GROUND-WATER RESOURCES

of

ADAMS and BOWMAN COUNTIES, NORTH DAKOTA

by
M.G. Croft
U.S. Geological Survey

COUNTY GROUND-WATER STUDIES 22 — PART III
North Dakota State Water Commission
Vernon Fahy, *State Engineer*

BULLETIN 65 — PART III
North Dakota Geological Survey
Lee Gerhard, *Acting State Geologist*

Prepared by the U.S. Geological Survey
in cooperation with the North Dakota Geological Survey,
North Dakota State Water Commission,
Adams County Water Management District
and the Bowman County Water Management District

1978

BISMARCK, NORTH DAKOTA

CONTENTS

ILLUSTRATIONS

Figure Page

TABLES

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

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

Multiply English units	By	To obtain SI units
Acres	0.4047	hectares (ha)
Acre-feet	1,233	cubic meters (m^3)
	1.233×10^{-3}	cubic hectometers (hm^3)
Cubic feet per second (ft^3/s)	.02832	cubic meters per second (m^3/s)
Feet	.3048	meters (m)
Feet per day (ft/d)	.3048	meters per day (m/d)
Feet per mile (ft/mi)	.1894	meters per kilometers (m/km)
Feet per second	.3048	meters per second (m/s)
Feet squared per day (ft^2/d)	.0929	meters squared per day (m^2/d)
Gallons	3.785	liters (L)
Gallons per day (gal/d)	3.785×10^{-3}	cubic meters per day (m^3/d)
Gallons per minute (gal/min)	.06309	liters per second (L/s)
Gallons per minute per foot [(gal/min)/ft]	.2070	liters per second per meter [(L/s)/m]
Inches	25.4	millimeters (mm)
Miles	1.609	kilometers (km)
Million gallons (10^6gal)	3,785	cubic meters (m^3)
Million gallons per day (Mgal/d)	.04381	cubic meters per second (m^3/s)
Square inches per pound (in^2/lb)	1,422	square millimeters per kilogram (mm^2/kg)
Square miles (mi^2)	2.590	square kilometers (km^2)
Ton (short, 2,000 lb)	9.071	kilogram (kg)

GROUND-WATER RESOURCES OF ADAMS AND BOWMAN COUNTIES, NORTH DAKOTA

By

M. G. Croft

ABSTRACT

Five aquifer systems containing usable water occur in the Fox Hills, Hell Creek, Ludlow, Cannonball, and Tongue River Formations in Adams and Bowman Counties.

The most important aquifer system is in the Fox Hills Formation and the basal part of the Hell Creek Formation. This aquifer system, which ranges in thickness from 340 to 520 feet (104 to 158 meters), crops out in western Bowman County and is as much as 940 feet (287 meters) below land surface in Adams County. The beds consist of fine- to medium-grained sandstone interbedded with siltstone and claystone. The transmissivity ranges from 110 feet squared per day (10 meters squared per day) in western Bowman County to 540 feet squared per day (50 meters squared per day) in eastern Adams County. Wells should yield as much as 100 gallons per minute (6 liters per second) with 50 feet (15 meters) of drawdown. The cities of Bowman, Hettinger, Reeder, and Scranton pump about 570 acre-feet (0.7 cubic hectometers) of water annually from the aquifer system. Water from the aquifer system is generally clear and lower in dissolved solids and sulfate than water in the overlying aquifer systems, probably because of passage through clay layers that act as semipermeable membranes in that they remove some mineral matter from solution. Dissolved constituents in water samples analyzed ranged from 504 to 1,680 milligrams per liter and averaged 1,050 milligrams per liter.

The overlying upper Hell Creek and lower Ludlow, middle Ludlow, Cannonball, and upper Ludlow and Tongue River aquifer systems are used only for domestic and livestock supplies. The aquifers consist of fine- to medium-grained sandstone, siltstone, claystone, and lignite. The sandstone has a low hydraulic conductivity. Much of the water is colored by organic compounds but is suitable for many purposes.

Approximately 4,000 acre-feet (4.9 cubic hectometers) of water was used in Adams and Bowman Counties in 1972. Of this amount, about 1,000 acre-feet (1.2 cubic hectometers) was pumped from the ground-water reservoir for municipal, domestic, and industrial uses. About 1,700 acre-feet (2.1 cubic hectometers) was pumped from streams for irrigation. About 1,300 acre-feet (1.6 cubic hectometers) obtained from wells and streams was used for livestock.

Dissolved minerals leached from excavated overburden or spoils at the Gascoyne lignite mine may locally contaminate the upper Ludlow and Tongue River aquifer. Available data near the mine indicate that the leachates may contain several times more dissolved solids than the water in the underlying upper Ludlow and Tongue River aquifer system.

INTRODUCTION

The investigation was made cooperatively by the U.S. Geological Survey, North Dakota State Water Commission, North Dakota Geological Survey, and Adams and Bowman Counties Water Management Districts. The results of the investigation are published in three separate parts of the bulletin series of the North Dakota Geological Survey and the county ground-water studies series of the North Dakota State Water Commission. Part I is an interpretive report describing the geology; part II (Croft, 1974) is a compilation of the ground-water basic data; and this report, part III, describes the ground-water resources. Part II contains well logs, chemical analyses, particle-size distribution curves for water-bearing materials, and water-level data collected during the county investigations; it is a reference for parts I and III. Data referred to in this report are in part II unless otherwise referenced.

The stratigraphic nomenclature used in this report is that of the North Dakota Geological Survey and does not necessarily follow the usage of the U.S. Geological Survey. Technical terms used in this report are defined in the "Definitions of Selected Terms" section. English units, abbreviations, and the factors for conversion to the equivalent International System (SI) of metric units and corresponding abbreviations are in the front of the report.

Purpose of the Investigation

The ground-water investigation of Adams and Bowman Counties (fig. 1) was made to provide geologic and hydrologic information needed for the orderly development of water supplies for municipal, domestic, livestock, irrigation, and industrial uses. The hydrologic investigation of the two counties began in July 1970. Specifically, the objectives were to: (1) determine the location, extent, and nature of the major aquifer systems and confining beds; (2) determine the movement of ground water, including the sources of recharge and discharge; (3) estimate the potential yields of wells; (4) evaluate the chemical quality of the ground water; and (5) estimate water use.

Acknowledgments

The collection of data for this report was aided by the cooperation of the County Commissioners, Adams County Water Management District, Bowman County Water Management District, and residents of the counties. Frederickson's, Inc., Moe Drilling Co., Dependable Drilling Co., H & H Service Co., Knutson Drilling Co., Sander Drilling Co., and Alfred Jacobson furnished logs and other information. L. L. Froelich and C. E. Naplin, ground-water geologists with the North Dakota State Water Commission, logged most of the test holes. M. O. Lindvig, Director, Hydrology Division, North Dakota State Water Commission, provided coordinating assistance for his agency.

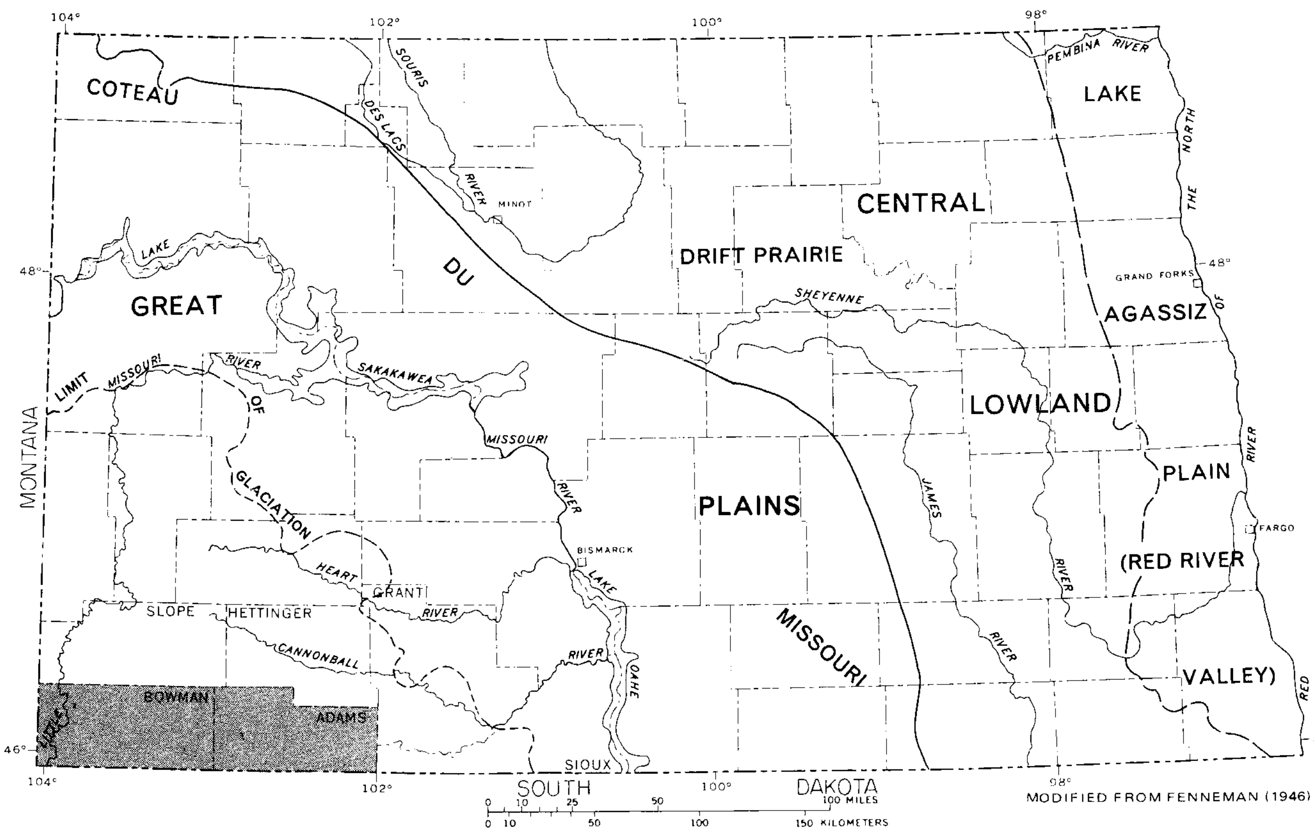


FIGURE 1.— Physiographic divisions in North Dakota and location of study area.

Well- and Station-Numbering System

The wells and test holes referred to in this report are numbered according to a system of land survey in use by the U.S. Bureau of Land Management and the U.S. Geological Survey. The U.S. Bureau of Land Management system is illustrated in figure 2. The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre or 4-ha tract). For example, well 132-096-15DAA is in the NE¼NE¼SE¼ sec. 15, T. 132 N., R. 96 W. Consecutive terminal numerals are added if more than one well or test hole is recorded within a 10-acre (4-ha) tract.

Climate

The climate of Adams and Bowman Counties is cool and semiarid. The mean temperature at Bowman during 1964-73 was 42°F (Fahrenheit), or 5.5°C (Celsius; fig. 3A) (National Weather Service, 1965-74). Temperatures average 69°F (20.5°C) in July and August. The highest temperature recorded at Bowman was 101°F (38.5°C) in August 1973. Winters are cold and temperatures frequently drop to −30°F (−34.5°C). The lowest temperature recorded at Bowman was −36°F (−38°C) in February 1962 (National Weather Service, 1963). The average growing season is about 125 days.

The mean annual precipitation recorded at Bowman (fig. 3B) during 1964-73 was 16.8 inches (427 mm). About 70 percent of the precipitation falls during the growing season (fig. 3C). Thunderstorms are common in June, July, and August.

Physiography and Drainage

The total area of Adams and Bowman Counties, 2,159 mi² (5,592 km²; U.S. Bureau of the Census, 1971), lies within the unglaciated area of the Great Plains (fig. 1). The rolling uplands have a maximum altitude of 3,467 feet (1,057 m) in the Medicine Pole Hills (fig. 4), about 12 miles (19 km) southwest of Bowman. The principal streams, the Little Missouri River, the North Fork Grand River, and Cedar Creek, are incised as much as 300 feet (90 m) below the upland surface. Drainage in the area is to the Gulf of Mexico by way of the Missouri River. The most striking physiographic feature is the large valley carved by the Little Missouri River in western Bowman County. The valley includes most of the area from the Montana State line to within a few miles west of Rhame. Steep bluffs, ridges, and badlands features border the valley. Isolated ridges and buttes capped by scoria — the local term for baked clay and burned lignite — are common throughout the area.

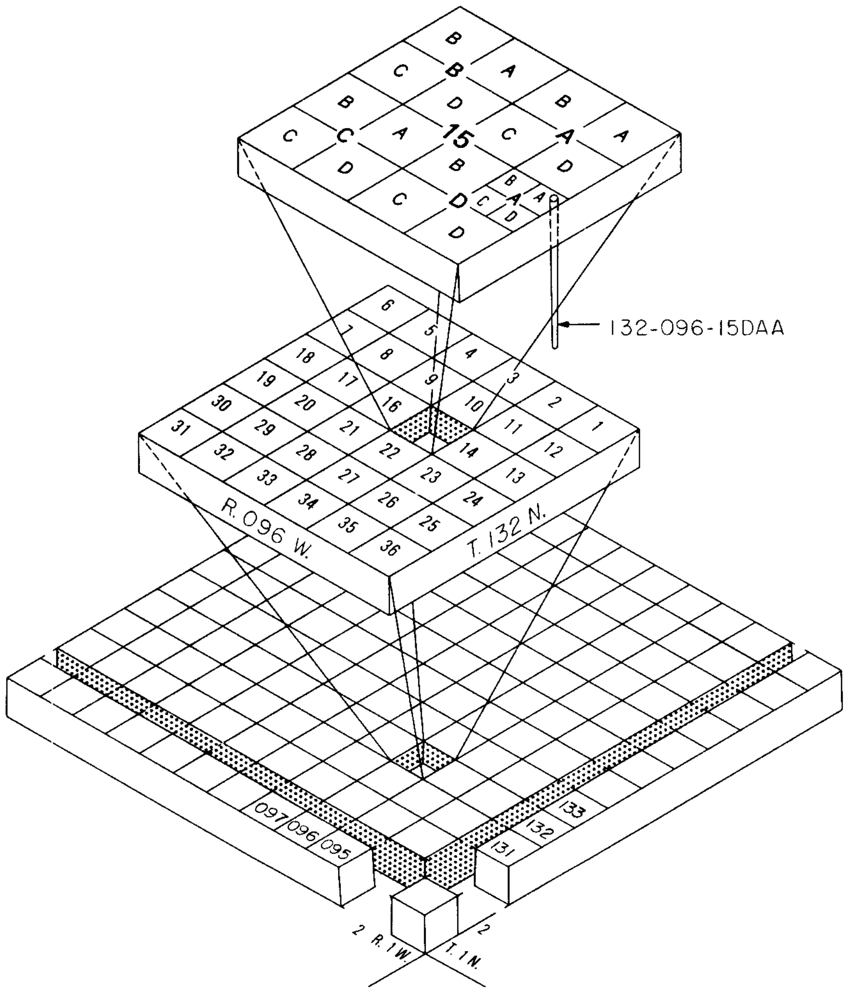


FIGURE 2.— System of numbering wells and test holes.

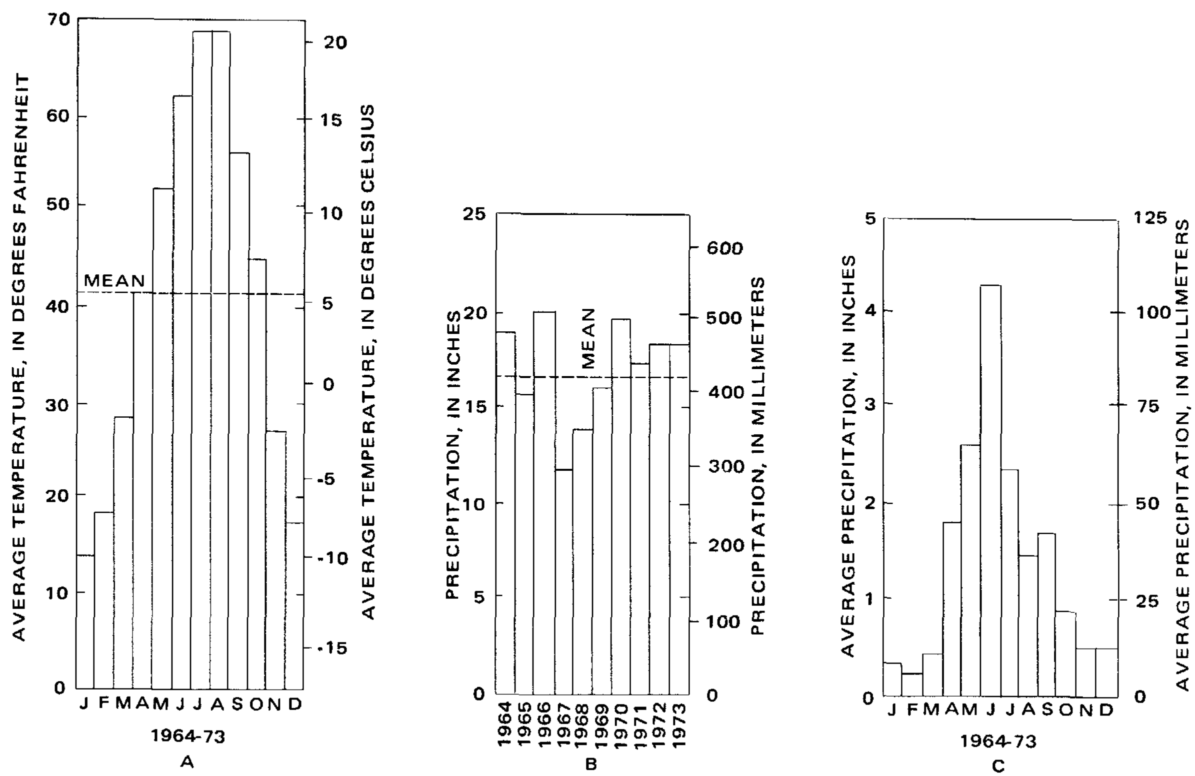


FIGURE 3.— Temperature and precipitation at Bowman, 1964-73.

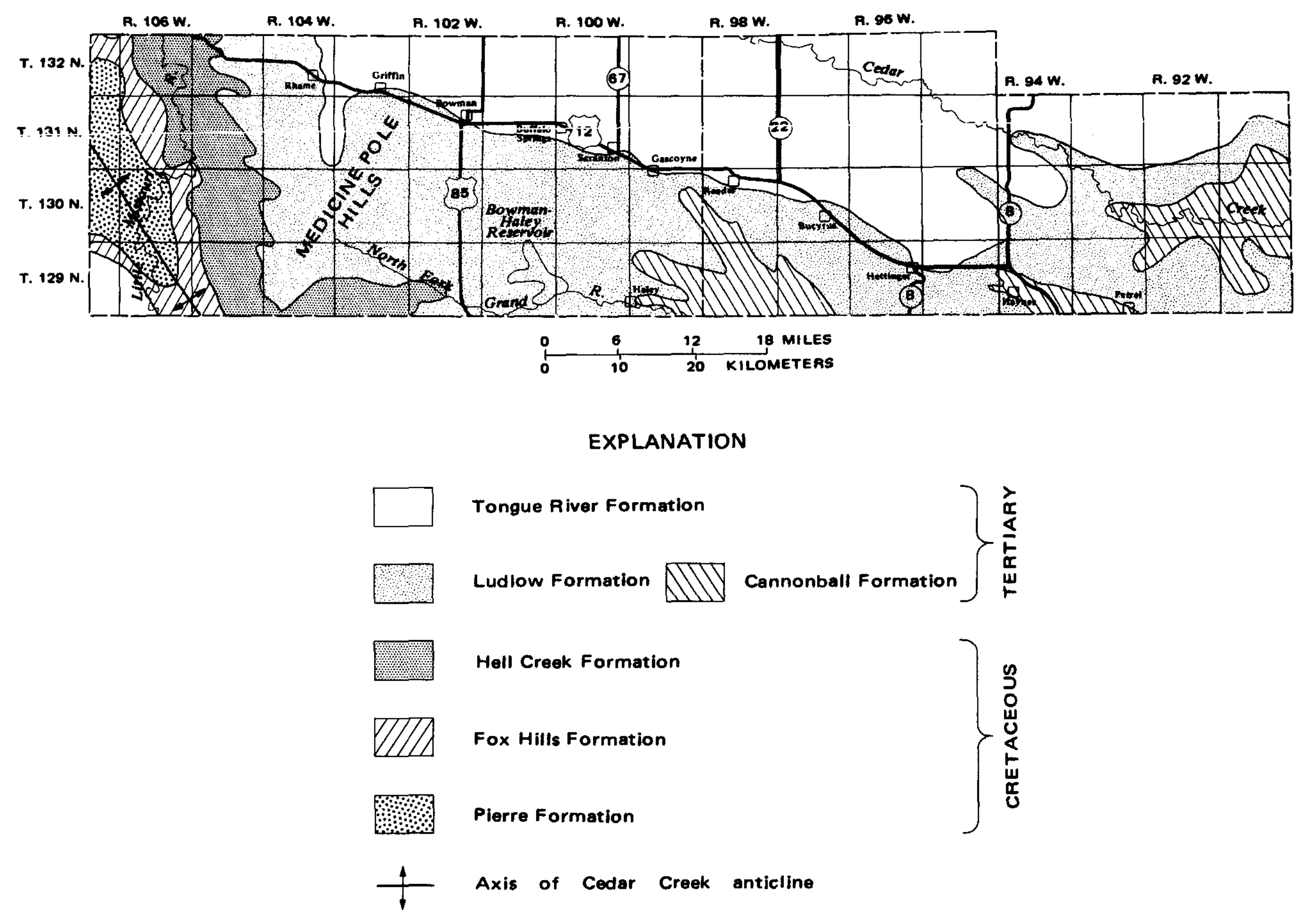


FIGURE 4.— Generalized surficial geology.

Population and Economy

The population in Adams County in 1970 was 3,832 and in Bowman County was 3,901 (U.S. Bureau of the Census, 1971). Hettinger, the county seat of Adams County, had a population of 1,655 and Bowman, the county seat of Bowman County, had a population of 1,762.

The economy of the area is based on agriculture, petroleum, and the strip mining of lignite near Gascoyne for use as fuel in electric generating plants. Agricultural products include small grains, corn, hay, cattle, and sheep.

Previous Investigations

Numerous geologic studies, spurred by the search for oil, gas, lignite, and uranium, have been made in southwestern North Dakota and surrounding areas. The earliest geologic investigations pertinent to the report area were made by Lloyd and Hares (1915) and Stanton (1920). Hares (1928) made a geologic study of the Marmarth lignite field in southwestern North Dakota. Recent geologic investigations have been made by Denson and Gill (1965), and Pipiringos, Chisholm, and Kepferle (1965). The location, tonnage, and characteristics of lignite and overburden in western North Dakota were described by Pollard, Smith, and Knox (1972).

Simpson (1929), who prepared the first comprehensive report on the geology and ground-water resources of North Dakota, included a brief discussion of the geology, ground-water resources, and quality of ground water in Adams and Bowman Counties. Robinove (1956) made a ground-water study near the city of Hettinger for local water supplies, and reported on the results of test drilling. Hamilton (1970) made a study of the ground-water flow in the Little Missouri River basin and concluded that the Little Missouri valley is the discharge area of a regional ground-water flow system. His dissertation included the northern parts of Adams and Bowman Counties. The hydrologic concepts expressed were patterned after studies by Meyboom (1966) and Meyboom and others (1966).

GEOHYDROLOGIC SETTING

The sedimentary rocks of Adams and Bowman Counties were deposited on the southern flank of the large subsiding Williston basin during the Paleozoic, Mesozoic, and Cenozoic Eras (table 1). The rocks are about 12,000 feet (3,700 m) thick. Those rocks older than the Pierre Formation are not exposed at land surface (fig. 4).

TABLE 1.—Adams and Bowman Counties stratigraphic column (Modified from North Dakota Geol. Soc., 1954, p. 2)

Era	Period	Group	Formation	Aquifer
Cenozoic	Quaternary		Aluvium	
	Tertiary	Fort Union	Tongue River	Upper Ludlow and Tongue River
			Cannonball	Cannonball
			Ludlow	Middle Ludlow
				Upper Hell Creek and lower Ludlow
Mesozoic	Cretaceous		Hell Creek	
			Fox Hills	Fox Hills and basal Hell Creek
		Montana	Pierre	Undifferentiated with regard to occurrence of aquifers
		Colorado	Niobrara Carlile Greenhorn Belle Fourche	
		Dakota	Mowry Newcastle Skull Creek Fall River Lakota	
	Jurassic		Morrison Swift Rierdon Piper	
	Triassic		Spearfish	
Paleozoic	Permian		Minnekahta Opeche	
	Pennsylvanian		Minnelusa	
	Mississippian		Amsden	
		Big Snowy	Heath Otter Kibbey	
		Madison	Charles Mission Canyon Lodgepole	
			Bakken	
	Devonian		Three Forks	
		Saskatchewan	Nisku Duperow	
		Beaverhill Lake	Souris River Dawson Bay	
			Prairie Winnipegosis	
			Ashern	
	Silurian		Interlake	
	Ordovician	Big Horn	Stony Mountain Red River	
			Winnipeg	
	Cambrian		Deadwood	

The rocks of the Paleozoic and Mesozoic Eras have been penetrated by numerous oil and gas test holes and have been divided into several formations by petroleum geologists. Well logs and lithologic descriptions are available from the North Dakota Geological Survey and are discussed in greater detail in part I. The rocks of Paleozoic age, mainly limestone, dolomite, sandstone, shale, and evaporites, generally contain saline water. A water sample from an oil and gas test hole in sec. 15, T. 130 N., R. 104 W., believed to be from the Paleozoic Red River Formation, contained about 100,000 mg/l (milligrams per liter) dissolved solids. The water in the rocks of Paleozoic age is too saline for most uses.

Rocks of the Mesozoic Era are largely shale, but sandstone forms part of the Dakota Group of Early Cretaceous age, and the Fox Hills and Hell Creek Formations of Late Cretaceous age. The Dakota Group, an important aquifer in parts of eastern North Dakota, is at depths greater than 4,000 feet (1,200 m) in Adams and Bowman Counties. Calculations from SP (spontaneous potential) curves of electric logs indicate the Dakota water has a conductivity of about 10,000 micromhos, and is too saline for most uses. Rocks overlying the Hell Creek Formation consist of semiconsolidated sandstone and claystone of Tertiary age, and sand, silt, and clay of Quaternary age.

Most of the usable ground water in Adams and Bowman Counties is pumped from several aquifers in the rocks of Late Cretaceous and Tertiary age. These rocks have a maximum thickness of about 1,400 feet (430 m) and are discussed further in the following sections with special reference to their water-bearing properties.

Rocks of Late Cretaceous Age

The rocks of Late Cretaceous age are exposed along the broad northwest-trending Cedar Creek anticline (fig. 4). They consist mainly of marine and continental shale, sandstone, claystone, and siltstone, and include the Pierre, Fox Hills, and Hell Creek Formations.

Pierre Formation

The Pierre Formation is a marine deposit composed of olive-gray to dark-greenish-gray gypsiferous shale, and rarely a few thin beds of very fine grained sandstone. More than 400 feet (122 m) of the formation (Hares, 1928, p. 15) crops out along the crest of the Cedar Creek anticline. The formation is about 1,500 feet (460 m) thick, as shown by logs of oil and gas test holes. No significant aquifers were found in the formation. For practical purposes, the Pierre Formation forms the base of the fresh-water-bearing units in the report area. The Pierre Formation is overlain by the Fox Hills Formation.

Fox Hills Formation

The Fox Hills Formation, a sequence of alternating beds of marine sandstone and shale, is 60 to 85 feet (20 to 26 m) thick where exposed along the

Cedar Creek anticline in western Bowman County (Hares, 1928, p. 16). The formation thickens to the east and is about 240 feet (73 m) thick in well 131-101-36CD (pl. 1, sec. A-A′, in pocket), where it is about 1,110 feet (338 m) below land surface. Structural contours of the base of the Fox Hills (pl. 2A, in pocket) show that the beds dip generally to the northeast between the Little Missouri River and State Highway 8 in Adams County. East of State Highway 8, the beds are gently folded into a northward-plunging syncline. The beds dip most steeply, as much as 100 feet per mile (20 m/km), along the Cedar Creek anticline in southwestern Bowman County. Hares (1928, p. 17-18) divided the Fox Hills into two members: (1) the Colgate Member, which occurs at the top of the formation and consists mainly of sandstone; and (2) a lower member, which consists mainly of sandy siltstone and claystone. However, the two members could not be distinguished in the subsurface. The Fox Hills Formation and the lower part of the overlying Hell Creek Formation form a major aquifer system (pl. 1).

Hell Creek Formation

The Hell Creek Formation crops out in western Bowman County (fig. 4). The rocks consist of alternating beds of olive-gray and brown continental sandstone, siltstone, claystone, and a few thin beds of carbonaceous shale and gray limestone. The siltstone and claystone are generally light olive gray to dark greenish gray. The deposits of the Hell Creek are as much as 560 feet (171 m) thick.

Frye (1969) divided the formation into nine members in an area extending from eastern Montana to central North Dakota. Most of these members could not be distinguished in the subsurface in Adams and Bowman Counties, but beds of olive-gray to dark-greenish-gray siltstone and claystone were tentatively identified as the Bacon Creek Member of Frye. These beds divide the deposits into two major aquifer systems (pl. 1). The Bacon Creek Member is more than 200 feet (61 m) thick in the northwestern part of the study area.

Brown (1952, p. 92) recommended that the contact between the Hell Creek Formation and the overlying Ludlow Formation be drawn at the base of the lowest coal bed in the Ludlow. This was done where practicable, but where data were insufficient, the contact was arbitrarily drawn at the base of some otherwise unidentifiable beds that showed a high resistivity on several electric logs. Lignite occurred near this arbitrary contact in several test holes, but rarely at greater depths.

Particle-size distribution curves constructed on data from three samples cored from a bed of sandstone in well 129-104-34ADA indicate that much of the sand is fine grained. The median particle diameter of the samples ranged from 0.13 to 0.2 mm. The specific gravity ranged from 2.66 to 2.69 g/cm^3 (grams per cubic centimeter), indicating the sandstone was mainly quartz.

Rocks of Tertiary Age

Rocks of Tertiary age, deposited during the Paleocene Epoch, form the uplands east of the Cedar Creek anticline (fig. 4). The deposits, mainly of continental origin, form the Ludlow and Tongue River Formations. Marine rocks form the Cannonball Formation.

Ludlow Formation

Continental rocks of the Ludlow Formation, which consist of carbonaceous brown claystone, olive-gray siltstone, yellowish-gray fine-grained sandstone, limestone, and lignite, crop out in the southern parts of Adams and Bowman Counties (fig. 4). The T-Cross bed, an extensive strippable lignite (Hares, 1928), occurs within the formation in the vicinity of Rhame. Well logs indicate that in the eastern part of the study area the formation contains numerous thin, hard beds that are probably limestone. The formation is about 310 feet (94 m) thick in well 131-104-09AA (pl. 1, sec. A-A′). East of Bowman the Ludlow Formation is divided into lower, middle, and upper members by interbedding with the Cannonball Formation. The middle member is a major aquifer, and the upper and lower members are parts of two other aquifers (pl. 1). The middle member probably thins and pinches out east of the Adams County line.

Cannonball Formation

Rocks of the Cannonball Formation are the youngest marine strata known in the northern Great Plains. They crop out in drainages in the southern part of Adams County and in the southeastern corner of Bowman County (fig. 4). The deposits consist of two members of light-olive-gray to dark-greenish-gray nearly impermeable claystone and siltstone that interfinger with deposits of the Ludlow. In well 129-096-12DBB (pl. 1, sec. A-A′) the lower member is about 38 feet (12 m) thick and the upper member is about 110 feet (34 m) thick. Brown (1962) reported that the two members are exposed in the Little Missouri River valley north of the study area. In eastern Adams County beds of olive-gray fine-grained sandstone are interbedded with siltstone and claystone in the upper member of the Cannonball. The fine-grained sandstone is a locally important shallow aquifer (pl. 1, sec. C-C′).

Tongue River Formation

The Tongue River Formation consists of continental deposits of Paleocene age that underlie the northern parts of Adams and Bowman Counties (fig. 4). The Tongue River is about 350 feet (107 m) thick.

The formation generally consists of interbedded light-olive-gray to dark-greenish-gray claystone and siltstone, yellowish-gray fine-grained sandstone, and lignite. The Harmon lignite, an extensive bed about 100 feet (30 m) above the base of the Tongue River, is mined at Gascoyne and is a strippable lignite deposit several miles north of Bowman (Kepferle and Culbertson, 1955). Gamma-ray logs indicate that the lignite is generally less radioactive than the sandstone and claystone in the formation. North of Hettinger, the lower part of the formation was observed to consist mainly of permeable crossbedded friable sandstone that is interbedded with some siltstone and claystone. However, the beds of sandstone are not present everywhere at the base of the formation. The Tongue River and the upper member of the underlying Ludlow Formation form a major aquifer system (pl. 1, sec. C-C′).

Unconsolidated Deposits of Quaternary Age

Alluvium of Pleistocene(?) and Holocene age overlies the consolidated rocks of Late Cretaceous and Tertiary age (table 1) adjacent to the Little Missouri River, Cedar Creek, and the North Fork Grand River. Much of the alluvium consists of dark-gray sandy silt and clay eroded from nearby older rocks. The maximum thickness of alluvium augered on the North Fork Grand River near Haley was 22 feet (6.7 m). The maximum thickness of alluvium augered near the Little Missouri River was 23 feet (7 m). At several localities it was observed that the Little Missouri River channel has been cut into the underlying Pierre Formation. The alluvium was not saturated in many holes, and, even where saturated, the alluvial deposits are not considered a major source for water supplies.

AVAILABILITY AND QUALITY OF GROUND WATER

The hydrology of the principal aquifers and the quality of the ground water available for domestic, industrial, and municipal supplies in Adams and Bowman Counties are shown on plates 2-4 (in pocket). Well yields of as much as 100 gal/min (6 L/s) of water suitable for industry and cities could be developed in parts of the two-county area. However, in order to obtain maximum yields the wells should fully penetrate the aquifers and be properly constructed.

General Concepts

The ground water in Adams and Bowman Counties is derived from precipitation. After precipitation falls on the earth's surface, part is returned to the atmosphere by evapotranspiration, part runs off into streams, and the remainder infiltrates into the ground. Some of the water that enters the soil is held by capillarity to replace the water that has evaporated or transpired by plants during the preceding dry period. After the soil and plant requirements have been satisfied, the excess water, if any, will infiltrate downward until it reaches the zone of saturation. After the excess water enters the zone of saturation, it becomes available to wells.

Ground water moves under the influence of gravity from areas of recharge to areas of discharge. Ground-water movement is generally very slow; it may be only a few feet per year. The rate of movement is governed by the hydraulic conductivity of the material through which the water moves and by the hydraulic gradient. Gravel, fine to coarse sand, and fractured lignite generally are highly conductive, and deposits of these materials commonly form aquifers. Fine-grained materials such as siltstone, claystone, and shale usually have low conductivity. In many ground-water circulation systems, horizontal strata of high conductivity may be separated by layers (clay or shale) of much lower conductivity. These clay layers may act as semipermeable membranes or filters that concentrate dissolved ions in overlying strata as the water moves downward through the clay. The process is described by McKelvey and Milne (1960).

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

Transmissivity maps can be used to estimate the yield of an aquifer. At any given location, the yield, in gallons per minute, of an efficient, fully penetrating well with 50 feet (15 m) of drawdown after 24 hours of pumping can be estimated by dividing the transmissivity by 5.3 (Brown, 1963, and Meyer, 1963). Greater yields can be obtained with drawdowns in excess of 50 feet (15 m).

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

The classifications of ground-water types, such as sodium bicarbonate or calcium bicarbonate, are derived from inspection of the analyses and represent the predominant cation (sodium, calcium, or magnesium) and anion (bicarbonate, sulfate, or chloride), expressed in milliequivalents per liter.

The suitability of water for various uses is determined largely by the kind and amount of dissolved matter. The chemical constituents, physical properties, and indices most likely to be of concern are: iron, sulfate, nitrate, fluoride, dissolved solids, hardness, temperature, odor, taste, specific conductance, sodium-adsorption ratio, and percent sodium. The sources of the major chemical constituents, their effects on usability, and the limits recommended by the U.S. Public Health Service are given in table 2. Additional information regarding recommended drinking-water standards may be found in the publication by the National Academy of Sciences-National Academy of Engineering (1973). Water-quality criteria for public supplies, farmsteads, industrial, and agricultural use were established by the U.S. Federal Water Pollution Control Administration (1968). The North Dakota State Department of Health (1970) adopted a set of water-quality standards within the framework of the national guidelines for interstate streams. Irrigation classifications in this report were derived by use of figure 5 (U.S. Salinity Laboratory Staff, 1954).

Aquifers of Late Cretaceous Age

Fox Hills and Basal Hell Creek Aquifer System

Location, thickness, and lithology. — The Fox Hills Formation and the lower part of the Hell Creek Formation form a major aquifer system that underlies all but the northwestern part of Bowman County (pl. 2) and extends into the adjoining counties. The aquifer system includes the Fox Hills Formation and beds that are below the Bacon Creek Member of the Hell Creek Formation (Frye, 1969). It is 940 feet (287 m) below land surface in well 129-096-12DBB (pl. 1, sec. A-A′), but in parts of western Bowman County it crops out at land surface. The aquifer system is 340 to 520 feet (104 to 158 m) thick and consists of fine- to medium-grained sandstone interbedded with siltstone and claystone. Rarely are individual beds of sandstone more than 100 feet (30 m) thick.

Hydrologic characteristics and properties. — The Fox Hills and basal Hell Creek aquifer system is recharged primarily by percolation from overlying beds (pl. 1, sec. A-A′). A map of the potentiometric surface of the aquifer system (pl. 2B) indicates that ground water generally moves northeast from the ground-water divide in western Bowman County and discharges to the counties to the north and east as underflow. The hydraulic gradient ranges from about 25 ft/mi (4.7 m/km) in southwestern Bowman County to less than 5 ft/mi (0.9 m/km) in northeastern Adams County. Cones of depression have developed beneath the cities of Bowman, Hettinger, Reeder, and North Lemmon, due to pumpage from wells. Although not shown, a small cone may also have developed at Scranton. Available data indicate that west of the ground-water divide in Bowman County ground water moves through the aquifer towards the Little Missouri River.

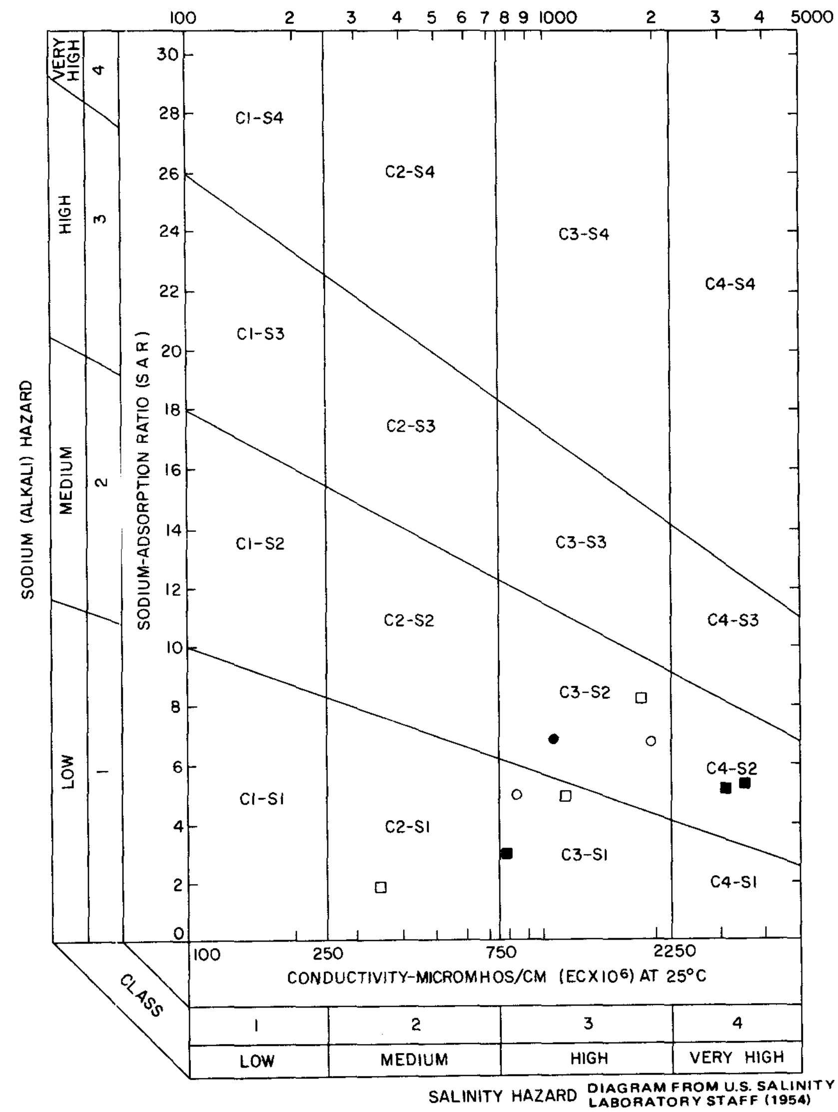
Porosity values obtained in the laboratory from sidewall cores (table 3) range from 31.2 to 37.7 percent. Porosity values calculated from bulk-density logs of the Fox Hills and basal Hell Creek aquifer system are comparable, ranging from 29 to 36 percent.

TABLE 2.—Major chemical constituents in water — their sources, effects upon usability, and recommended concentration limits

(Modified from Durfor and Becker, 1964, table 2; Hem, 1970, and U.S. Public Health Service, 1962)

Constituents	Major source	Effects upon usability	National Academy of Sciences-National Academy of Engineering (1973) 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
Minor elements	Byproducts of industrial processes, and weathering of lignite.		
Arsenic (As)			0.1 mg/L
Barium (Ba)			1.0 mg/L
Cadmium (Cd)			.01 mg/L
Chromium (hexavalent, as Cr)			.05 mg/L
Copper (Cu)			1.0 mg/L
Cyanide (CN)			.2 mg/L
Lead (Pb)			.05 mg/L
Mercury (Hg)			.002 mg/L
Selenium (Se)			.01 mg/L
Zinc (Zn)			5.0 mg/L
Iron (Fe)	Natural sources: amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, carbonates, and clay minerals. Manmade sources: well casings, pump parts, and storage tanks.	If more than 100 ug/L (micrograms per 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[1]	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.

[1] Values discussed in this report were determined by residue on evaporation.



EXPLANATION

□ Little Missouri River at Marmarth

■ Cedar Creek near Haynes

○ North Fork Grand River below Bowman-Haley Dam

● Bowman-Haley Reservoir

FIGURE 5.— Classification of water samples from streams and reservoirs for irrigation purposes.

TABLE 3.—Porosity and hydraulic-conductivity data
(Laboratory analyses by the U.S. Geological Survey)

Well	Aquifer system	Sampled depth (feet)	Porosity (percent): Laboratory	Porosity (percent): Bulk-density logs Pma[1] = 2.68	Hydraulic conductivity (ft/d): Laboratory	Hydraulic conductivity (ft/d): Drill-stem test[2]
131-094-20CBC	Middle Ludlow	224	35.5	31	1.3	
	Upper Hell Creek and lower Ludlow	698	34.2	31	1.1	
	Fox Hills and basal Hell Creek	1,014	37.7	35	1.2	[3]1.5
		1,016	35.7	34	1.9	
		1,104	32.3	31	2.6	
132-097-07CAB1	Tongue River	91	30.5	31	.006	
	Upper Hell Creek and lower Ludlow	573	33.5	31	.9	
		686	35.7	36	.6	
	Fox Hills and basal Hell Creek	1,062	36.8	29	1.3	[4]2.1
		1,144	37.3	31	1.7	
		1,240	31.2	36	1.2	

[1] Matrix density, grams/cm^3.
[2] Drill-stem test by Johnston, Williston, N. Dak.
[3] Interval 1,011 to 1,044 feet in depth.
[4] Interval 1,061 to 1,080 feet in depth.

The drill-stem test in well 131-094-20CBC1 indicates a hydraulic-conductivity value of 1.5 ft/d (0.46 m/d) for the depth interval of 1,011 to 1,044 feet (308 to 318 m) and approximates the value obtained from the sidewall cores. The drill-stem test in well 132-097-07CAB1 indicates a hydraulic conductivity of 2.1 ft/d (0.64 m/d) for the depth interval of 1,061 to 1,080 feet (323 to 329 m), slightly higher than the value obtained from sidewall cores that are from about the same interval.

Two aquifer tests and four specific-capacity tests were made using city wells at Bowman and Hettinger. Results are summarized in table 4. Transmissivity of the aquifer was also calculated from resistivity curves of electric and induction logs using methods described by Alger (1966) and Croft (1971). The two wells discharged 169 and 171 gal/min (10.7 and 10.8 L/s), repsectively, during the tests, and the values for transmissivity were 138 and 464 ft^2/d (12.8 and 43.1 m^2/d). The calculated values for transmissivity made from the electric and induction logs were generally higher than the values obtained from the aquifer tests (pl. 2C and table 4) because the wells only partially penetrated the aquifer, whereas calculated values were for the entire aquifer thickness. The specific capacity of the four city wells (table 4) ranged from 0.25 to 2.0 (gal/min)/ft [0.05 to 0.4 (L/s)/m]. The average hydraulic conductivities of the sandstone in wells 129-096-13ACA and 131-102-14AAB, calculated from the aquifer tests, were about 2 and 3 ft/d (0.6 and 0.9 m/d), respectively. Well 129-096-12DBB has a low specific capacity because the sandstone at the site is thin, and the well is screened in only the lower part of the aquifer system. The aquifer tests, the drill-stem tests, and the values for hydraulic conductivity obtained from cores indicate the hydraulic conductivity of the sandstone forming the aquifer is low.

TABLE 4. — Summary of aquifer tests

Location and city	Transmissivity (T)		Discharge (gal/min)	Specific capacity [(gal/min)/ft]
	Aquifer recovery test (ft^2/d)	Electric- and induction-log methods (ft^2/d)		
129-096-13ACA, Hettinger	138	240	169	0.75
129-096-12DBB, Hettinger	—	53	—	.25
131-102-02DDA, Bowman	—	290	—	1.1
131-102-14AAB, Bowman	464	500	171	2.0

Ground-water flow analyses were made using data from the potentiometric-surface map (pl. 2B) to calculate the transmissivity of the aquifer system at Bowman and Hettinger. The method used to analyze the flow of ground water is described by Foley, Walton, and Drescher (1953, p. 76). The value for transmissivity determined by this method is for a much larger sample of the aquifer system than that determined by an aquifer test of a single well. A transmissivity of 208 ft^2/d (19 m^2/d) was calculated for the Bowman area using the 2,750-2,800-foot (838-853-m) potentiometric contours. The pumpage at Bowman was about 247,000 gal/d (935 m^3/d). A transmissivity of 134 ft^2/d (12.4 m^2/d) was calculated for Hettinger, using the 2,450-2,500-foot (747-762-m) potentiometric contours. The pumpage at Hettinger was about 219,000 gal/d (829 m^3/d). The cone of depression at Hettinger is steeper than the cone at Bowman because the transmissivity is smaller.

The transmissivity map (pl. 2C) indicates that the transmissivity of the aquifer system ranges from 110 ft^2/d (10 m^2/d) to 540 ft^2/d (50 m^2/d). The sandstone that forms the aquifer system in the eastern part of Adams County is better sorted and more permeable than in other parts of the study area. The map was constructed from values calculated from resistivity curves of electric and induction logs. The values obtained from electric logs west of Bowman approximate the value obtained from the ground-water flow analysis.

A value for the storage coefficient was calculated using data obtained from a sonic log of an oil and gas test hole in sec. 23, T. 132 N., R. 102 W. following a method described by Taylor (1968, p. 12-18). A 550-foot (168-m) section of the aquifer had an average longitudinal velocity of about 7,880 ft/s (2,400 m/s). The vertical compressibility of $1.12 x 10^{-6}$ in^2/lb (0.0016 mm^2/kg) was determined with the formula presented by Birch (1942, p. 64). A value of 34 percent was used for the aquifer porosity, approximately the average value obtained from the cores and bulk-density logs (table 3). The storage coefficient calculated at the site was 0.0003, indicating that small withdrawals from the aquifer will cause relatively large cones of depression to develop. If the value for transmissivity is large, the cone will be shallow and large in areal extent. If the value for transmissivity is low, the cone will be deep and small in areal extent.

Water quality. — A bar diagram (fig. 6) shows that water in the Fox Hills and basal Hell Creek aquifer system generally is a sodium bicarbonate type and is lower in dissolved constituents than water in the overlying aquifer systems. Water-quality data from 13 selected wells in the aquifer system are plotted on a trilinear diagram (fig. 7). In the wells deeper than about 230 feet (70 m), the water was a sodium bicarbonate type with sodium constituting more than 94 percent of the cations. Calcium and magnesium are the principal cations in most natural fresh waters (Hem, 1970, p. 131, 175). Analyses of water obtained from the aquifer system indicated that calcium and magnesium had been removed by cation exchange for sodium as the water passed through overlying beds of siltstone and claystone.

Bicarbonate and carbonate (fig. 7) constitute most of the anions. Water in the confined part of the aquifer changes in anionic composition as it moves from west to east, as indicated by chemical diagrams (pl. 2B). Sulfate, a common

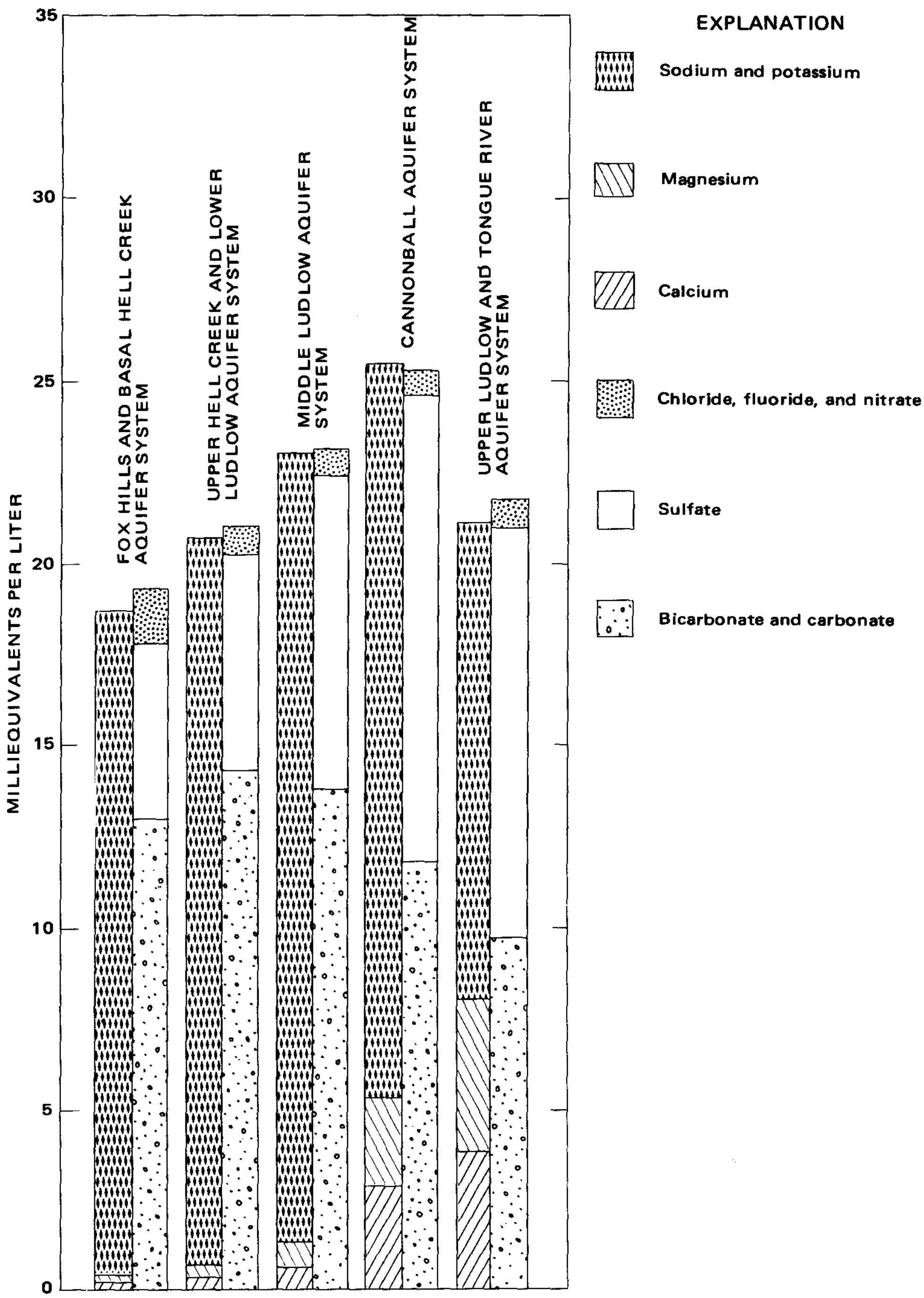
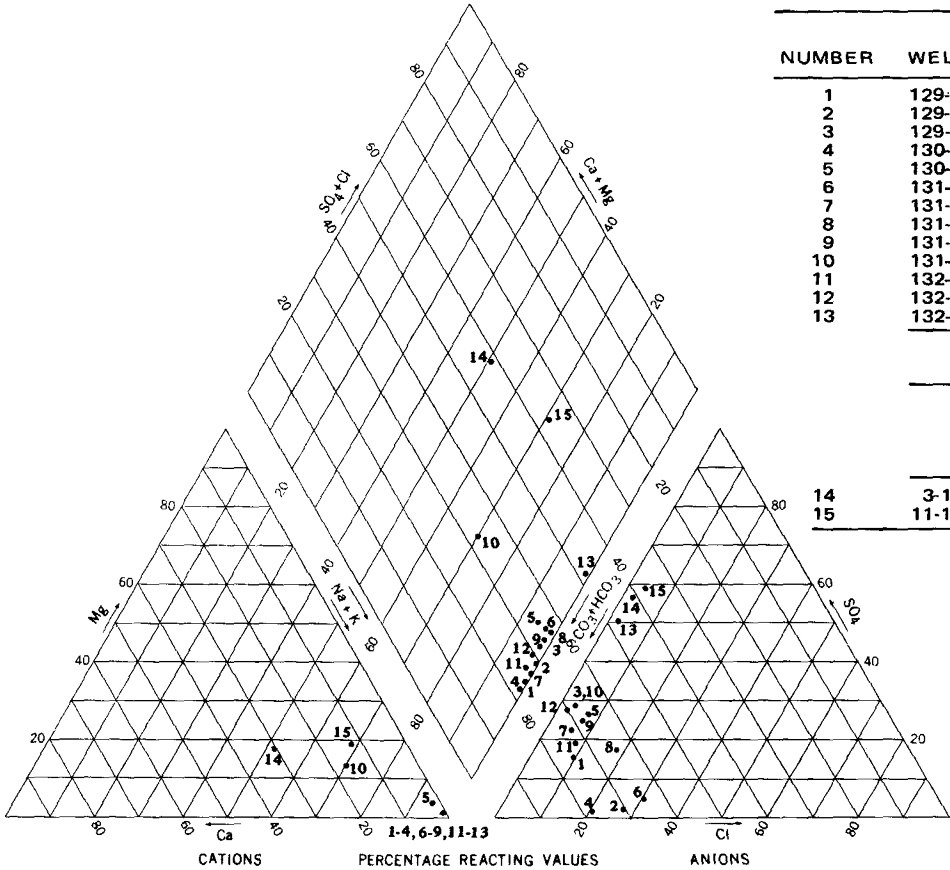


FIGURE 6.— Average values of major constituents in water in principal aquifer systems.



NUMBER	WELL NUMBER	WELL DEPTH	DISSOLVED SOLIDS (MG/L)
1	129-096-04DCB	880	1,010
2	129-096-13ACA	1,140	1,130
3	129-104-34ADA	543	1,010
4	130-098-04DCC	1,200	1,050
5	130-101-25AAA	893	971
6	131-094-20CBC1	1,045	1,330
7	131-100-23DBA	1,180	997
8	131-102-07DDD1	963	1,190
9	131-102-14AAB	1,096	1,050
10	131-106-04DCC	66	504
11	132-097-07CAB1	1,080	1,110
12	132-105-16BDB	459	1,100
13	132-106-26BDC	229	1,640

LITTLE MISSOURI RIVER NEAR MARMARTH

	DATE	DIS-CHARGE (FT^3/S)	DISSOLVED SOLIDS (MG/L)
14	3-18-71	2,960	216
15	11-14-72	35	1,350

FIGURE 7.— Major constituents in water from the Fox Hills and basal Hell Creek aquifer system and the Little Missouri River at Marmarth.

constituent in wells in western Bowman County, is generally derived from aerobic bacterial processes and weathering of shale and lignite. As the water moves downgradient, the concentration of sulfate generally decreases (fig. 8 and pl. 2B), whereas the percentage of chloride increases.

A geochemical study of the Fox Hills and basal Hell Creek aquifer system by Thorstenson, Fisher, and Croft (written commun., 1977) indicates that the chloride probably is entering the aquifer system from the underlying rocks. A detailed discussion of the mechanics and geochemistry is not warranted in this report but may be briefly stated as follows:

The average lateral particle velocity through the aquifer is defined by the following equation:

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

where $\bar{v}$ = average particle velocity

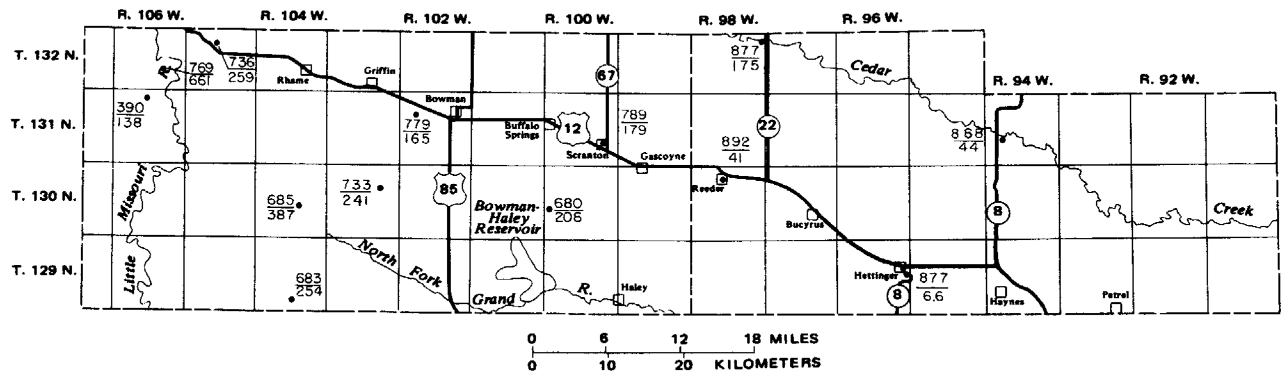
K = hydraulic conductivity

$\frac{dh}{dl}$ = hydraulic gradient

θ = porosity

$$\bar{v} = \frac{(2 \text{ ft/d}) \left(\frac{100 \text{ ft}}{10 \text{ miles} \times 5{,}280 \text{ ft/mi}}\right)}{0.35} = 0.01 \text{ ft/d, or } 4 \text{ ft/yr.}$$

Water entering the aquifer system from overlying rocks is low in chloride, as described in following sections. Ground-water movement is from the recharge area in Adams and Bowman Counties northeastward toward the Missouri River, where the aquifer discharges (Croft, 1973), a distance of about 150 miles (240 km). The lateral rate of flow, about 4 feet (1.2 m) per year, suggests that any saline connate water entrapped at the time of deposition of the marine Fox Hills, about 70,000,000 years ago, would have been flushed under the present hydrologic conditions in about 200,000 years. The mathematical model, described in the section on effects of expanded ground-water development, required recharge to the Fox Hills and basal Hell Creek aquifer system from underlying saline aquifers in the area where chloride is abundant. The required recharge of 8.6×10^{-7} to 6.0×10^{-5} ft/d (2.6×10^{-7} to 1.8×10^{-5} m/d) is possible because the head in the underlying Dakota aquifer (Swenson, 1968), and in the Madison Group (Konikow, 1976) are both higher than the head in the Fox Hills and basal Hell Creek aquifer system.



EXPLANATION

• $\frac{892}{41}$ WELL -- Upper number is concentration of bicarbonate, in milligrams per liter. Lower number is concentration of sulfate, in milligrams per liter

FIGURE 8.— Concentration of bicarbonate and sulfate in the Fox Hills and basal Hell Creek aquifer system.

The concentration of bicarbonate increases slightly from west to east. The decrease in sulfate and the increase in bicarbonate may be due to sulfate reduction by anaerobic bacteria (Kuznetsov and others, 1963; Hem, 1970, p. 158-159).

Water from two wells tapping the aquifer system in the outcrop area west of the Little Missouri River contained 504 and 1,640 mg/L dissolved solids (fig. 7 and pl. 2B). In the area east of the Little Missouri River, where the aquifer system is confined (pl. 2B), dissolved solids ranged from 866 to 1,330 mg/L and the median was 1,060 mg/L. The water was generally soft as the samples contained 3 to 63 mg/L hardness as calcium carbonate. Sulfate ranged from 4.1 mg/L to 387 mg/L. Sodium-adsorption ratios ranged from 41 to 100, with the exception of the sample from well 130-101-25AAA, which had a ratio of 20. Because the sodium-adsorption ratios were high, most of the samples could not be classified for irrigation purposes in figure 5. Boron ranged from 0 to 2,000 ug/L and was generally within acceptable limits.

Water samples were collected and analyzed for gas content (table 5). Water from Bowman city well 131-102-14AAB, which had an odor of hydrogen sulfide, contained 0.2 mg/L sulfur as sulfide. The hydrogen sulfide odor is destroyed in the public supply by chlorination.

TABLE 5. — Analyses of selected gases, ammonia, and sulfide in ground water (Analytical results are in milligrams per liter)

Local well number	Depth of well (ft)	Ar	CH_4	CO_2	N_2	NH_4^+	O_2	S as S^{--}	Temp. °C
131-099-19DDD	74	1.1	0.10	1.64	31	0.3	0.09	4.2	10
131-099-21DDD	90	1.1	.70	2.69	31	.4	—	6.9	9
131-102-14AAB	1,096	1.1	.09	.88	40	.6	.10	.2	20

Although a standard for color was not used for comparative purposes, water from the Fox Hills and basal Hell Creek aquifer system generally was clear, except for a few wells west of Bowman where the water had a slightly yellow color.

Utilization and potential for future development. — Wells drilled as deep as 1,314 feet (400 m) tap the Fox Hills and basal Hell Creek aquifer system for municipal, domestic, and livestock supplies. The aquifer system is the most dependable in the counties and supplies most of the municipal water. Wells can be developed in most areas underlain by the aquifer system. Yields should range from 1 to 100 gal/min (0.06 to 6 L/s; pl. 2C) — the highest yields will be obtainable where transmissivity values are the greatest.

Aquifers of Late Cretaceous and Tertiary Age

Upper Hell Creek and Lower Ludlow Aquifer System

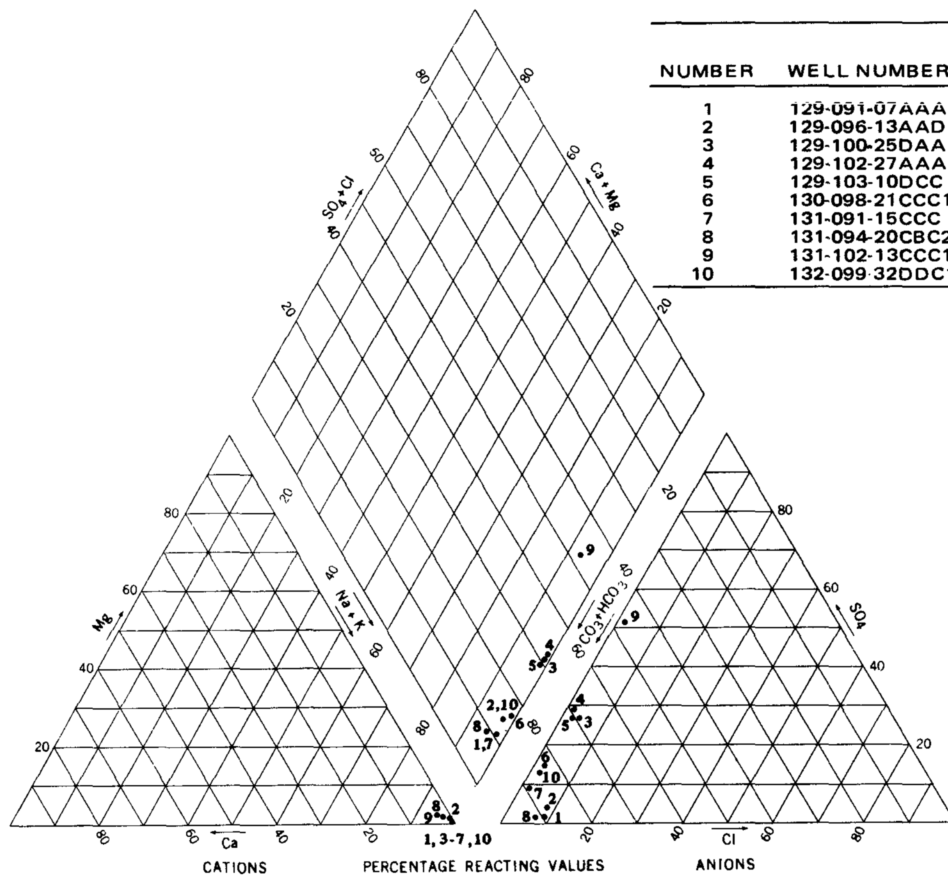
Location, thickness, and lithology. — The upper Hell Creek and lower Ludlow aquifer system underlies Adams and most of Bowman County east of the Little Missouri River (pl. 3). It crops out at land surface in western Bowman County, but at Hettinger the top of the aquifer system is about 490 feet (150 m) below land surface. The aquifer system ranges from 0 to 420 feet (0 to 128 m) in thickness (pl. 1), and consists of fine- to medium-grained sandstone in the upper part of the Hell Creek Formation and fine-grained sandstone and lignite in the lower part of the Ludlow Formation. The sandstone is interbedded with siltstone and claystone. The part of the aquifer system that is in the Hell Creek Formation overlies the Bacon Creek Member of Frye (1969). Thick beds of nearly impermeable siltstone and claystone forming the Cannonball Formation overlie and confine the aquifer system east of Bowman.

Hydrologic characteristics and properties. — Most of the recharge (pl. 1) to the upper Hell Creek and lower Ludlow aquifer system is probably from precipitation and seepage from streams in the area southwest of Bowman where the aquifer is not overlain by the upper member of the Cannonball Formation. A map of the potentiometric surface of the aquifer system (pl. 3A) indicates that ground-water flow is from west to east. The hydraulic gradient between Scranton and Reeder is about 8 ft/mi (1.5 m/km). Most of the natural discharge is underflow to the adjoining counties on the east. At Griffin the head in the upper Hell Creek and lower Ludlow aquifer system is about 100 feet (30 m) higher than the head in the Fox Hills and basal Hell Creek aquifer system. At Bucyrus the head is about 50 feet (15 m) higher. Some water may percolate downward into the underlying Fox Hills and basal Hell Creek aquifer system because of the higher head in the overlying aquifers.

The porosity values (table 3) obtained from sidewall core samples from the aquifer system ranged from 33.5 to 35.7 percent and approximated the values obtained from the bulk-density logs. The laboratory values for hydraulic conductivity (table 3) obtained from sidewall cores ranged from 0.6 to 1.1 ft/d (0.2 to 0.34 m/d). The indicated hydraulic conductivity is low.

A transmissivity map (pl. 3B) shows that the transmissivity of the aquifer system generally ranges from 30 ft^2/d (3 m^2/d) in the western part of Bowman County to 440 ft^2/d (41 m^2/d) in southeastern Adams County where the sand is better sorted and more permeable. The values were based on calculations from resistivity and induction curves of electric logs.

Water quality. — Water in the upper Hell Creek and lower Ludlow aquifer system is generally a sodium bicarbonate type (fig. 6) and is generally lower in dissolved mineral constituents than water in the overlying rocks. Water-quality data from 10 wells tapping the aquifer system are plotted on a trilinear diagram (fig. 9). Sodium in these samples constituted more than 94 percent of the



NUMBER	WELL NUMBER	WELL DEPTH	DISSOLVED SOLIDS (MG/L)
1	129-091-07AAA1	348	1,090
2	129-096-13AAD	463	1,040
3	129-100-25DAA1	530	1,020
4	129-102-27AAA	390	1,040
5	129-103-10DCC	242	999
6	130-098-21CCC1	411	1,160
7	131-091-15CCC	537	1,250
8	131-094-20CBC2	537	1,340
9	131-102-13CCC1	432	1,410
10	132-099-32DDC1	572	1,700

FIGURE 9.— Major constituents in water from the upper Hell Creek and lower Ludlow aquifer system.

cations; bicarbonate and carbonate constituted from 46 to 92 percent of the anions. In one sample, sulfate constituted as much as 52 percent of the anions. Chloride generally constituted less than 10 percent of the anions. Chemical diagrams on plate 3A indicate that the percentage of bicarbonate and carbonate increases and the percentage of sulfate decreases as water moves downgradient from west to east. The anions in the water from well 131-102-13CCC1 near Bowman (pl. 3A) consisted of 47 percent bicarbonate and carbonate, 52 percent sulfate, and about 1 percent chloride. The anions in the water from well 129-096-13AAD, at Hettinger, consisted of about 87 percent bicarbonate and carbonate, 5 percent sulfate, and about 8 percent chloride. The concentration of sulfate (fig. 10) in the water generally decreases from west to east and is slightly greater than in the underlying Fox Hills and basal Hell Creek aquifer system (fig. 8). The decrease in sulfate and the increase in bicarbonate may be due to sulfate reduction by anaerobic bacteria (Kuznetsov and others, 1963; Hem, 1970, p. 158-159).

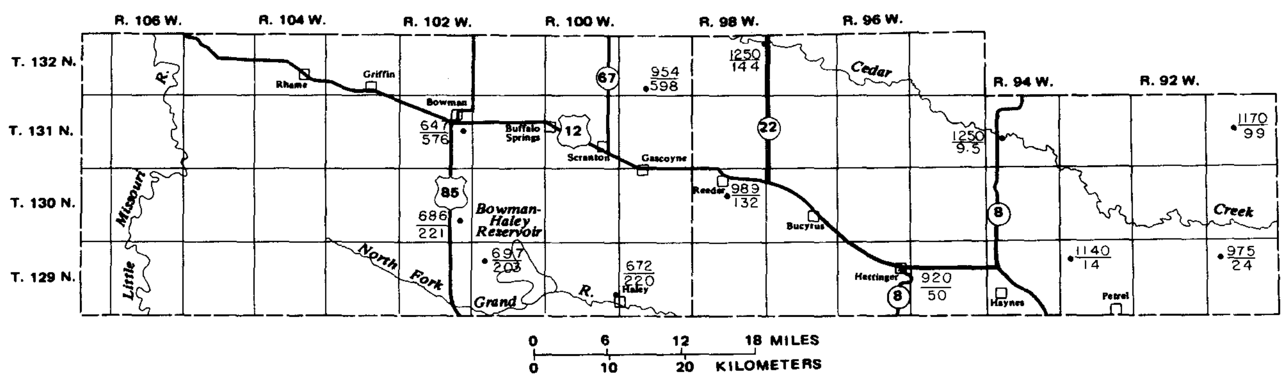
About 60 percent of the water samples collected from test holes tapping the upper Hell Creek and lower Ludlow aquifer system were yellow to dark brown due to organic hydrocarbon compounds, probably derived from lignite. Dissolved solids ranged from 969 to 2,270 mg/L and the median was 1,110 mg/L. Dissolved solids generally were higher in the northern part of the area than in the southern part (pl. 3A). The samples contained 9.5 to 1,150 mg/L sulfate and 0.2 to 14 mg/L fluoride. Sodium-adsorption ratios ranged from 19 to 83 and most of the values were too high to plot in figure 5. The water generally was soft; hardness ranged from 6 to 176 mg/L and the median was 18 mg/L. Boron ranged from 350 to 1,600 ug/L and iron from 0 to 2,500 ug/L.

Utilization and potential for future development. — Many livestock and domestic wells tap the upper Hell Creek and lower Ludlow aquifer system southwest of Bowman. Elsewhere the aquifer system is practically unused. Wells that flow have been drilled in the lowest part of the valley of the North Fork Grand River between Haley and U.S. Highway 85 flow. Well 129-101-31AC was observed to flow about 10 gal/min (0.6 L/s), and test well 129-100-25DAA1 had a head of +2.0 feet (0.6 m) above land surface. These wells are 254 and 530 feet (77.4 and 162 m) deep, respectively. Additional flowing wells could be drilled in low areas along the river; however, flows should be restricted to conserve water and the head. Wells tapping the aquifer system should yield 1 to 100 gal/min (0.06 to 6 L/s; pl. 3B) with about 50 feet (15 m) of drawdown after 24 hours of pumping. The largest yields are expected in southeastern Adams County.

Aquifers of Tertiary Age

Middle Ludlow Aquifer System

Location, thickness, and lithology. — The middle Ludlow aquifer system underlies Adams County and Bowman County east of Rhame and Bowman-Haley Reservoir (pl. 4). The top of the aquifer system is 38 to 400 feet (12 to 122



EXPLANATION

• $\frac{672}{220}$ WELL -- Upper number is concentration of bicarbonate, in milligrams per liter. Lower number is concentration of sulfate, in milligrams per liter

FIGURE 10.— Concentration of bicarbonate and sulfate in the upper Hell Creek and lower Ludlow aquifer system.

m) below land surface (pl. 1). The aquifer system ranges from 40 feet (12 m) to 185 feet (56 m) in thickness and consists of sandstone interbedded with siltstone, claystone, and lignite. Most of the aquifer system lies between the nearly impermeable upper and lower members of the Cannonball Formation.

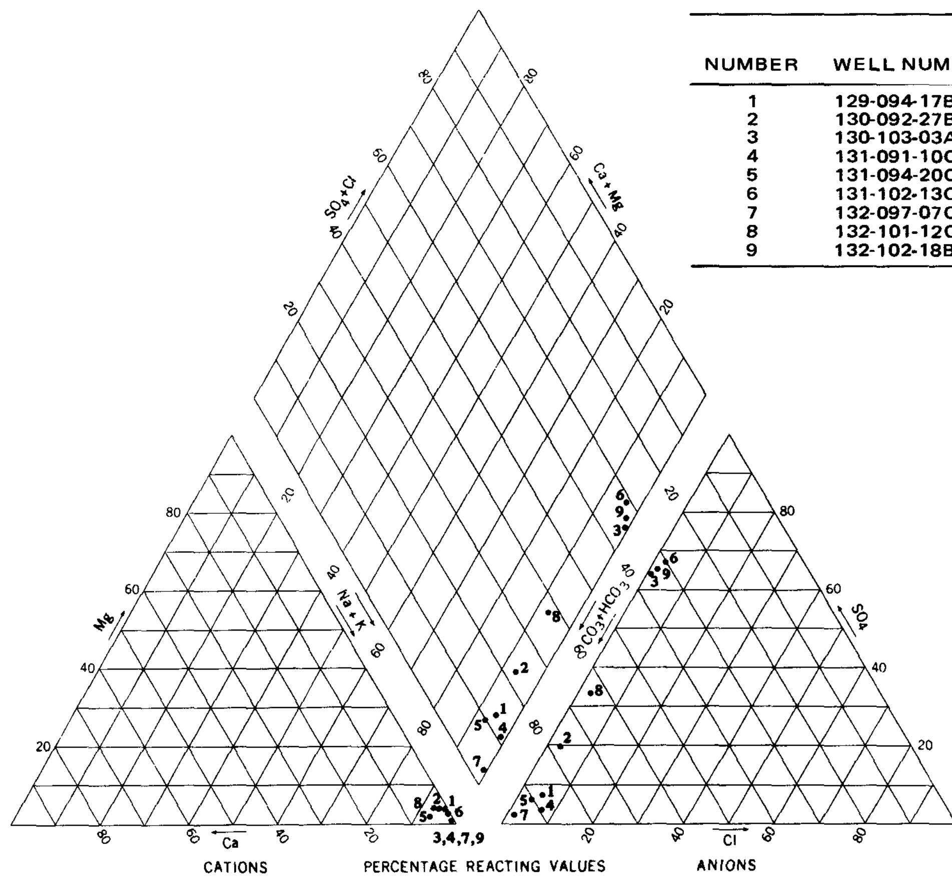
Hydrologic characteristics and properties. — Most of the recharge to the middle Ludlow aquifer system is from precipitation and from seepage from lakes and streams in Bowman County where the aquifer system is not overlain by the upper tongue of the Cannonball Formation (pl. 1, sec. A-A′). A map of the potentiometric surface (pl. 4A) indicates the general movement of ground water is from west to east. The hydraulic gradient south of Gascoyne is about 29 ft/mi (5.5 m/km), and about 8 ft/mi (1.5 m/km) at Bowman. The average hydraulic gradient in the aquifer is about 10 ft/mi (1.9 m/km). Most of the natural discharge is underflow to adjoining counties on the east. At Bowman the head in the middle Ludlow aquifer is about 100 feet (30 m) higher than the head in the upper Hell Creek and lower Ludlow aquifer system. At Hettinger the head is about 60 feet (18 m) higher. Therefore, some water may percolate downward through the confining beds to recharge the upper Hell Creek and lower Ludlow aquifer system.

A sidewall core sample from a depth of 224 feet (68.3 m) in well 131-094-20CBC1 (table 3) had a porosity of 35.5 percent and a hydraulic conductivity of 1.3 ft/d (0.4 m/d). A porosity of 31 percent was obtained from the bulk-density log. The indicated hydraulic conductivity for this one sample is low.

A transmissivity map (pl. 4B) of the aquifer system shows that the transmissivity ranges from 20 ft^2/d (2 m^2/d) north of Gascoyne to 390 ft^2/d (36 m^2/d) at Hettinger, where the sandstone is coarser, better sorted, and more permeable. The values for transmissivity were based on calculations from resistivity curves of electric and induction logs. At some localities the transmissivity may be greater than shown because of fracture systems in the lignite.

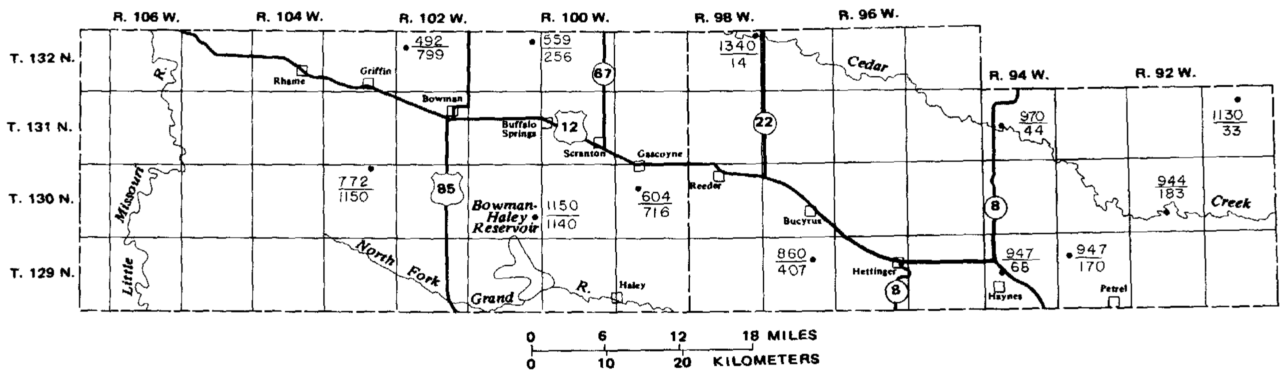
Water quality. — Most of the water samples from the middle Ludlow aquifer system were a sodium bicarbonate type (fig. 6). Sodium constituted more than 92 percent of the cations in water from the nine representative wells tapping the middle Ludlow aquifer system (fig. 11). Bicarbonate, carbonate, and sulfate were the main anions. Chloride constituted less than 6 percent of the anions. Chemical diagrams plotted on plate 4A indicate that the percentage of bicarbonate and carbonate increases and the percentage of sulfate decreases as water moves downgradient from west to east. For example, sulfate in the water from well 131-102-13CCC2 constituted about 68 percent of the anions, but sulfate in the water from well 132-097-07CAB4 constituted less than 2 percent of the anions. The concentration of sulfate (fig. 12) generally is higher than in the underlying aquifer systems.

About 60 percent of the water samples collected from test holes tapping the middle Ludlow aquifer system were yellow to dark brown due to hydrocarbon compounds, probably derived from lignite. Dissolved solids for water samples collected from the aquifer ranged from 573 to 3,060 mg/L and the median was



NUMBER	WELL NUMBER	WELL DEPTH	DISSOLVED SOLIDS (MG/L)
1	129-094-17BBC2	290	973
2	130-092-27BBA2	204	1,250
3	130-103-03AAA	207	2,210
4	131-091-10CCC	408	1,170
5	131-094-20CBC3	224	1,020
6	131-102-13CCC2	184	1,670
7	132-097-07CAB4	335	1,310
8	132-101-12CCC	411	935
9	132-102-18BAA	261	1,630

FIGURE 11.— Major constituents in water from the middle Ludlow aquifer system.



EXPLANATION

$\frac{1150}{1140}$ WELL - Upper number is concentration of bicarbonate, in milligrams per liter. Lower number is concentration of sulfate, in milligrams per liter

FIGURE 12.— Concentration of bicarbonate and sulfate in the middle Ludlow aquifer system.

1,180 mg/L. Analyses plotted on plate 4A show that the highest concentration of dissolved solids was around the southwest margin of the aquifer system. The samples contained 0.1 to 19 mg/L fluoride and 8 to 734 mg/L hardness. The water generally was soft; the median was 32 mg/L. Sodium-adsorption ratios ranged from 3.3 to 96. About half of the samples would be classified as C4-S4 for irrigation purposes (fig. 5), but the remaining samples were too high to classify with this diagram. Boron ranged from 190 to 2,300 ug/L.

Utilization and potential for future development. — Although many widely scattered livestock and domestic wells tap the middle Ludlow aquifer system for water supplies, it is relatively undeveloped. A flowing well, 156 feet (47.5 m) in depth, about 3 miles (5 km) west of Haley in the valley of the North Fork Grand River, probably taps the aquifer system. Other flowing wells probably could be drilled in nearby low-lying areas. Wells drilled along some reaches of Cedar and Chanta Peta Creeks probably would flow. Flows from wells should be restricted to conserve the head. Wells tapping the aquifer system should yield 1 to 75 gal/min (0.06 to 4.7 L/s; pl. 4B).

Cannonball Aquifer System

Location, thickness, lithology, and development. — The Cannonball aquifer system underlies about 160 mi^2 (410 km^2) of eastern Adams County (fig. 13). It consists of a series of prominent beds of standstone within the upper member of the Cannonball Formation. The top of the aquifer system is 30 to 240 feet (9 to 73 m) below land surface (pl. 1). The beds consist of 0 to 50 feet (0 to 15 m) of light-olive-gray fine- to medium-grained sandstone and olive-gray siltstone. In adjoining areas a few wells obtain water supplies from other thin isolated beds of sandstone within the Cannonball Formation.

Although a few scattered livestock and domestic wells tap the aquifer system for water supplies, it is relatively undeveloped. Several flowing wells, as much as 120 feet (37 m) deep, are located in the lower parts of Cedar Creek valley.

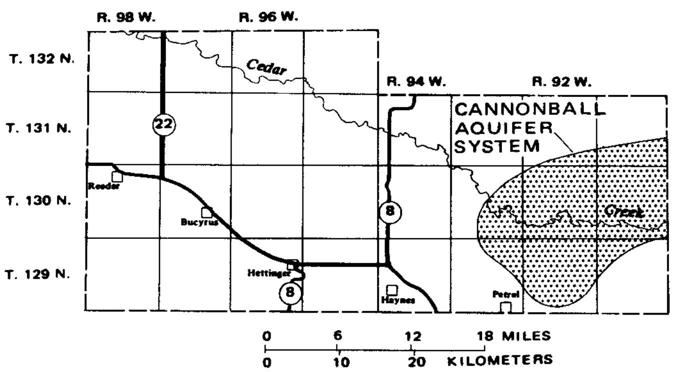


FIGURE 13.—Extent of Cannonball aquifer system within the upper member of the Cannonball Formation.

Hydrologic characteristics and properties. — A transmissivity of about 20 ft^2/d (2 m^2/d) was calculated from a flow and recovery test of well 130-092-22CBB. The sandstone penetrated by the well is about 23 feet (7 m) thick. Therefore, the indicated hydraulic conductivity is about 1 ft/d (0.3 m/d). The storage coefficient was 0.0008. The discharge from most flowing wells was observed to be about 10 gal/min (0.6 L/s); however, the discharge should be restricted to 1 or 2 gal/min (0.06 or 0.13 L/s) to prolong natural discharge. A flow of 1 or 2 gal/min (0.06 or 0.13 L/s) should be sufficient to prevent freezing during the winter. The low transmissivity and storage coefficient indicate that small withdrawals from the aquifer system will cause large water-level declines and extensive cones of depression.

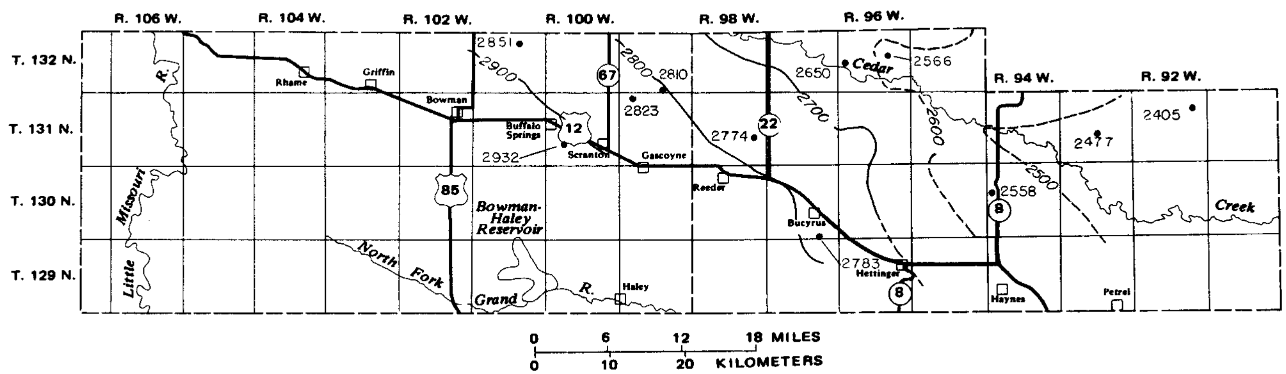
Water quality. — Water samples collected from the Cannonball aquifer system are higher in dissolved solids than water samples from the underlying aquifers (fig. 6). The water is a sodium sulfate type. Two water samples were collected from wells tapping the sandstone forming the aquifer system within the area shown in figure 13. Sodium constituted more than 85 percent of the cations in both samples. Bicarbonate constituted about 75 percent of the anions in well 130-092-22CBB and about 51.3 percent of the anions in well 131-098-23DAD1. Sulfate constituted 21 percent of the anions in well 130-092-22CBB and 43 percent of the anions in well 131-098-23DAD1. The sample from well 130-092-22CBB was light brown; it contained 1,170 mg/L dissolved solids, 207 mg/L sulfate, 1,500 ug/L boron, and 1,700 ug/L iron. The sodium-adsorption ratio was 48 and the hardness was 17 mg/L. The sample from 131-098-23DAD1 was dark brown; it contained 1,260 mg/L dissolved solids, 426 mg/L sulfate, 680 ug/L boron, and 40 ug/L iron. The sodium-adsorption ratio was 18 and the hardness was 104 mg/L.

Several water samples collected from isolated thin beds of sandstone elsewhere in the Cannonball Formation were sodium sulfate types.

Upper Ludlow and Tongue River Aquifer System

Location, thickness, and lithology. — The aquifer system in the upper member of the Ludlow Formation and in the Tongue River Formation underlies the outcrop area of the Tongue River in the northeast corner of Bowman County and the northern part of Adams County (fig. 4), generally north of U.S. Highway 12. The aquifer system consists of as much as 450 feet (137 m) of fine- to medium-grained sandstone, siltstone, claystone, and lignite. The sandstone generally has a low hydraulic conductivity, but some sandstone beds that are fractured may have a higher hydraulic conductivity. Ground water is obtained mainly from the sandstone. Large yields could be obtained locally from fractured lignite.

Hydrologic characteristics. — The upper Ludlow and Tongue River aquifer system is recharged by precipitation and seepage from lakes, streams, and reservoirs. A map of the potentiometric surface of the aquifer system (fig. 14)



EXPLANATION

•2477 **WELL** -- Number is altitude of potentiometric surface, in feet above mean sea level

—2600-- **POTENTIOMETRIC CONTOUR** -- Shows altitude at which water level would have stood in tightly cased wells, 1971-72. Dashed where approximately located. Contour interval 100 feet (30 m). Datum is mean sea level

FIGURE 14.— Potentiometric surface of the upper Ludlow and Tongue River aquifer system, 1971-72.

indicates that ground water northwest of Hettinger moves northeastward, toward Cedar Creek, and eventually southeastward down Cedar Creek valley. The head in the aquifer system at Scranton and Hettinger is more than 100 feet (30 m) higher than the head in the underlying middle Ludlow aquifer system (pl. 4A and fig. 14), indicating that some ground water from the upper Ludlow and Tongue River aquifer system may be passing through the upper member of the Cannonball Formation to recharge the underlying middle Ludlow aquifer system. A hydrograph of well 132-097-07CAB3 (fig. 15) shows that the water level rose in the spring after the thaw, and during periods of heavy precipitation, and declined during other periods.

Water quality. — Most water from the upper Ludlow and Tongue River aquifer system is a sodium sulfate type (fig. 6), and is high in dissolved solids. Analyses of 10 representative water samples from wells tapping sandstone in the aquifer system are plotted on a trilinear diagram (fig. 16). Sodium constituted more than 89 percent of the cations in all but one of the wells greater than 110 feet (34 m) in depth. Sulfate ranged from 13 to 79 percent of the anions, and bicarbonate and carbonate ranged from 21 to 83 percent of the anions. Chloride constituted less than 5 percent of the anions in the samples.

Dissolved solids in 78 samples ranged from 249 to 6,150 mg/L and the median was 1,120 mg/L. The samples contained 12 to 3,950 mg/L sulfate; the median was 331 mg/L. Fluoride ranged from 0.1 to 6.5 mg/L and boron ranged from 0 to 3,300 ug/L and had a median value of 460 ug/L. Sodium-adsorption ratios ranged from 0.1 to 64. Most water was hard to very hard; the hardness ranged from 7 to 2,480 mg/L, and had a median value of 301 mg/L. About 60 percent of the water samples collected from test wells were yellow to brown, due to organic hydrocarbon compounds.

Two water samples from shallow wells near Gascoyne were analyzed for gas content (table 5). Well 131-099-21DDD taps the Harmon lignite and well 131-099-19DDD is screened below the lignite. Both wells had the odor of hydrogen sulfide and contained 4.2 and 6.9 mg/L sulfur as sulfide. The samples

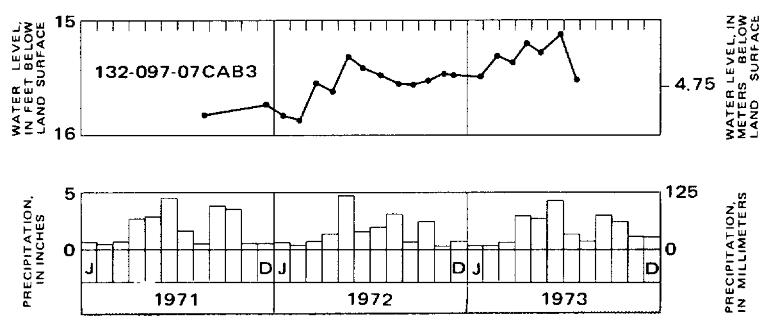
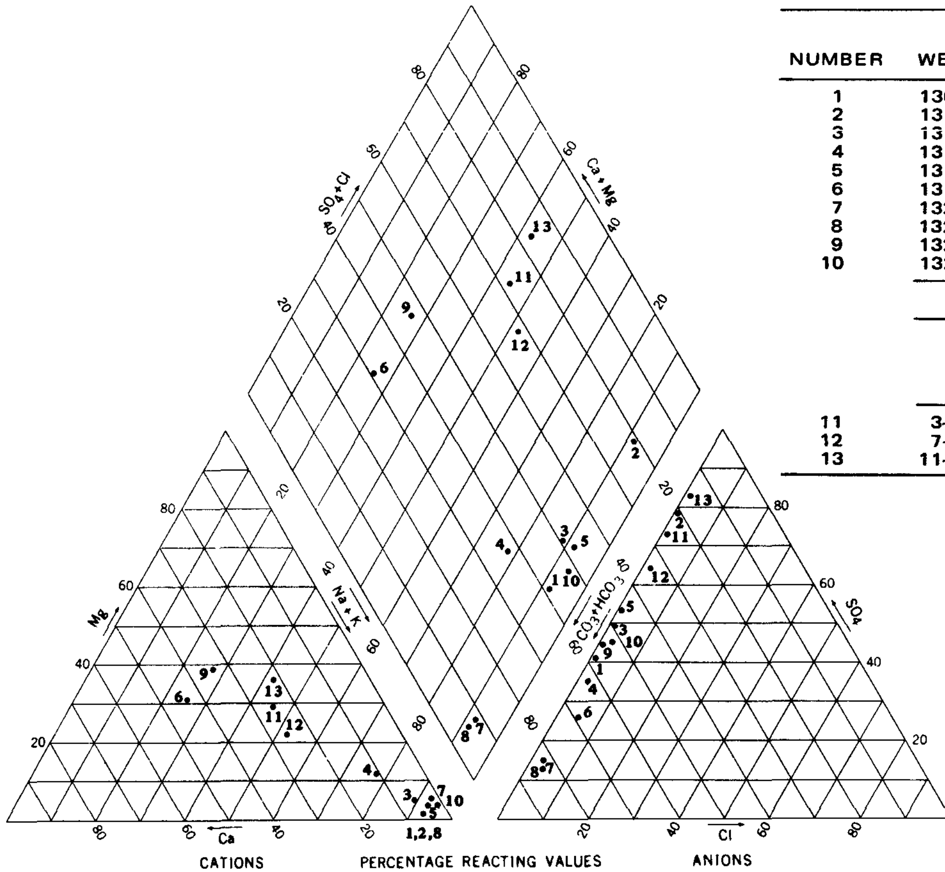


FIGURE 15.—Water-level fluctuations in the upper Ludlow and Tongue River aquifer system and precipitation at Hettinger, Adams County.



NUMBER	WELL NUMBER	WELL DEPTH	DISSOLVED SOLIDS (MG/L)
1	130-097-35BCB2	72	1,080
2	131-093-21AAA3	143	2,510
3	131-098-23DAD2	248	1,240
4	131-100-24AAB	71	643
5	131-100-29BBB2	228	1,330
6	131-102-11CBA	50	579
7	132-096-22ABC2	188	1,060
8	132-097-07CAB3	229	1,010
9	132-099-32DDC2	110	753
10	132-101-10DDD	264	1,630
	CEDAR CREEK NEAR HAYNES		
	DATE	DIS-CHARGE (FT^3/S)	DISSOLVED SOLIDS (MG/L)
11	3-17-71	856	655
12	7-14-71	1,250	539
13	11-15-72	16	2,820

FIGURE 16.— Major constituents in water from the upper Ludlow and Tongue River aquifer system and Cedar Creek near Haynes.

were much higher in sulfide and carbon dioxide than the sample collected from well 131-102-14AAB, which taps the Fox Hills and basal Hell Creek aquifer system.

Utilization and potential for future development. — Livestock and domestic water wells throughout northern Adams and Bowman Counties commonly tap the upper Ludlow and Tongue River aquifer system for water supplies. Numerous wells about 50 feet (15 m) deep also obtain water from the aquifer at Bowman for lawn watering and domestic use. These wells probably yield 5 to 50 gal/min (0.3 to 3 L/s). Wells properly developed and screened in the thick beds of sandstone at the base of the Tongue River Formation north of Hettinger would probably yield as much as 100 gal/min (6 L/s).

REGIONAL GROUND-WATER FLOW SYSTEM AND GEOCHEMICAL RELATIONSHIPS

Adams and Bowman Counties are located in the recharge area at the western edge of a large and complex regional ground-water flow system that extends, in part, to the Missouri River. The scope of this investigation did not permit the collection and analysis of data that would define accurately the entire ground-water flow system of the study area; however, the data are sufficient to indicate the general system of recharge, discharge, and ground-water movement. The system resembles in some aspects the "prairie profile" in south-central Saskatchewan described by Meyboom (1966). Meyboom stated that surface watersheds rising 300 feet (90 m) or more above the surrounding plains influenced water levels to a depth of at least 1,000 feet (300 m).

Ground-water recharge areas are characterized by decreasing potentiometric head with depth, whereas discharge areas are characterized by increasing head with depth. Most of the area of Adams and Bowman Counties is regarded as a recharge area because the potentiometric surface of the aquifers of Late Cretaceous and Tertiary age generally have decreasing head with depth. However, some stream valleys and other areas of low topography in northeastern Adams County are areas of ground-water discharge as evidenced by flowing wells. In these areas, ground water is moving upwards from as deep as the middle Ludlow aquifer system.

Values for dissolved-solids concentrations of ground water plotted on plates 2, 3, and 4 and in figure 6 suggest that dissolved solids in ground water generally decrease with depth in each progressively deeper aquifer. This is also illustrated by samples from wells 130-099-17AAA1 and 17AAA2, 131-102-14AAB, 131-102-13CCC1 and 13CCC2 (pl. 1, sec. A-A′). The decrease in dissolved solids may be partly explained by a process described by McKelvey and Milne (1960). They believe that clay layers act as semipermeable membranes that filter out selected ions as water moves through the clay. However, this single process does not explain the change in dissolved mineral constituents that has occurred. Although the analytical equations have not been written, the decrease in dissolved solids may be better explained by a combination of the following processes.

The increase in bicarbonate and the decrease in sulfate content of ground water downgradient and with depth in the aquifer systems (figs. 8, 10, and 12) is due to the reduction of sulfate to hydrogen sulfide gas and possibly to sulfur and iron pyrite. Kuznetsov and others (1963) believed that sulfate reduction is caused by anaerobic bacteria through the following process:

$$Na_2SO_4 + 2C_{org} + 2H_2O = 2NaHCO_3 + H_2S$$

F. J. Pearson (written commun., May 1974) and D. W. Fisher (written commun., July 1974) suggested that (1) sulfate is reduced by methane gas as water moves through lignite, and that (2) the chemical processes involved in sulfate reduction, the exchange of calcium and magnesium for sodium, and the precipitation of calcium and magnesium carbonate in the aquifer systems could account, in part at least, for the decrease in the dissolved-solids concentration of ground water with depth in the aquifer systems. Methane and hydrogen gas probably are the principal reducing agents for sulfate ion. The role played by bacteria in sulfate reduction is not well understood. However, this much is obvious; the water in the Fox Hills and basal Hell Creek aquifer system is a mixture of water from overlying and underlying rocks. Cations in the water are predominantly sodium, as the calcium and magnesium that were originally in the water have been exchanged. Sulfate is in the process of being reduced and most of the chloride appears to be derived from underlying aquifer systems.

WATER USE IN ADAMS AND BOWMAN COUNTIES

Approximately 4,000 acre-feet (4.9 hm^3) of water from rivers, streams, and ground-water reservoirs was used in Adams and Bowman Counties in 1972.

About 1,700 acre-feet (2.1 hm^3) of water was used to irrigate 331 acres (134 ha) in Adams County and 1,323 acres (535 ha) in Bowman County (U.S. Bureau of the Census, 1972). The water was obtained mainly from the Little Missouri River, Cedar Creek, Duck Creek, and Box Elder Creek. The demand for irrigation water will probably increase greatly in the future.

An estimated 1,000 acre-feet (1.2 hm^3) was pumped from the aquifers for municipal, domestic, and industrial uses in 1972. About 610 acre-feet (0.8 hm^3) of this amount was used for municipal and domestic purposes. The cities of Bowman, Hettinger, Reeder, and Scranton pumped about 570 acre-feet (0.7 hm^3) from the Fox Hills and basal Hell Creek aquifer. Total pumpage from the other aquifers by the remaining cities and rural residents is estimated to be 40 acre-feet (0.05 hm^3). Not included in the estimate is the amount of ground water pumped from the upper Ludlow and Tongue River aquifer at the lignite mines near Gascoyne. Pumpage was reported to vary, but annual discharge was about 1,500 acre-feet (1.8 hm^3).

About 1,300 acre-feet (1.6 hm^3) of water was obtained from wells and streams for livestock use. The estimate was made from data supplied by the U.S. Bureau of the Census, Census of Agriculture, 1969 (1972), and by Murray (1968, table 3).

Surface-Water Sources

The principal streams draining Adams and Bowman Counties are the Little Missouri River, Cedar Creek, and the North Fork Grand River.

Little Missouri River

The Little Missouri River had a maximum discharge of 45,000 ft^3/s (1,300 m^3/s) on March 23, 1947, and no flow for part of most years, at the gaging station near Marmarth, about 1 mile (1.6 km) north of the Bowman County line. The average annual discharge is about 248,500 acre-feet (306 hm^3), for a 34-year period of record.

The water samples collected at the gaging station are low in dissolved solids during the spring breakup and during periods when flow in the river consists mainly of surface runoff following periods of heavy precipitation in the spring and summer (fig. 7). For example, on March 18, 1971, the discharge was about 2,960 ft^3/s (84 m^3/s), and the water contained 216 mg/L dissolved solids. Calcium and sodium constituted 31 and 45 percent of the cations, respectively, and sulfate constituted 56 percent of the anions. Dissolved-solids concentration is greatest when discharge is least and precipitation is light during fall and winter. On November 14, 1972, when the discharge was about 35 ft^3/s (1.0 m^3/s), the water contained 1,350 mg/L dissolved solids. Calcium constituted about 13 percent of the cations, and sodium and potassium constituted about 68 percent of the cations.

The potentiometric contours (pl. 2B) of the Fox Hills and basal Hell Creek aquifer system indicate that, in an area west of a ground-water divide about 10 to 15 miles wide east of the Little Missouri River, ground water is moving toward the river, and that at least part of the flow during the late fall and winter is from ground-water storage. The water in the river and the water in well 132-106-26BDC (fig. 7) are similar in anionic composition and dissolved-solids concentration.

Selected samples (fig. 5) for irrigation classification plotted C2-S1 during periods of high runoff to C3-S2 during periods of low runoff. Water of similar quality has been studied for irrigation purposes on soils of the Shadehill area in South Dakota by Umback and others (1959). Accumulation of salts or alkali in the soil due to irrigation was not reported. The Shadehill area is on the North Fork Grand River about 10 miles (16 km) south of Lemmon, S. Dak.

Cedar Creek

Cedar Creek had a maximum discharge of 7,870 ft^3/s (223 m^3/s) on April 7, 1952, and no flow at times in some years, at the gaging station near Haynes. The average discharge for a 22-year period of record is 24,300 acre-feet (30 hm^3) per year.

Water samples collected at the gaging station are low in dissolved solids during the spring breakup and during periods of heavy precipitation in the spring and summer (fig. 17). On July 14, 1971, when the discharge was about

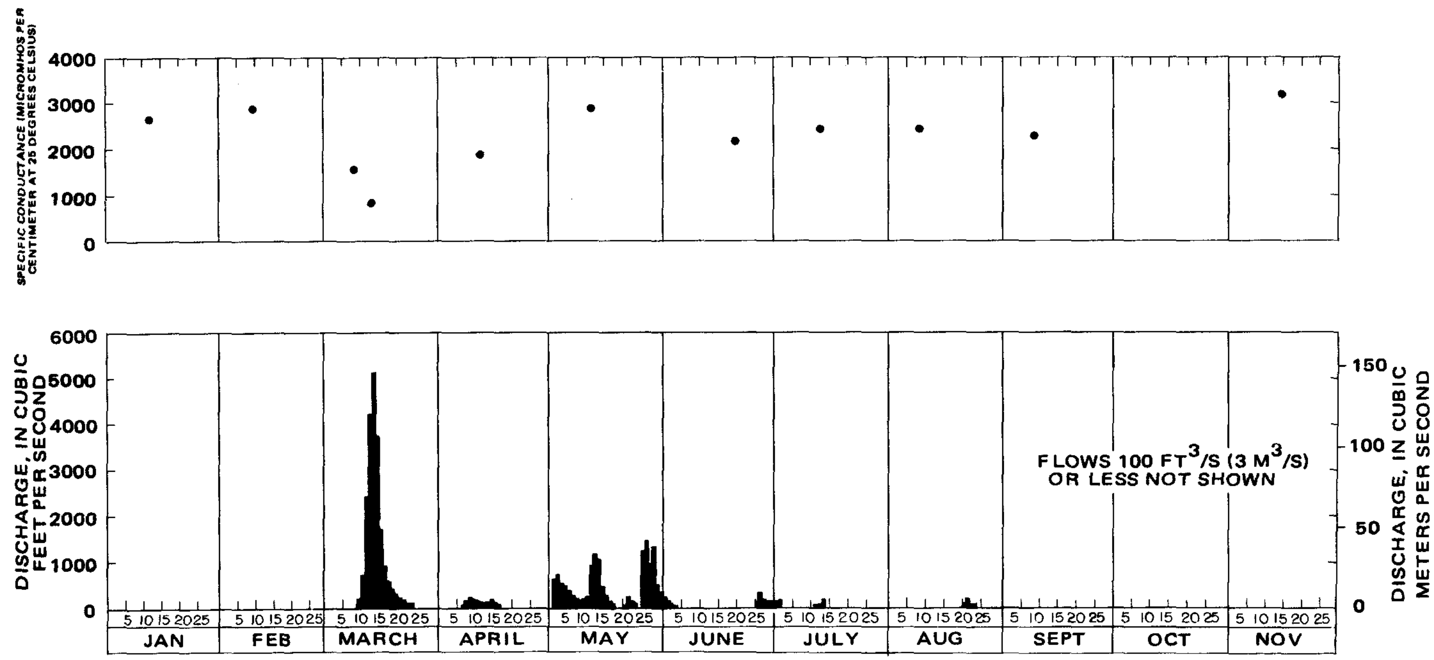


FIGURE 17.— Daily discharge and specific conductance of Cedar Creek near Haynes, 1972.

1,250 ft^3/s (35.4 m^3/s; fig. 16) the water contained 539 mg/L dissolved solids. Dissolved-solids concentrations are greatest when precipitation is light during fall and winter. On November 15, 1972, when the discharge was about 16 ft^3/s (0.45 m^3/s; fig. 16), the water contained 2,820 mg/L dissolved solids. During periods of low flow, dissolved-solids concentrations commonly are higher in the creek than in ground water from many wells in the area; the water also contains considerable calcium and magnesium. The high dissolved-solids concentration in the stream during periods of low flow probably represents ground water released from storage in which the dissolved solids were concentrated in ground water by evapotranspiration and other undefined processes.

Samples selected for irrigation classification plotted C2-S1 (fig. 5) during periods of high runoff to C3-S2 during periods of low runoff.

North Fork Grand River

The North Fork of the Grand River had a maximum discharge at Haley of 14,100 ft^3/s (399 m^3/s) on April 7, 1952; the river has no flow at times in some years. The discharge is regulated at Bowman-Haley Reservoir.

Ground-Water Supplies

Most of the residents of Adams and Bowman Counties depend on wells for water supplies. Five cities (table 6) have modern distribution systems, but inhabitants in other small communities depend on private wells. Most of the municipal pumpage is estimated from data supplied by city water managers, because many wells are not metered.

EFFECT OF DEVELOPMENT ON GROUND-WATER SUPPLIES IN ADAMS AND BOWMAN COUNTIES

Decline of Water Levels at Bowman, Hettinger, and Reeder

Pumpage from municipal wells tapping the Fox Hills and basal Hell Creek aquifer system has produced cones of depression in the potentiometric surface beneath Bowman, Hettinger, and Reeder. The water-level data (table 7) suggest a decline of about 120 feet (37 m) at Bowman from 1930 to 1971 and a decline of about 150 feet (46 m) at Hettinger from 1965 to 1971. However, the potentiometric map (pl. 2B) suggests that the decline at Hettinger is about 300 feet (90 m) since 1930, assuming that the 2,450-foot (747-m) potentiometric contour originally extended beneath the city. The cones will eventually stabilize in size if pumpage is not increased. Significant increases in pumpage from the Fox Hills and basal Hell Creek aquifer system for municipal or industrial supplies will cause the water levels to decline further and the hydraulic gradient to steepen.

TABLE 6. — Summary of pumpage, well data, and water quality for public supplies, 1972

City	Average pumpage (gal/d)	Per capita use (gal/d)	Well number	Well depth (feet)	Well yield (gal/min)	Dissolved solids (mg/L)
Bowman	247,000	140	131-102-02DDA	1,067	100	1,080
			131-102-11CAB	1,042	85	1,050
			131-102-11DAD	1,050	90	1,050
			131-102-14AAB	1,096	171	1,050
Hettinger	219,000	130	129-096-12DBB	1,314	28	1,110
			129-096-13ACA	1,140	168	1,130
			129-096-13ADD	1,050	50	983
			129-096-13BBB1	1,180	50	941
			129-096-13BDD1	1,182	50	950
			129-096-13BDD2	1,171	Not in use.	—
			129-096-13BDD3	1,190	do.	—
Reeder	21,900	71	130-098-04DBB	1,274	do.	—
			130-098-04DCC	1,200	Not available.	1,050
Rhame	13,200	64	132-104-27ADA	31	do.	1,510
Scranton	20,500	57	131-100-23DBA	1,180	do.	997
			131-100-26ABA	1,193	Not in use.	1,080

TABLE 7. — Water levels in wells tapping the Fox Hills and basal Hell Creek aquifer system

	Date	Water level, in feet below land surface [1]	Date	Water level, in feet below land surface
Bowman city wells				
131-102-02DDA			1971	359
131-102-11CAB	1930	220	1971	[2]340
131-102-11DAD	1960	244	1971	[2]320
131-102-14AAB	1968	280	1971	305
Hettinger city wells				
129-096-13ADD	1964	332	1971	359
129-096-12DBB	1965	520	1971	670
129-096-13BB1	1964	331	1971	397

[1] Data obtained from well driller's records.
[2] Approximate water level determined from water-level map.

Effects of Expanded Ground-Water Development

The cities of Bowman, Rhame, and Scranton are possible sites for growth due to development of lignite mining. Parameters from the Fox Hills and basal Hell Creek aquifer system in Bowman County and a ground-water digital model written by Trescott (1973) were used to evaluate the effects of expanded withdrawals at these cities on the water levels within the Fox Hills and basal Hell Creek aquifer system. The model uses the following partial-differential equation of ground-water flow derived by Pinder and Bredehoeft (1968) to describe the movement of ground water:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) = S\frac{\partial h}{\partial t} + W(x,y,t) \qquad (2)$$

where T_{xx} and T_{yy} are the transmissivity tensors, L^2/T;

h is the hydraulic head in the aquifer, L;

S is the storage coefficient, L^0;

t is the time, T, and

W is the volume flux per unit area, L/T.

Numerical solutions of the partial-differential equation (equation 2) are obtained using a digital computer. Exact solutions of the equation cannot be obtained because aquifers have variable properties and boundary conditions.

A program with a 32×32 grid system and a node spacing of 1 mile (1.6 km) was used in the model. Transmissivity values were obtained from plate 2C and a value of 0.0004 was used for the storage coefficient. The original head in the aquifer system in 1930 was extrapolated from data in table 7 and plate 2B. The thickness of the overlying Bacon Creek Member (?) of Frye (1969) was obtained from cross sections (pl. 1) and well logs. The confining bed was assumed to have a vertical hydraulic conductivity of 0.00001 ft/d (0.000003 m/d). The head in the overlying aquifer was obtained from plate 3A. Recharge from underlying aquifers was required in areas east of Bowman.

The pumping depression in the potentiometric surface at Bowman (1971-72) was successfully duplicated by the digital model. According to results obtained from the computer model, if pumpage at Bowman was increased in 1976 to 300 gal/min (20 L/s), and at the same time well fields were established at Rhame and Scranton with yields of 100 gal/min (6 L/s) each, the theoretical drawdown in 1986 in the Fox Hills and basal Hell Creek aquifer would approximate the drawdown values shown in figure 18.

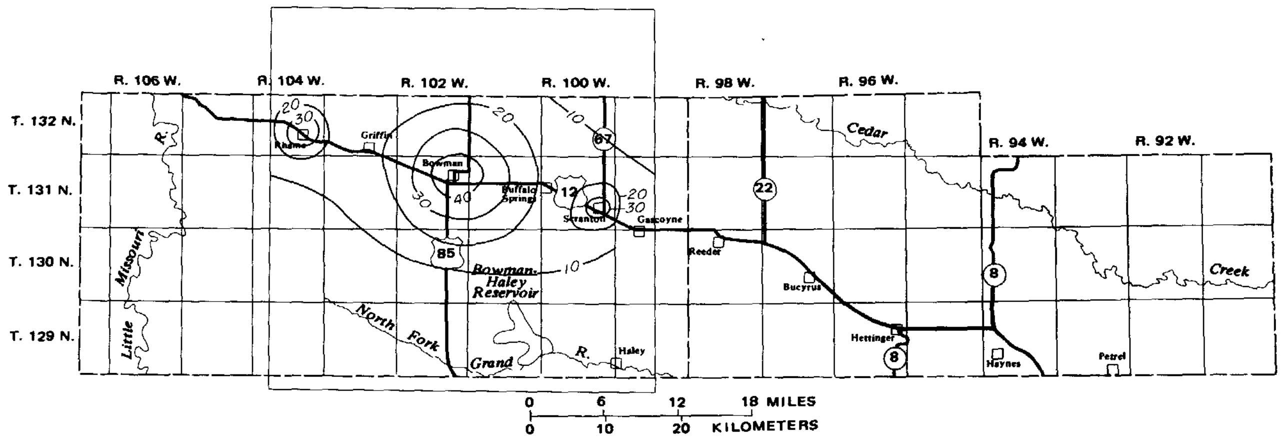
An increase in pumpage from the aquifer system may cause the water to increase in dissolved solids and in sulfate. As the head declines, water with a higher sulfate and dissolved mineral concentration probably will be drawn from the overlying aquifers and confining beds. The filtering ability of clays is reduced as the difference in head between the aquifers is increased. Some degradation of water in the aquifer system may have occurred already, as the concentration of sulfate is slightly higher in Bowman city wells 131-102-02DDA and 131-102-14AAB than in observation well 131-102-07DDD1, which is on the edge of the cone.

Water with a higher sulfate and dissolved mineral concentration can also enter the aquifer from the overlying aquifers through abandoned, rusted well casings.

EFFECT OF STRIP MINING ON GROUND WATER

The most detrimental effect of strip mining on the ground-water system may be the contamination of the water stored in the aquifer by dissolved minerals leached from the excavated overburden or spoils, which are used for mine backfill (Ground-Water Subgroup of Water Work Group, Northern Great Plains Resource Program, 1974). Available data indicate that the leachate may contain several times more dissolved solids than water in the underlying aquifers.

Sandoval and others (1973, p. 12) injected distilled water into samples obtained from spoilbank materials from various sites in North Dakota. The water extracted was generally a sodium sulfate type; specific conductance ranged from 2,000 to 8,000 umho/cm (micromhos per centimeter) at 25°C. A water sample from a shallow well tapping the lignite directly upgradient from the mine had a conductivity of 2,150 umho/cm at 25°C. Several shallow wells drilled south of the mine yielded water with conductivities greater than 5,000 umho/cm at 25°C.



EXPLANATION

AREA OF DIGITAL MODEL

—20— LINE OF EQUAL DRAWDOWN OF POTENTIOMETRIC SURFACE -- With increased pumpage from 1976-86. Interval 10 feet (3 m)

FIGURE 18.— Theoretical drawdown of the Fox Hills and basal Hell Creek aquifer system, 1976-86.

The conductivity of water in a tributary of Buffalo Creek below the mine at U.S. Highway 12 was 3,600 umho/cm at 25°C on April 20, 1974, and 4,500 umho/cm at 25°C on May 1, 1974. A water sample collected October 16, 1974, had a conductivity of 6,750 umho/cm at 25°C and was a sodium sulfate type. Water in Buffalo Creek had a conductivity of 4,800 umho/cm at 25°C on May 1, 1974. These measurements of surface-water conductivity are higher than the recorded values measured in the fall at most stations in southwestern North Dakota.

These data, although not conclusive, suggest that the leachate derived from weathering of pyrite in the lignite and the solution of gypsum from spoil materials at the Gascoyne mine percolates downward in the mine area and mixes with water in the underlying upper Ludlow and Tongue River aquifer system. The leaching problem is intensified by the fact that it probably will continue long after mining has ceased.

The underlying aquifers are protected from direct contamination by the relatively impervious Cannonball Formation and by confining beds in the Hell Creek Formation. Leakage through these confining beds is relatively small.

SUMMARY

Ground water for municipal, domestic, livestock, and industrial supplies in Adams and Bowman Counties is obtained from five aquifer systems consisting of semiconsolidated sandstone of Late Cretaceous and Tertiary age. Thickness, depth, transmissivity, yield, and water quality of these aquifer systems are summarized in the summary table. Rocks older than Late Cretaceous extend to 12,000 feet (3,700 m) below land surface, and generally contain saline water that is unsuitable for most purposes.

The Fox Hills and basal Hell Creek aquifer system is used as a source for municipal, industrial, and domestic supplies. Although it is as much as 940 feet (287 m) below land surface in some areas, it is the most dependable source of water in the counties and supplies most of the municipal water. Transmissivities are as high as 540 ft^2/d (50 m^2/d) in eastern Adams County, and wells should yield as much as 100 gal/min (6 L/s) with 50 feet (15 m) of drawdown after 24 hours of pumping. The water generally is clear. Dissolved solids are lower than in the overlying aquifer systems, due possibly to the filtering ability of clay beds acting as semipermeable membranes. Pumpage from the Fox Hills and basal Hell Creek aquifer system by the cities of Bowman, Hettinger, Reeder, and Scranton in 1972 is estimated at 570 acre-feet (0.7 hm^3) and has produced cones in the potentiometric surface.

The overlying upper Hell Creek and lower Ludlow, middle Ludlow, Cannonball, and upper Ludlow and Tongue River aquifer systems are relatively unused except for domestic and livestock supplies. They consist of interbedded fine- to medium-grained sandstone, siltstone, claystone, and lignite. The sandstone has a low hydraulic conductivity. Much of the water is colored but is suitable for many purposes.

Summary of hydrologic properties of major aquifer systems and chemical characteristics of ground water, Adams and Bowman Counties

Aquifer system	Thickness (feet)	Depth to top (feet)	Transmissivity (ft²/d)	Maximum yield with 50 feet of drawdown (gal/min)	General water quality
Fox Hills and basal Hell Creek	340-520	0-940	110-540	100	Sodium bicarbonate; most water samples are clear; dissolved solids range from 504 to 1,680 mg/L and the median is 1,050 mg/L.
Upper Hell Creek and lower Ludlow	0-420	0-490	30-440	100	Sodium bicarbonate to sodium sulfate; many water samples colored; dissolved solids range from 969 to 2,270 mg/L and the median is 1,090 mg/L.
Middle Ludlow	40-185	38-400	20-390	75	Sodium bicarbonate to sodium sulfate; many water samples colored; dissolved solids range from 573 to 3,060 mg/L and the median is 1,230 mg/L.
Cannonball	0-50	30-240	20	—	Sodium sulfate.
Upper Ludlow and Tongue River	0-450	—	—	100	Sodium sulfate; many water samples colored; dissolved solids range from 249 to 6,150 mg/L and the median is 1,300 mg/L.

Approximately 4,000 acre-feet (4.9 hm^3) of water was used in Adams and Bowman Counties in 1972. Of this amount, about 1,000 acre-feet (1.2 hm^3) was from the ground-water reservoir for municipal, domestic, and industrial use. About 1,700 acre-feet (2.1 hm^3) was pumped from streams for irrigation. About 1,300 acre-feet (1.6 hm^3) of water was obtained from wells and streams for livestock use. Mathematical analysis of data from the Fox Hills and basal Hell Creek aquifer system underlying Bowman County indicates that additional withdrawals can be made from the system.

Dissolved minerals leached from excavated overburden or spoils resulting from lignite mining operations may have a detrimental effect on the ground-water system by locally contaminating the shallow ground-water resources. Available data indicate that the leachate may contain several times more dissolved solids than the water in the underlying upper Ludlow and Tongue River aquifer system. Leaching will probably continue long after mining has ceased. The underlying aquifer systems are protected from contamination by the relatively impervious Cannonball Formation and by confining beds in the Hell Creek Formation.

SELECTED REFERENCES

Alger, R. P., 1966, Interpretation of electric logs in fresh-water wells in unconsolidated formations: Soc. Prof. Well Log Analysts Trans., 7th Ann. Logging Symposium, sec. cc, p. 1-25.

Benson, W. E., 1952, Geology of the Knife River area, North Dakota: U.S. Geol. Survey open-file rept.

Birch, Francis, ed., 1942, Handbook of physical constants: Geol. Soc. America Spec. 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: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 257-269.

Brown, R. H., 1963, Estimating the transmissibility of an artesian aquifer from the specific capacity of a well; *in* Bentall, Ray, and others, Method of determining permeability, transmissibility, and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 336-338.

Brown, R. W., 1952, Tertiary strata in eastern Montana and western North and South Dakota, *in* Billings Geol. Soc. Guidebook, 3d Ann. Field Conf., Black Hills-Williston basin, 1952, p. 89-92.

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

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

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

——— 1973, Ground-water resources, Mercer and Oliver Counties, North Dakota: North Dakota Geol. Survey Bull. 56, pt. III, and North Dakota State Water Comm. County Ground Water Studies 15, pt. III, 81 p.

——— 1974, Ground-water basic data, Adams and Bowman Counties, North Dakota: North Dakota Geol. Survey Bull. 65, pt. II, and North Dakota State Water Comm. County Ground-Water Studies 22, pt. II, 294 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. Geol. Survey Prof. Paper 463, 75 p.

Foley, F. C., Walton, W. C., and Drescher, W. J., 1953, Ground-water conditions in the Milwaukee-Waukesha area, Wisconsin: U.S. Geol. Survey Water-Supply Paper 1229, 96 p.

Frye, C. I., 1969, Stratigraphy of the Hell Creek Formation in North Dakota: North Dakota Geol. Survey Bull. 54, 65 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. Geol. Survey open-file Rept. 74-371.

Hamilton, T. M., 1970, Groundwater flow in part of the Little Missouri River basin, North Dakota: Univ. of North Dakota, Grand Forks, N. Dak., Unpub. Ph. D. dissert.

Hares, C. J., 1928, Geology and lignite resources of the Marmarth field, southwestern North Dakota: U.S. Geol. Survey Bull. 775, 110 p.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geol. Survey Water-Supply Paper 1473, 2d ed., 363 p.

Kepferle, R. C., and Culbertson, W. C., 1955, Strippable lignite deposits, Slope and Bowman Counties, North Dakota: U.S. Geol. Survey Bull. 1015-E, 182 p.

Konikow, L. F., 1976, Preliminary digital model of ground-water flow in the Madison group, Power River Basin and adjacent areas, Wyoming, Montana, South Dakota, North Dakota, and Nebraska: U.S. Geol. Survey Water Resources Inv. 63-77.

Kuznetsov, S. I., Ivanov, M. V., and Lyalikova, N. N., 1963, Introduction to geological microbiology: New York, McGraw Hill Book Co., Inc., 252 p.

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: Jour. Geology, v. 23, p. 523-547.

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

McKelvey, J. G., and Milne, I. H., 1960, Flow of salt solution through compacted bentonite: Paper on 9th Natl. Clay Conf., Purdue Univ., Lafayette, Ind.

Meyboom, Peter, 1966, Groundwater studies in the Assiniboine River drainage basin: pt. I: The evaluation of a flow system in south-central Saskatchewan: Canada Geol. Survey Bull. 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: Canada Geol. Survey Bull. 147, 57 p.

Meyer, R. R., 1963, A chart relating well diameter, specific capacity, and coefficients of transmissibility and storage, *in* Bentall, Ray, and others, Methods of determining permeability, transmissibility, and drawdown: U.S. Geol. Survey Water-Supply Paper 1536-I, p. 338-340.

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

National Academy of Sciences-National Academy of Engineering, 1973, Water quality criteria 1972: U.S. Environmental Protection Agency Ecol. Research Ser. Rept., EPA R3-73-033, 594 p.

National Weather Service, 1963-74, Climatological data, North Dakota: Annual Summaries 1962-73.

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.

Olsen, H. W., 1972, Liquid movement through kaolinite under hydraulic, electric, and osmotic gradients: Am. Assoc. Petroleum Geologists Bull., v. 56, no. 10, p. 2022-2028.

Pinder, G. F., and Bredehoeft, J. D., 1968, Application of the digital computer for aquifer evaluation: Water Resources Research, v. 4, no. 5, p. 1069-1093.

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. Geol. Survey Prof. Paper 476-A, 64 p.

Pollard, B. C., Smith, J. B., and Knox, C. C., 1972, Strippable lignite reserves of North Dakota: U.S. Bur. Mines Circ. 8537, 37 p.

Robinove, C. J., 1956, Geology and ground-water resources of the Hettinger area, Adams County, North Dakota: North Dakota State Water Comm. Ground Water Studies no. 24, 44 p.

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., ed., Some environmental aspects of strip mining in North Dakota: North Dakota Geol. Survey Educ. Ser. 5, 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. Geol. Survey Water-Supply Paper 598, 312 p.

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

Swenson, F. A., 1968, New theory of recharge to the artesian basin of the Dakotas: Geol. Soc. of America Bull., v. 79, p. 163-182.

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

Trescott, P. C., 1973, Iterative digital model for aquifer evaluation: U.S. Geol. Survey open-file rept., 63 p.

Umback, C. R., Fine, L. O., and Wiersma, Frank, 1959, Effects of irrigating soils of the proposed Shadehill project with waters high in sodium and bicarbonate ions: Proc. South Dakota Acad. Sci., v. 38, p. 88-95.

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 rept. PC(1)-A36.

—— 1972, Census of agriculture, 1969: Area reports, North Dakota, county data: v. 1, pt. 18, sec. 2.
U.S. Federal Water Pollution Control Administration, 1968, Report of the committee on water-quality criteria: Washington, U.S. Govt. Printing Office, 234 p.
U.S. Geological Survey, 1969, Surface water supply of the United States 1961-65, pt. 6, Missouri River Basin: U.S. Geol. Survey Water-Supply Paper 1917, 560 p.
—— 1966-71, Water resources data for North Dakota: Surface-water records, pt. 1: U.S. Geol. Survey, Bismarck, N. Dak.
U.S. Public Health Service, 1962, Drinking water standards: U.S. Public Health Service Pub. 956, 61 p.
U.S. Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Dept. Agriculture Handb. 60, 160 p.

DEFINITIONS OF SELECTED TERMS

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

Aquifer system – a series of interconnected aquifers, lakes, and streams.

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 glacial and alluvial deposits of Pleistocene and(or) Holocene age.

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

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

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

Ground water – water in the zone of saturation.

Hardness – the adjectives "hard" and "soft" 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

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.

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

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 mean sea level.

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

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

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

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

Scoria – the local term for burned lignite and baked clay.

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°C.

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

Storage coefficient – the volume of water an aquifer releases or takes into storage per unit surface area of the aquifer per unit change in head.

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

Transmissivity – 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 flow of water through the soil or a subsurface stratum.

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.