquifers; such as restricting the flow rate with either a valve or small diameter pipe or for properly completed wells with stable casings, a complete shutdown of the flow, using measures to prevent freezing, when the water is not being used.

SURFACE WATER

The Little Missouri River is not only the main drainage in the study area but the river valley itself significantly influences ground-water movement. The U.S. Geological Survey operates two gaging stations on the river; one at Marmarth in southwestern Slope County and one at Medora in central Billings County (presently in limited operation). On March 23, 1947, the river had a maximum discharge of 45,000 ft^3/s (1,270 m^3/s) at Marmarth and 65,000 ft^3/s (1,840 m^3/s) at Medora (U.S. Geological Survey, 1976). Periods of no flow have been recorded frequently at both stations during January and February. The mean discharge at Marmarth is 245,600 acre-feet (303 hm^3) per year for a 38-year period of record (U.S. Geological Survey, 1976); at Medora the mean discharge is 342,000 acre-feet (422 hm^3) per year for a 42-year period of record (U.S. Geological Survey, 1975).

Water samples collected at the gaging stations on the Little Missouri River at Marmarth and Medora showed that during periods of high flow, when the flow is mostly from surface-water runoff (spring snowmelt and heavy thunderstorms), dissolved-solids concentrations had a mean of 600 mg/L (U.S. Geological Survey 1973-74 and 1975-76). Sodium constituted about 80 percent of the total cations (mean concentration was 190 mg/L), and sulfate constituted about 80 percent of the total anions (mean concentration was 500 mg/L). During periods of low flow,

TABLE 5. — Flowing-well measurements

Aquifer or aquifer system/location	Depth (feet below LSD)	Head (feet above LSD)	Date measured[1]	Head (feet above LSD)	Date measured	Altitude (feet above NGVD of 1929)	Flow (gal/min, 1976)
Fox Hills-lower Hell Creek							
135-102-03CDB	945	—	—	23.2	9-76	2560	3.0
135-102-19DAA	1080	—	—	3.2	9-76	2620	1.9
136-102-20BBD	1120	—	—	40.4	11-75	2510	3.6
136-104-12BAD	987	39.1	—	27.1	9-76	2550	3.5
137-101-29CCA	865	40.6	7-69	37.6	9-76	2450	2.6
137-103-12BAB	950	103.9	6-69	97.4	9-76	2415	—
138-102-34CCB	997	—	—	89.8	9-76	2400	1.0
138-102-34DDA	988	92.4	6-69	69.0	9-76	2435	4.8
139-102-18ACA	1180	—	—	2.5	11-75	2465	1.0
140-102-10DDA	1196	46.2	8-68	28.5	7-76	2345	—
140-102-18DCC	1200	—	—	42.9	6-76	2380	4.8
140-102-22DBD	1050	—	—	124.8	11-76	2260	—
140-102-34AAD	1100	103.9	6-69	59.9	7-76	2355	5.6
141-101-03AAB	—	—	—	71.5	6-76	2322	2.0
141-101-21CAC	1200	94.7	8-68	59.4	9-76	2270	4.6
141-101-26ACB	—	—	—	22.9	9-76	2370	2.0
141-102-02DDB	1280	—	—	66.5	9-76	2260	13
142-101-33DBA	1333	—	—	2.3	8-76	2320	—
143-102-34BBA	1120	—	—	175.0	9-76	2160	47
144-102-27DCC	1280	103.9	9-67	85.0	6-76	2200	—
144-103-22CCD	1280	—	—	89.4	6-76	2220	—
Upper Hell Creek-lower Ludlow							
137-101-19BBD	580	—	—	33.2	9-76	2420	.5
137-101-33CCA	600	23.1	7-69	3.2	9-76	2455	.5
137-103-01ACA	550	17.3	6-69	5.4	9-76	2393	1.6
138-102-20ADA	777	28.9	6-69	17.1	9-76	2388	—
138-103-25DBA	405	13.9	6-69	4.0	9-76	2390	—
139-102-10DBD1	460	13.6	9-68	13.1	9-76	2295	2.2
139-102-20ABB	460	23.1	6-69	17.1	9-76	2328	—
139-102-33AAA	720	—	—	30.5	9-76	2370	6.7
139-102-33CBB	400	—	—	27.8	9-76	2316	6.0
140-102-17CCA	600	—	—	9.2	6-76	2350	.1
144-102-16BBB	600	27.7	7-69	26.0	9-76	2118	—
Upper Ludlow-lower Tongue River							
137-104-10ABB	230	1.0	6-69	0.0	6-76	2610	—
138-105-33CAB	60	—	—	20.2	9-76	2770	2.9
140-102-11ADD	424	—	—	21.0	8-76	2252	—
140-102-35CCC	450	13.9	6-69	10.7	6-76	2300	.3
142-101-31DDA	570	27.7	8-68	20.5	8-76	2230	1.0
143-102-15ACD	400	—	—	34.0	8-76	2160	—

[1]*T. M. Hamilton (written commun., 1969).*

when flow is mostly from ground-water discharge (late summer, fall, and winter), dissolved solids increased to a mean of 1,800 mg/L. However, sodium still constituted about 80 percent of the total cations (mean concentration was 440 mg/L), and sulfate constituted about 70 percent of the total anions (mean concentration was 900 mg/L).

Perennial tributaries to the Little Missouri River include Little Beaver, Beaver, Deep, Sand, and Bullion Creeks. Little Beaver Creek, at the gaging station just southwest of Marmarth, has an average discharge of 31,440 acre-feet (38.8 hm^3) per year for a 38-year period (U.S. Geological Survey, 1976). Gaging stations recently have been installed on Beaver Creek near Trotters (Golden Valley County) and on Deep Creek near its mouth (Slope County). These creeks flow from ground-water discharge during late summer, fall, and winter. Water-level recorders were installed in the alluvial aquifers at both new gaging stations to study ground water-surface water relationships.

The Green River, which is perennial, is in the Heart River basin and has an average discharge of 13,190 acre-feet (16.3 hm^3) per year for a 12-year period of record at a gaging station in eastern Billings County (U.S. Geological Survey, 1976). Chemical analyses of water samples taken during the low flow (ground-water discharge) indicate that water in the river has about an equal amount of bicarbonate-carbonate but only about one-quarter as much sulfate as does water from the Little Missouri River during low flow. The area drained by the Green River includes only the Sentinel Butte Member of the Fort Union Formation, whereas the area drained by the Little Missouri River includes Upper Cretaceous shales, the Fox Hills Sandstone, the Hell Creek Formation, and the Ludlow and Tongue River Members of the Fort Union Formation.

WATER UTILIZATION

Most of the water used for public, domestic, and livestock purposes in Billings, Golden Valley, and Slope Counties is obtained from drilled wells ranging in depth from 10 to 2,200 feet (3 to 670 m). Most of the wellu yield less than 10 gal/min (0.6 L/s), although yields vary depending on the transmissivity of the aquifer, the type of well construction, and the capacity of the pump installed in the well.

The Fox Hills-lower Hell Creek aquifer system generally is tapped for public supplies and for most livestock supplies requiring large yields. The aquifer system is becoming a popular target for dependable supplies of relatively good quality water.

Domestic and Livestock Use

The upper Hell Creek-lower Ludlow aquifer system and aquifers in the upper part of the Ludlow and Tongue River Members, Sentinel Butte Member, and alluvial deposits are tapped for domestic and livestock supplies.

Estimates of the quantity of water pumped daily for domestic and livestock purposes in Billings, Golden Valley, and Slope Counties are listed in the following table.

Use	Individual requirements (gal/d)[1]	Population or number	Total pumpage (gal/d)
Domestic (not including communities having municipal supplies)	100	[2]5,293	529,000
Cattle	15	[3]108,000	1,620,000
Milk Cows	35	[3]2,200	77,000
Sheep	1.5	[3]1,800	2,700
Chickens	.10	[3]10,000	1,000
Hogs	5	[3]81,000	405,000
Total pumpage			2,640,000 (rounded)

[1]*Murray, 1968.*
[2]*U.S. Bureau of the Census, 1971.*
[3]*North Dakota State University, 1974.*

Public Supplies

Beach

The city of Beach obtains its water supply from several drilled wells. The most frequently used well is 1,259 feet (384 m) deep and taps the Fox Hills-lower Hell Creek aquifer system. Presently, the well yields 200 gal/min (13 L/s) of soft, sodium bicarbonate-sulfate type water containing 1,430 mg/L dissolved solids. Total pumpage from this well since installation in 1961 is 650 Mgal (2.5, hm^3); the mean annual production is 43 Mgal (0.16 hm^3).

Two wells tapping aquifers in the lower part of the Tongue River Member — above the Harmon lignite bed — are used as backup wells during the periods of high usage in the summer. These wells are approximately 100 feet (30.5 m) deep and yield 50 and 200 gal/min (3.2 and 13 L/s) of hard sodium bicarbonate-sulfate type water.

Golva

The city of Golva obtains its water supply from a 967-foot (295-m) well tapping the Fox Hills-lower Hell Creek aquifer system. The water is soft and is a sodium bicarbonate type containing 1,100 mg/L dissolved solids.

Marmarth

The city of Marmarth obtains its water supply from two wells, both tapping the Fox Hills-lower Hell Creek aquifer system. One well, obtained from the Chicago, Milwaukee, St. Paul, and Pacific Railroad, is 215 feet (65.5 m) deep and yields 132 gal/min (8.3 L/s). The second well is 270 feet (82 m) deep and yields 75 gal/min (4.7 L/s). Both wells yield soft, sodium bicarbonate-sulfate type water, with dissolved solids of 1,720 and 1,680 mg/L, respectively.

Medora

The city of Medora obtains its water supply from one recently drilled well and several backup wells. All the wells tap the Fox Hills-lower Hell Creek aquifer system. The recently drilled well is 1,050 feet (320 m) deep and has a free-flow potential of approximately 110 gal/min (6.9 L/s). The flow, however, is restricted to a maximum of approximately 100 gal/min (6.3 L/s). The backup wells free flow at approximately 40 gal/min (2.5 L/s) and can be pumped an additional 40 or 50 gal/min (2.5 or 3.2 L/s).

During the months of June, July, and August, tourists place a heavy demand on the city's water supply. During these three months the city uses a mean of 43,520 gal/d (164,720 L/d). For the remaining 9 months local residents use only a mean of 32,480 gal/d (122,940 L/d), for a mean of 38,000 gal/d (143,800 L/d), or 13.9 Mgal (0.05 hm^3) per year.

The water from the main well is soft and of a sodium bicarbonate type; dissolved-solids concentration was 1,080 mg/L.

Irrigation

During high flow, water from the Little Missouri River and Beaver Creek is used to irrigate small areas of cropland. During low flows, however, the water quality is poor; therefore, the irrigation potential from surface-water sources will be limited. Water from alluvial aquifers has a limited potential even for small-scale irrigation due to the limited extent of the aquifers and small yield potentials. Generally, unsuitable quality restricts the use of water from the bedrock aquifers for irrigation.

Industrial

At the present time there is no water being used for industrial purposes; however, energy-resource and associated economic development may entail substantial use of water for industry. Notably, a gasification or power-generation plant is planned near Beach (Golden Valley County); and *in situ* leaching of uranium may become a reality in Billings and Slope Counties if deposits of economic importance are found.

SUMMARY

Ground water for public, domestic, livestock, and industrial supplies in Billings, Golden Valley, and Slope Counties is obtained from aquifers consisting mostly of semiconsolidated sandstone of Late Cretaceous and Tertiary age. The mean thickness, lithology, and water-yielding characteristics of the geologic units are summarized in table 6. Sedimentary rocks below the Pierre Shale extend to at least 15,000 feet (4,570 m) below land surface. They generally contain saline water that is unsuitable for most purposes.

The Fox Hills-lower Hell Creek aquifer system is used as a source for public, livestock, and domestic supplies. Because water in the aquifer system is the most dependable for quality and quantity in the three-county area, the Fox Hills-lower Hell Creek aquifer system supplies most of the municipal water. Transmissivities range from less than 200 to more than 500 ft^2/d (19 to 46 m^2/d) and wells may yield as much as 300 gal/min (19 L/s). Water movement in the aquifer system generally is from southwest to northeast.

The upper Hell Creek-lower Ludlow aquifer system, aquifers in the upper part of the Ludlow and Tongue River Members, and aquifers in the Sentinel Butte Member are tapped for domestic and livestock supplies. They consist of interbedded very fine to medium sandstone and lignite. Generally the hydraulic conductivities of these aquifers are lower than those of the Fox Hills-lower Hell Creek aquifer system, and the water quality is more variable than that from the Fox Hills-Hell Creek aquifer system.

Alluvial aquifers also are tapped for domestic and livestock supplies. They consist of approximately 10 to 15 feet (3.0 to 4.6 m) of sand and gravel.

Three strippable lignite areas (Beach, Bowman, and New England) occur in the study area. Where drilled, the lignite deposits were saturated and yielded water to most wells. Generally the water quality was variable.

Approximately 2,950 acre-feet (3.6 hm^3) of water is used annually in Billings, Golden Valley, and Slope Counties, of which almost all is derived from ground-water sources.

Flowing wells along the valley of the Little Missouri River and its tributaries have caused deflections in the potentiometric surface of the major bedrock aquifer systems. Water levels in the flowing wells have declined at a rate of 4.0 percent per year since 1967, and will continue to decline unless conservation measures are adopted.

TABLE 6.—Generalized geologic section and water-yielding characteristics of geologic units in Billings, Golden Valley, and Slope Counties, North Dakota

System	Series	Formation or Member		Thickness (feet)	Lithology	Water-yielding characteristics
Quaternary				0-15	Alluvium.	Maximum yield of less than 50 gal/min to individual wells from thicker and more permeable sand and gravel deposits. Water generally is a sodium bicarbonate-sulfate type.
Tertiary	Oligocene	White River Formation		0-250	Sandstone, siltstone, and claystone.	No major aquifers
Tertiary	Eocene	Golden Valley Formation		0-100	Sandstone, siltstone, claystone, and lignite.	No major aquifers.
Tertiary	Paleocene	Fort Union Formation	Sentinel Butte Member	0-450	Sandstone, claystone, and lignite.	Individual wells in sandstone will yield 5 to 50 gal/min. Individual wells in lignite may yield 1 to 200 gal/min. Water quality is variable.
Tertiary	Paleocene	Fort Union Formation	Tongue River Member and upper part of Ludlow Member	0-1,000	Sandstone, siltstone, silty claystone, claystone, and lignite.	Yields to individual wells in sandstone are from 1 to 250 gal/min. Water quality is variable.
Tertiary	Paleocene	Fort Union Formation	Cannonball Member and Lebo Shale Member equivalent	0-200	Marine claystone, silty claystone, and siltstone.	Yields little or no water.
Cretaceous	Upper Cretaceous		Lower part of Ludlow Member and upper part of Hell Creek Formation	0-500	Sandstone, siltstone, silty claystone, claystone, and lignite.	Yields to individual wells generally are less than 150 gal/min. Water generally is a sodium bicarbonate type.
Cretaceous	Upper Cretaceous	Lower part of Hell Creek Formation and Fox Hills Sandstone		0-420	Sandstone, siltstone, and claystone.	Yields to individual wells generally are less than 300 gal/min depending on aquifer thickness and hydraulic conductivity. Water generally is a sodium bicarbonate type.
Cretaceous	Upper Cretaceous	Pierre Shale		2,200	Shale.	Yields little or no water.

SELECTED REFERENCES

Alger, R. P., 1966, Interpretation of electric logs in fresh-water wells in unconsolidated formations: Society of Professional Well Log Analysts, Transactions, 7th Annual Logging Symposium, sec. cc, p. 1-25.

Anna, L. O., 1980, Ground-water data, Billings, Golden Valley, and Slope Counties, North Dakota: North Dakota State Water Commission County Ground-Water Studies 29, pt. II, and North Dakota Geological Survey Bulletin 76, pt. II, 241 p.

Benson, W. E., 1952, Geology of the Knife River area, North Dakota: U.S. Geological Survey Open-File Report.

Bergstrom, J. R., 1956, The general geology of uranium in southwestern North Dakota: North Dakota Geological Survey Report of Investigations no. 23.

Birch, Francis, ed., 1942, Handbook of physical constants: Geological Society of America, Special Paper 36, 325 p.

Bredehoeft, J. D., Blyth, C. R., White, W. A., and Maxey, G. B., 1963, Possible mechanism for concentration of brines in subsurface formations: American Association of Petroleum Geologists Bulletin, v. 47, p. 257-269.

Brown, R. W., 1952, Tertiary strata in eastern Montana and western North and South Dakota, *in* Billings Geological Society Guidebook, 3d Annual Field Conference, Black Hills-Williston Basin, 1952, p. 89-92.

——— 1962, Paleocene flora of the Rocky Mountains and Great Plains: U.S. Geological Survey Professional Paper 375, 119 p.

Carlson, C. G., 1969, Bedrock geologic map of North Dakota: North Dakota Geological Survey Miscellaneous Map no. 10.

Committee on Water Quality Criteria, 1972, Water quality criteria 1972: Environmental Protection Agency, Washington, D.C., 594 p.

Croft, M. G., 1971, A method of calculating permeability from electric logs: U.S. Geological Survey Professional Paper 750-B, p. B265-B269.

——— 1974A, Water supply at Painted Canyon Overlook, Theodore Roosevelt National Memorial Park (South Unit), southwestern North Dakota: U.S. Geological Survey Open-File Report 74-136, 33 p.

——— 1974B, Ground-water basic data, Adams and Bowman Counties, North Dakota: North Dakota Geological Survey Bulletin 65, pt. II, and North Dakota State Water Commission County Ground-Water Studies 22, pt. II, 294 p.

——— 1978, Ground-water resources of Adams and Bowman Counties, North Dakota: North Dakota Geological Survey Bulletin 65, pt. III, and North Dakota State Water Commission County Ground-Water Studies 22, pt. III, 54 p.

Cvancara, A. M., 1976, Geology of the Fox Hills Formation (Late Cretaceous) in the Williston basin of North Dakota, with reference to uranium potential: North Dakota Geological Survey Report of Investigations no. 55, 16 p.

Denson, N. M., and Gill, J. R., 1965, Uranium-bearing lignite and carbonaceous shale in the southwestern part of the Williston basin — a regional study: U.S. Geological Survey Professional Paper 463, 75 p.

Durfor, C. N., and Becker, Edith, 1964, Public water supplies of the 100 largest cities in the United States, 1962: U.S. Geological Survey Water-Supply Paper 1812, 364 p.
Feldman, R. M., 1972, Stratigraphy and paleoecology of the Fox Hills Formation (Upper Cretaceous) of North Dakota: North Dakota Geological Survey Bulletin 61, 65 p.
Fenneman, N. M., 1946, Physiographic divisions of the United States: U.S. Geological Survey map prepared in cooperation with Physiographic Committee, U.S. Geological Survey, Scale 1:7,000,000 (reprinted 1964).
Fisher, S. P., 1954, Structural geology of the Skaar-Trotters area, McKenzie and Golden Valley Counties, North Dakota: North Dakota Geological Survey Report of Investigations no. 15.
Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geological Survey Bulletin 54, 65 p.
Gill, J. R., and Cobban, W. A., 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Professional Paper 776, 37 p.
Ground-Water Subgroup of Water Work Group, Northern Great Plains Resource Program, 1974, Shallow ground water in selected areas in the Fort Union coal region: U.S. Geological Survey Open-File Report 74-371.
Hamilton, T. M., 1970, Groundwater flow in part of the Little Missouri River basin, North Dakota: Unpublished Ph.D. Dissertation, University of North Dakota, Grand Forks, N. Dak.
Hanson, B. M., 1953, Geology of the Elkhorn Ranch area, Billings and Golden Valley Counties, North Dakota: North Dakota Geological Survey Report of Investigations no. 18.
Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geological Survey Bulletin 775, 110 p.
Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water (2d ed.): U.S. Geological Survey Water-Supply Paper 1473, 363 p.
Jacob, A. F., 1975, Criteria for differentiating the Tongue River and Sentinel Butte Formation (Paleocene), North Dakota: North Dakota Geological Survey Report of Investigations no. 53, 55 p.
—— 1976, Geology of the upper part of the Fort Union Group (Paleocene), Williston basin, with reference to uranium: North Dakota Geological Survey Report of Investigations no. 58, 49 p.
Johnson, E. E., Inc., 1966, Ground water and wells: St. Paul, Minn., Edward E. Johnson, Inc., 440 p.
Klausing, R. L., 1978, Ground-water resources of Dunn County, North Dakota: North Dakota Geological Survey Bulletin 68, pt. III, and North Dakota State Water Commission County Ground-Water Studies 25, pt. III, 48 p.
Kuznetsov, S. I., Ivanov, M. V., and Lyalikova, N. N., 1963, Introduction to geological microbiology: New York, McGraw Hill Book Co., Inc., 252 p.
Laird W. M., and Folsom, C. B., Jr., 1956, North Dakota Nesson Anticline: North Dakota Geological Survey Report of Investigations no. 22, 12 p.

Leffingwell, H. A., 1970, Palynology of the Lance (Late Cretaceous) and Fort Union (Paleocene) Formations of the type Lance area, Wyoming, *in* Symposium on Palynology of the Late Cretaceous and early Tertiary, Kosanke, R. M., editor, Geological Society of America Special Paper 127, p. 1-64.

Lloyd, E. R., and Hares, C. J., 1915, The Cannonball marine member of the Lance Formation of North and South Dakota and its bearing on the Lance-Laramide problem: Journal of Geology, v. 23, p. 523-547.

Lohman, S. W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

May, P. R., 1954, Strippable lignite deposits, Wibaux area, Montana and North Dakota: U.S. Geological Survey Bulletin 995-G, p. 255-292.

Meyboom, Peter, 1966, Groundwater studies in the Assiniboine River drainage basin: pt. I: The evaluation of a flow system in south-central Saskatchewan: Geological Survey of Canada Bulletin 139, 65 p.

Meyboom, Peter, van Everdinger, R. O., and Freeze, R. A., 1966, Patterns of groundwater flow in seven discharge areas in Saskatchewan and Manitoba: Geological Survey of Canada Bulletin 147, 57 p.

Moore, W. L., 1976, The stratigraphy and environments of deposition of the Cretaceous Hell Creek Formation (Reconnaissance) and the Paleocene Ludlow Formation (Detailed), southwestern North Dakota: North Dakota Geological Survey Report of Investigations no. 56, 40 p.

Murray, C. R., 1968, Estimated use of water in the United States, 1965: U.S. Geological Survey Circular 556, 53 p.

National Academy of Sciences-National Academy of Engineering, 1972 [1973], Water quality criteria 1972: U.S. Environmental Protection Agency, Ecological Research Series, Report EPA R3-73-033, 594 p.

North Dakota Geological Society, 1954, Stratigraphy of the Williston basin: 70 p.

North Dakota State Department of Health, 1970, Water quality standards for surface waters of North Dakota: 45 p.

North Dakota State University, 1974, North Dakota crop and livestock statistics, annual summary for 1973, revisions for 1972: Agricultural Statistics no. 32, 76 p.

Piper, A. M., 1944, A graphical procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914-923.

Pipiringos, G. N., Chisholm, W. A., and Kepferle, R. C., 1965, Geology and uranium deposits in the Cave Hills area, Harding County, South Dakota: U.S. Geological Survey Professional Paper 476-A, 64 p.

Pollard, B. C., Smith, F. B., and Knox, C. C., 1972, Strippable lignite reserves of North Dakota: U.S. Bureau of Mines Circular 8537, 37 p.

Rahbein, E. A., 1977, Preliminary report on stratigraphy, depositional environments, and lignite resources in the Fort Union Formation, west-central North Dakota: U.S. Geological Survey Open-File Report 77-69, 23 p.

Royce, C. F., 1967, Tongue River-Sentinel Butte contact in western North Dakota: North Dakota Geological Survey Report of Investigations no. 45, 53 p.

—— 1970, A sedimentological analysis of the Tongue River-Sentinel Butte interval (Paleocene) of the Williston basin, western North Dakota: Sedimentary Geology, v. 4, p. 19-80, and North Dakota Geological Survey Miscellaneous Series no. 43, 80 p., 1971.

Sandoval, F. M., Bond, J. J., Power, J. F., and Willis, W. O., 1973, Lignite mine spoils in the Northern Great Plains — Characteristics and potential for reclamation, *in* Wali, M. K., editor, Some environmental aspects of strip mining in North Dakota: North Dakota Geological Survey Educational Series 4, p. 1-24.

Simpson, H. E., 1929, Geology and ground-water resources of North Dakota, *with* a discussion of the chemical character of the water by H. B. Riffenburg: U.S. Geological Survey Water-Supply Paper 598, 312 p.

Stanton, T. W., 1920, The fauna of the Cannonball marine member of the Lance Formation: U.S. Geological Survey Professional Paper 128-A, p. 1-60.

Stone, D. S., 1969, Wrench faulting and Rocky Mountain Tectonics: Mountain Geologist, v. 6, no. 2, p. 67-69, and Earth Science Bulletin, v. 2, no. 2, p. 37-41.

Taylor, O. J., 1968, Ground-water resources of the northern Powder River valley, southeastern Montana: Montana Bureau of Mines and Geology, Bulletin 66, 34 p.

Trapp, Henry, Jr., and Croft, M. G., 1975, Geology and ground-water resources of Hettinger and Stark Counties, North Dakota: North Dakota State Water Commission County Ground-Water Studies 16, pt. I, 51 p.

U.S. Bureau of the Census, 1971, United States census of population, 1970, Number of inhabitants, North Dakota: U.S. Bureau of the Census Final Report PC(1)-A36.

—— 1972, Census of Agriculture, 1969: Area reports, North Dakota, county data: v. 1, pt. 18, sec. 2.

U.S. Environmental Data Service, 1973, Monthly normals of temperature, precipitation, and heating and cooling degree days 1941-70: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Climatography of the United States, no. 81 (by state), North Dakota.

—— 1977, Hourly precipitation and climatological data, North Dakota: v. 86.

U.S. Federal Water Pollution Control Administration, 1968, Report of the Committee on water-quality criteria: Washington, U.S. Government Printing Office, 234 p.

U.S. Geological Survey, 1973-74, Water resources data for North Dakota; Part 1, surface-water records, Part 2, water-quality records.

—— 1974, Stripping coal deposits of the northern Great Plains, Montana, Wyoming, North Dakota, and South Dakota: U.S. Geological Survey Miscellaneous Field Studies Map MF-590, 1 sheet.

—— 1975-76, Water resources data for North Dakota, water years 1975 and 1976: U.S. Geological Survey Data Reports ND75-1, and ND76-1.

—— 1975, Plan of study of the hydrology of the Madison Limestone and associated rocks in parts of Montana, Nebraska, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Open-File Report 75-631.

U.S. Public Health Service, 1962, Drinking water standards: U.S. Public Health Service Publication 956, 61 p.
U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Department of Agriculture Handbook 60, 160 p.
Waage, K. M., 1968, The type Fox Hills Formation, Cretaceous (Maestrichtian) South Dakota, Part I, Stratigraphy and paleoenvironments: Peabody Museum of Natural History, Yale University, Bulletin 27, 171 p.

DEFINITIONS OF TERMS

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

Aquifer system – a heterogeneous body of interconnected permeable and less permeable material that acts as a water-yielding hydraulic unit of regional extent.

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. An artesian well obtains its water from a 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 alluvial deposits of Quanternary 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.

Formation – the basic rock-stratigraphic unit in the local classification of rocks, consisting of a sedimentary stratum generally characterized by lithologic homogeneity and by mappability at the surface or subsurface.

Ground water – water in the zone of saturation.

Hardness – the adjectives "hard" and "soft" as applied to water 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

Head – pressure of a fluid upon a unit area due to the height at which the fluid stands above the point where the pressure is determined.

Hydraulic conductivity – 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 – movement of ground water into an area in response to the hydraulic gradient.

National Geodetic Vertical Datum of 1929 (NGVD of 1929) – NGVD is a geodetic datum derived from a general adjustment of the first order level nets of both the United States and Canada. It was formerly called "Sea Level Datum of 1929" or "mean sea level" in this series of reports. Although the datum was derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific Coasts, it does not necessarily represent local mean sea level at any particular place.

Perched aquifer – unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

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

Permeability, intrinsic – a measure of the relative ease with which a porous medium can transmit a liquid under a potential gradient. It is a property of the medium alone and is independent of the nature of the liquid and of the force field causing movement.

Porosity – the property of rock containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume.

Potentiometric surface – as related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells. The potentiometric surface is reported in feet above NGVD of 1929.

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

Sodium-adsorption ratio (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 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 – 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 electric current. The electrical 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° Celsius.

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 – the volume of water an aquifer releases or takes into storage per unit of 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 – 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 – as used in this report the term unconfined refers to an aquifer in which the water is under atmospheric pressure.

Underflow – the downstream movement of ground water through the permeable deposits beneath a stream.

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