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GROUND-WATER RESOURCES
MERCER and OLIVER COUNTIES, NORTH DAKOTA

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Prepared by the United States Geological Survey in cooperation with the North Dakota State Water Commission, North Dakota Geological Survey, Mercer County Water Management District, and Oliver County Water Management District.

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GROUND–WATER RESOURCES OF
MERCER AND OLIVER COUNTIES, NORTH DAKOTA

By M. G. Croft

ABSTRACT

Important artesian aquifers, consisting of fine- to medium-grained sandstone, occur in the Fox Hills and Hell Creek Formations of Late Cretaceous age and the Tongue River Formation of Tertiary age. The water from the aquifers is suitable for livestock, domestic, and some industrial uses, but probably not for irrigation. The total withdrawal from the artesian aquifers is about 1 million gallons per day. Individual well yields probably would not exceed 150 gallons per minute.

Glacial and alluvial deposits of sand and gravel form potentially productive aquifers beneath the valleys of Goodman, Antelope, Square Butte, and Elm Creeks and the Knife and Missouri Rivers. The aquifers, which are relatively undeveloped, are 1 to 5 miles in width, have a maximum thickness of about 250 feet, and contain about 2,640,000 acre-feet of ground water. The water generally is suitable for domestic, livestock, and industrial purposes. About 1,215,000 acre-feet of water in these aquifers is suitable for irrigation. A test of the Knife River aquifer near Stanton indicated a transmissivity of 176,000 gallons per day per foot (23,500 square feet per day) and a storage coefficient of 0.0003. A test of the Missouri River aquifer near Hensler indicated a transmissivity of 107,000 to 121,000 gallons per day per foot (14,300 to 16,200 square feet per day), and a storage coefficient of 0.02. In places individual well yields of more than 500 gallons per minute should be obtainable from these aquifers.

Approximately 137,000 acre-feet of water was used in Mercer and Oliver Counties in 1968. Most of this water was taken from the Missouri River for cooling purposes in electric-generating plants and for irrigation. About 2,270 acre-feet was obtained from ground-water sources for industrial, livestock, and domestic use.

INTRODUCTION

Purpose and Objectives of the Investigation

The purpose of the hydrologic investigation in Mercer and Oliver Counties, North Dakota (figure 1), was to determine the quantity and

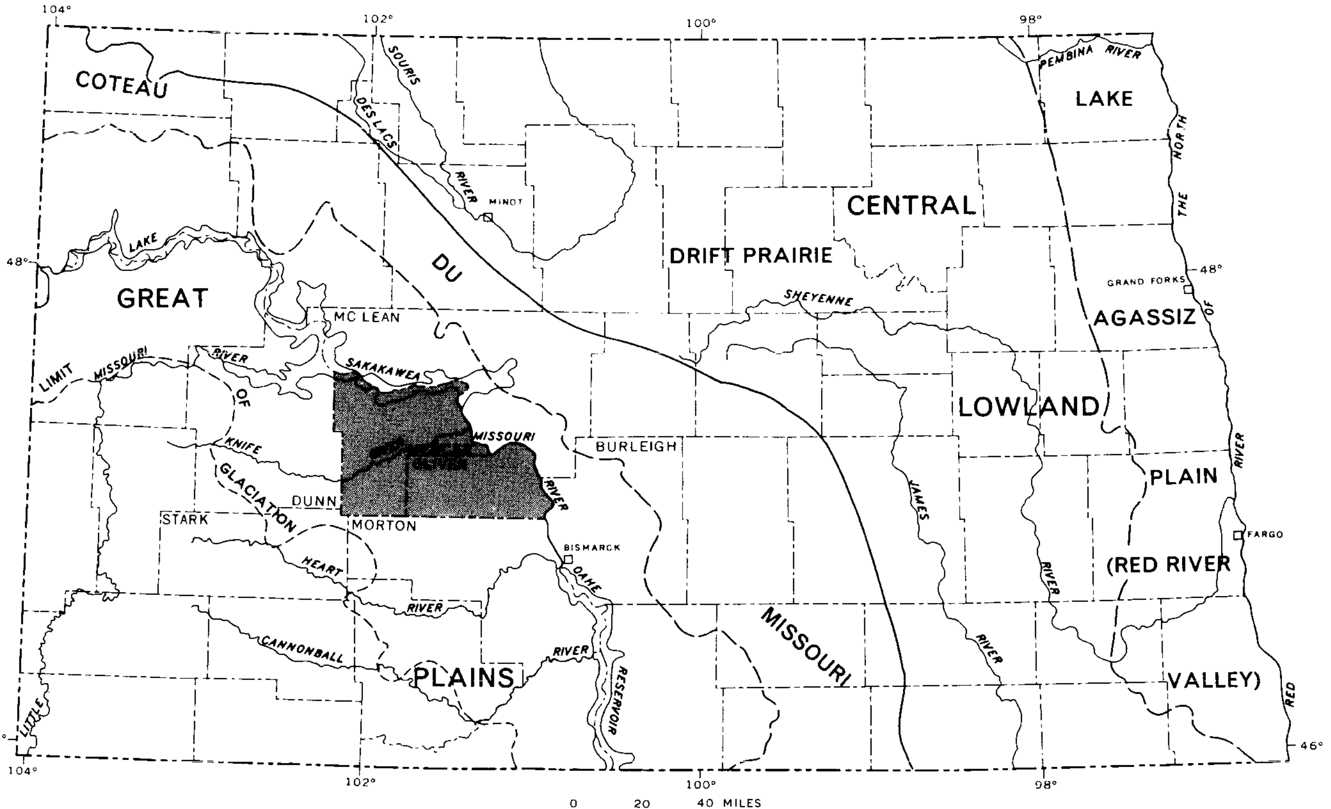


FIGURE 1.--Physiographic divisions in North Dakota and location of report area.

quality of ground water available for municipal, domestic, livestock, industrial, and irrigation uses. Specifically the objectives were to: (1) determine the location, extent, and nature of the major aquifers; (2) evaluate the occurrence and movement of ground water, including the sources of recharge and discharge; (3) estimate the potential yields of wells tapping the major aquifers; (4) estimate the quantities of water stored in the aquifers; and (5) determine the chemical quality of the ground water.

The investigation was made cooperatively by the U.S. Geological Survey, North Dakota State Water Commission, North Dakota Geological Survey, and Mercer and Oliver Counties Water Management Districts. The results of the investigation will be published in three separate parts of the bulletin series of the North Dakota Geological Survey and the county ground-water series of the North Dakota State Water Commission. Part I is an interpretive report describing the geology; Part II (Croft, 1970), 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, and water-level data collected during the county investigations and 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, in some instances, differs from that of the U.S. Geological Survey. Definitions for the technical terms used in this report are in the "Definition of Terms" section. The base maps for the geologic sections of the glacial-drift and alluvial aquifers are the available 1:24,000 topographic maps. Plate 1 is the base map for areas where topographic maps are not available.

Well-Numbering System

The wells, springs, and test holes are numbered according to a system based on the location in the public land classification of the United States Bureau of Land Management. The system is illustrated in figure 2. The first numeral denotes the township north of a base line, the second numeral denotes the range west of the fifth principal meridian, and the third numeral denotes the section in which the well is located. The letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quarter section, quarter-quarter section, and quarter-quarter-quarter section (10-acre tract). For example, well 146-90-15DAA1 is in the NE¼NE¼SE¼ sec. 15, T. 146 N., R. 90 W. Consecutive terminal numerals are added if more than one well, spring, or test hole is recorded within a 10-acre tract.

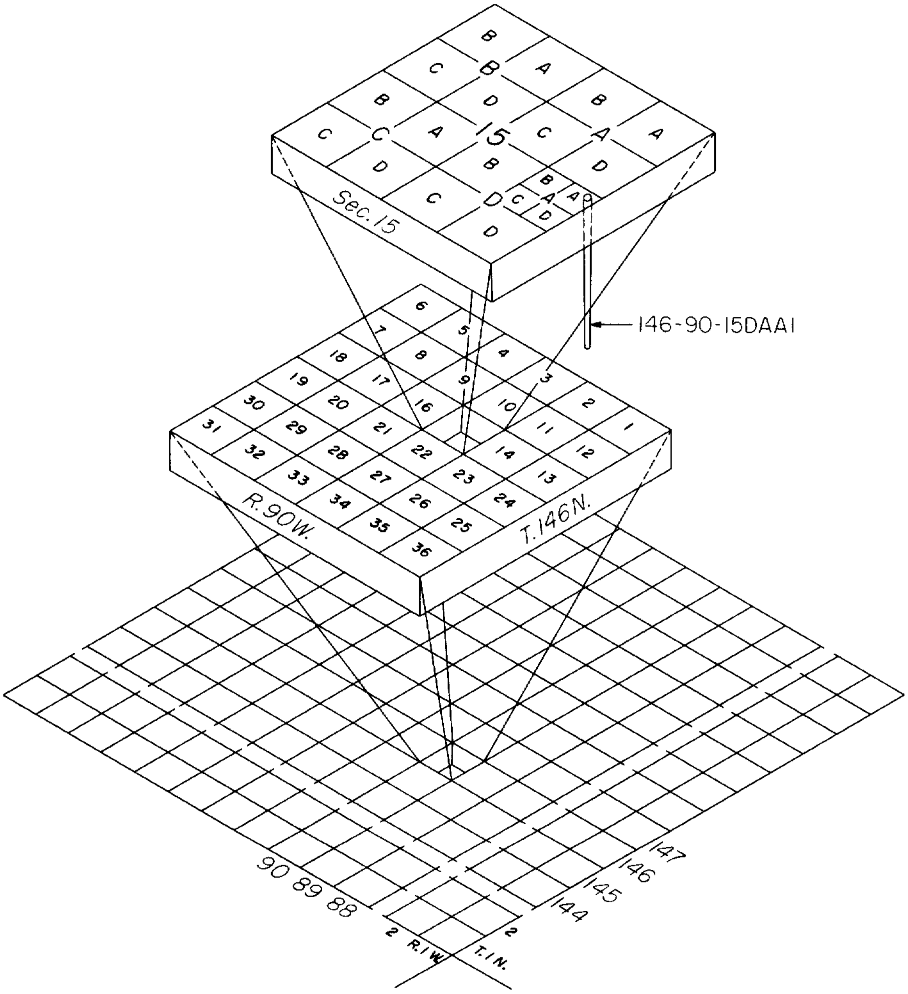


FIGURE 2.–System of numbering wells, springs, and test holes.

Acknowledgments

The collection of data for this report was made possible by the cooperation of the County Commissioners, residents of the counties, the U.S. Bureau of Reclamation, and electric power companies in the area. Bandy Drilling Co., Ray Mohl, Lloyd Erickson, Opp Drilling Co., and Mann Drilling Co. furnished logs and other information. L. L. Froelich, ground-water geologist with the North Dakota State Water Commission, logged most of the test holes. Recognition also is due M. O. Lindvig, ground-water engineer, and R. W. Schmid, ground-water hydrologist with the North Dakota State Water Commission.

Climate

The climate of Mercer and Oliver Counties is cool and semiarid. The mean annual temperature recorded by the U. S. Weather Bureau (1960-69) at Beulah during 1959-68 was about 41°F (figure 3A). Temperatures average 71°F in July and 68°F in August. The highest temperature recorded at Beulah was 108°F in July 1960. Cold waves in the winter are frequent and temperatures may drop to 30 or 40° below zero. The lowest temperature recorded at Beulah was -42°F in January 1968 and February 1959. The average growing season is about 120 days.

The average annual precipitation recorded at Beulah during 1959-68 was about 16 inches (figure 3B). The greatest amount of precipitation falls in the spring and summer during the growing season (figure 3C). The least precipitation is in the fall and winter. Thunderstorms are frequent in June, July, and August.

During the winter of 1968-69, the thickest cover of snow since the winter of 1896-97 accumulated in Mercer and Oliver Counties. Beulah recorded about 33 inches of snow and Center recorded 25.5 inches of snow. Very little snow fell in March, but temperatures remained cold and little thawing occurred. Warm weather in April rapidly melted the accumulated snow and caused wide-spread flooding along the principal streams.

Physiography and Drainage

The total area of Mercer and Oliver Counties, about 1,761 square miles (U.S. Bureau of the Census, 1970), lies within the glaciated area of the Great Plains (figure 1). The rolling uplands, which are veneered with glacial drift, have a maximum elevation of about 2,380 feet. The principal streams, the Missouri River, the Knife River, and Square Butte

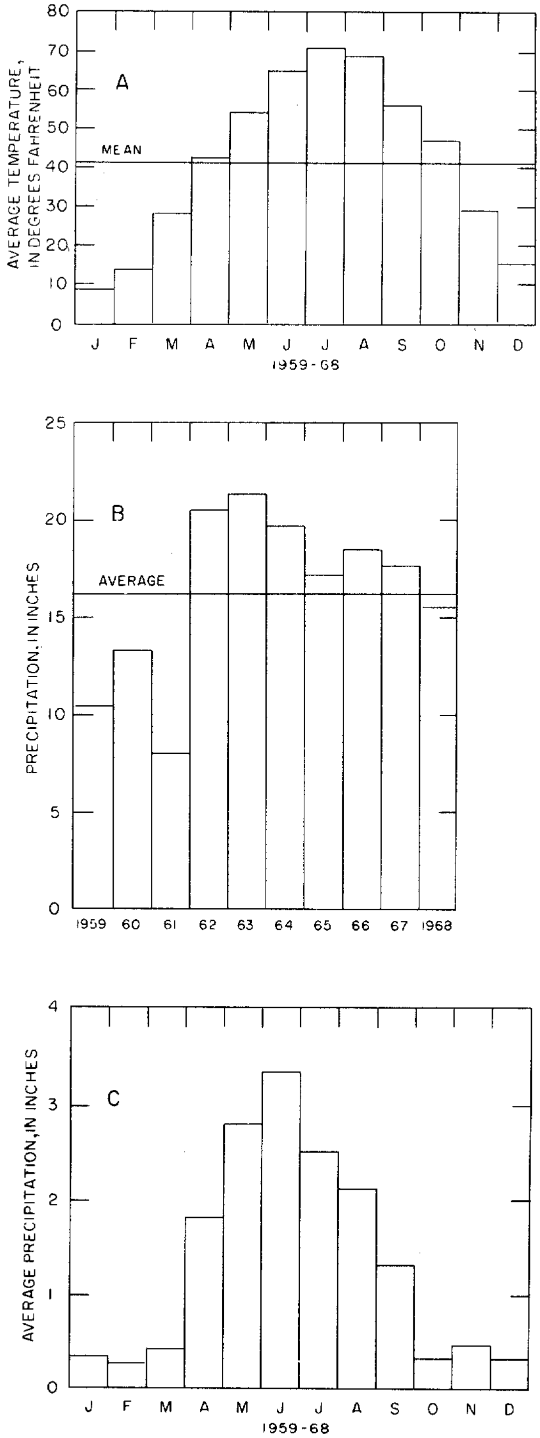


FIGURE 3.--Precipitation and temperature at Beulah.

Creek, are incised 400 to 600 feet below the upland surface. Buttes and badland features are common. Steep bluffs, carved by the Missouri River, flank the eastern border. Lake Sakakawea, formed behind Garrison Dam, borders the area on the north.

Probably the most striking topographic features in the area are the large valleys or trenches (plate 1, in pocket) that cross the area from the northwest to southeast. Although these valleys are impressive, they contain only small streams. They probably were carved by the combined flow of the Missouri, Little Missouri, and Yellowstone Rivers, augmented by glacial melt water flowing at or near the edge of an ice sheet (Leonard, 1916, p. 299). The Knife River channel, which occupies a preglacial valley, also was enlarged and deepened by melt water. The Knife River drains more than half the study area.

Most streams have thoroughly reestablished a drainage system following the retreat of the last ice sheet. Interior drainage occurs only in the uplands midway between Beulah and Lake Sakakawea where undrained depressions, called sloughs or prairie potholes, are common. Most of the depressions contain water for only a few months during the spring and early summer.

Population and Economy

The population in 1970 was 6,175 in Mercer County and 2,322 in Oliver County (U.S. Bureau of the Census, 1970). In Mercer County, Hazen and Beulah had populations of 1,240 and 1,344, respectively, and Stanton, the county seat, had a population of 517. In Oliver County, Center, the county seat and largest community, had a population of 619.

The economy of the area is based on agriculture and the strip mining of lignite for production of electric power. Agricultural products include small grains, corn, cattle, sugar beets, and hay. Thermal-electric powerplants are located near Beulah, Stanton, and Center. Hydroelectric power is produced at Garrison Dam.

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). Recent geologic investigations have been made by Benson (1952), Johnson and Kunkel (1959), Denson and Gill (1965), Pipiringos, Chisholm, and Kepferle (1965), and Kume and Hansen (1965).

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 Mercer and Oliver Counties. Greenman (1953) investigated the geology and ground-water potential of the Missouri River flood plain between Garrison Dam and Bismarck for irrigation supplies. The geology and ground-water resources of the Fort Berthold Indian Reservation were described by Dingman and Gordon (1954). Bradley and Jensen (1962) made a ground-water study near the city of Beulah for local water supplies, and reported on the results of test drilling.

PRINCIPLES OF GROUND–WATER OCCURRENCE

All ground water is derived from precipitation. After the precipitation falls on the earth's surface, part is returned to the atmosphere by evaporation, part runs off to the streams, and the remainder infiltrates into the ground. Much of the water that infiltrates into the ground is held temporarily in the soil and is returned to the atmosphere either by evaporation or by transpiration. The remainder infiltrates downward to the water table.

Ground water moves under the influence of gravity from areas of recharge to areas of discharge along paths generally normal to the hydraulic gradient, as shown by contour lines on a water-level map. Ground-water movement is generally very slow and may be only a few feet per year. The rate of movement is directly proportional to the hydraulic gradient and to the permeability of the deposits. Gravel, coarse sand, and fractured rocks generally are highly permeable. Well-cemented deposits and fine-grained materials such as silt, clay, and shale have low permeability and restrict ground-water movement. Areas where ground-water withdrawals exceed recharge are indicated by depressions in potentiometric contour maps.

Recorded water-level changes in a well yield valuable information about the aquifer. Water levels usually fluctuate in response to changes in the amount of water stored in the aquifer. Changes in atmospheric pressure and surface loading also cause fluctuations in confined aquifers. Data obtained from pumping a well are used to determine aquifer characteristics (Ferris and others, 1962; Walton, 1962). The transmissivity and storage properties of the aquifer are determined from the drawdown in the pumping well and in adjacent observation wells. A constant rate of discharge from a well in an extensive aquifer causes the water level to decline rapidly at first and then at a decreasing rate as the cone of depression expands. The size of the cone is determined by time of pumping, transmissivity of the deposits, and the storage coefficient. Artesian aquifers have storage coefficients that generally range from 0.001 to about 0.00001. Water-table aquifers have storage coefficients that range from about 0.2 to 0.001. A well pumping from an artesian aquifer will develop a much larger cone of depression than a well pumping at the same rate from a water-table aquifer.

A well pumping from deposits in a narrow valley may develop a cone that expands the full width of the aquifer. If this occurs, sufficient water may not move towards the pumping well to stabilize the cone, thus causing the water level in the pumping well to decline at an accelerated rate. In very narrow aquifers, the water level in the well may decline as long as the well is pumped and the cone of depression will elongate parallel to the aquifer.

If the water level continues to decline it may cause water of undesirable quality to move into the aquifer, the yield of the well may decrease because of interference from other wells or from aquifer boundaries, the pumping lift may increase until pumping becomes uneconomical, or the water level may decline below the top of the well screen.

Methods of Determining the Hydraulic Properties of Aquifers in the Consolidated Rocks

Methods of determining the hydraulic properties of aquifers by using a flowing artesian well were devised by Jacob and Lohman (1952). They developed equations for a graphical solution for transmissivity and the storage coefficient for short periods of flow, and a simpler equation for straight-line graphical solutions that gives accurate results for slightly longer periods of flow. The formulas for the straight-line solutions are:

$$T = \frac{264}{\Delta\,(s_w/Q)} \text{ and} \qquad (1)$$

$$S = 2.1\text{x}10^{-4}T(t/r_w{}^2)_o, \text{ or} \qquad (2)$$

$$S = \frac{2.1\text{x}10^{-4}T(t/r_w{}^2)}{\log_{10}{}^{-1}[s_w/Q/\Delta(s_w/Q)]}\ , \qquad (3)$$

in which

T = coefficient of transmissivity, in gallons per day per foot,
S = storage coefficient,
s_w = drawdown, in feet,
Q = flow rate, in gallons per minute,
t = time between beginning of flow and flow measurement, in minutes, and
r_w = effective radius of the well through the aquifer, in feet.

The values, s_w/Q, are plotted on the linear scale on semilog paper, and the corresponding values of t/r_w^2 are plotted on the logarithmic scale. The slope, $\Delta(s_w/Q)$, is the change in s_w/Q over one log cycle of t/r_w^2. The value, $(t/r_w^2)_o$, (equation 2) is taken at the point $(s_w/Q)=0$. When the slope of the curve is steep, equation 3 is used to avoid large extrapolation errors. In this case, the values of t/r_w^2 and s_w/Q are arbitrarily selected from a specific point on the line. The value for transmissivity in gallons per day per foot can be converted to transmissivity in square feet per day by multiplying by 0.134.

After each flow test is completed, a check of the calculated value for T can be made using the Theis (1935, p. 522) recovery formula. The formula is:

$$T = \frac{264Q}{s'} \log_{10} t/t', \qquad (4)$$

in which

Q = the weighted average discharge in gallons per minute,
t = the time since discharge started, in minutes,
t' = the time since discharge stopped, in minutes, and
s' = the residual drawdown, in feet.

Croft and Wesolowski (1970) made 49 flow and recovery tests of the aquifers in the Fox Hills and Hell Creek Formations in Mercer and Oliver Counties with the methods devised by Jacob and Lohman (1952) and Theis (1935). The results of these tests are discussed in this report under the sections dealing with the specific aquifers.

Methods of Determining the Hydraulic Properties of Aquifers in the Glacial Drift and Alluvium

The hydraulic properties of the glacial-drift and alluvial aquifers were estimated from lithologic logs, using the following values:

Material	Coefficient of permeability (gallons per day per square foot)	Hydraulic conductivity (feet per day)
Till or clay	1	0.134
Till or clay, silty	50	6.7
Till or clay, sandy	100	13.4
Sand, fine	200	26.8
Sand, medium	500	67
Sand, coarse	900	120
Lignite	900	120
Sand and gravel	1,500	200
Gravel	3,000	400
Gravel, very coarse	5,000	670

Hydraulic conductivity of a material is determined in the laboratory at a water temperature of 16°C. If the temperature of water in the aquifer is not 16°C, the laboratory values must be corrected to field conditions. The correction is necessary because water becomes more viscous with decreasing temperatures and therefore will flow at a decreased rate through a given medium at a given gradient. In Mercer and Oliver Counties, temperatures of water in the glacial drift and alluvium generally ranged from 6°C to 10°C. Todd (1959, p. 50-51, figure 3) showed that the ratio of laboratory permeability (hydraulic conductivity) to field permeability for the field temperature of 8.5°C (47°F) is about 1.20. Therefore, laboratory values of hydraulic conductivity, or estimated values based on laboratory determinations of similar material, were divided by 1.20 to obtain the estimated field hydraulic conductivities for this area.

After the hydraulic conductivity of each lithologic unit in a test hole was estimated, the transmissivity was determined by multiplying the hydraulic conductivity of each unit by the bed thickness; the products were then totaled. Probable specific capacities then were determined using the graph developed by Meyer (1963). An arbitrary drawdown of 15 feet was used to compute the yields from glacial-drift and alluvial aquifers shown on plate 1. Most of the test holes were drilled by hydraulic rotary methods, which commonly produce nonrepresentative sand samples containing less silt and clay than is actually present. Allowances were made for this discrepancy when hydraulic conductivity values were assigned. Aquifer tests in the field indicated that the transmissivities determined by laboratory methods were conservative, but reasonably accurate.

QUALITY–OF–WATER STANDARDS

All natural water contains dissolved minerals. Rain dissolves mineral matter as it falls and continues to dissolve mineral matter as the water infiltrates the soil. The quantity and type of solutes in ground water are dependent upon the type of rocks dissolved, the amount and kind or organic compounds contained in the soil through which precipitation infiltrated, the temperature of the ground water, and the length of time that the water is in contact with the soil and rocks. Water that has been underground a long time, or has traveled a long distance from the recharge area, generally is more highly mineralized than water that has been in transit for only a short time and is withdrawn near the recharge area.

The dissolved mineral constituents in water are generally reported in parts per million (ppm), milligrams per liter (mg/l), or grains per U.S. gallon (gr/gal). A part per million is a unit weight of a constituent in a million unit weights of water. Milligrams per liter is practically equivalent to parts per million for water containing less than 7,000 ppm dissolved solids (Hem, 1959, p. 30). Parts per million can be converted to grains per gallon by dividing parts per million by 17.12. Equivalents per million (epm) is the unit chemical combining weight of a constituent in a million weights of water. These units are usually not reported, but are frequently used to classify water according to its chemical character on the basis of percentage values of constituents in solution. A percentage value is the ratio, expressed in percent, of the concentration in equivalents per million of each cation or anion to the sum of cations or anions, respectively. For example, equivalents per million are used to calculate percent sodium, the sodium-absorption ratio (SAR), or to check the accuracy of a chemical analysis.

The suitability of water for various uses is determined largely by the kind and amount of dissolved mineral matter. Chemical properties and constituents most likely to be of concern are: (1) dissolved solids and the related specific conductance, (2) sodium-adsorptions ratio, (3) hardness, (4) iron, (5) sulfate, (6) nitrate, and (7) fluoride. The relative importance of the above properties and constituents of water depends primarily on the use of the water. For example; hardness has very little effect on the suitability of water for drinking, but it can make water undesirable for laundry use. Additional information may be found in "Drinking Water Standards" published by the U.S. Public Health Service (1962).

Table 1, modified from Durfor and Becker (1964, table 2) shows the major constituents normally found in water, their major sources, and their effects upon usability.

Dissolved Solids and Specific Conductance

The concentration of dissolved solids is a measure of the total mineralization of water. The dissolved-solids concentration is significant because it may limit the use of water for many purposes. In general, the suitability of water decreases with an increase in dissolved solids. The limits shown in table 1 for drinking water were originally set for common carriers in interstate commerce. Residents in areas where dissolved solids are as high as 2,000 ppm have consumed the water with no noticeable ill effects. Livestock has been known to survive on water containing 15,000 ppm. However, growth and reproduction of livestock may be affected by water containing more than 3,000 ppm dissolved solids.

The specific conductance of water is a measure of the water's ability to conduct an electrical current, and is a function of the amount and kind of dissolved mineral matter. Specific conductance usually is reported in micromhos at 25°C. An estimate of the total dissolved solids in parts per million can be obtained by multiplying specific conductance by 0.65; although the factor may range from 0.5 to 1.0 depending upon the type and amount of dissolved minerals. The conversion factor should not be used for estimating dissolved solids of more than 50,000 ppm, nor should it be used if the specific conductance has not been adjusted to the standard temperature of 25°C.

Irrigation Indices

Two indices of the suitability of water for irrigation are SAR and specific conductance. SAR is related to the sodium hazard; the specific conductance is related to the salinity hazard. Figure 4 shows the 16

TABLE 1.–Major chemical constituents in water–their sources, effects upon usability, and recommended concentration limits.
(Concentrations are in parts per million)

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

Constituents	Major source	Effects upon usability	U.S. Public Health Service recommended limits for drinking water 1/
Silica (SiO_2)	Feldspars, ferromagnesian and clay minerals.	In presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat transfer.	
Iron (Fe)	Natural sources: Amphiboles, ferromagnesian minerals, ferrous and ferric sulfides, oxides, and carbonates, and clay minerals. Manmade sources: well casings, pump parts, and storage tanks.	If more than 0.1 ppm 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 0.2 ppm is objectionable for most industrial uses.	0.3 ppm
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 actions 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, and evaporites.	More than 50 ppm sodium and potassium with suspended matter causes foaming, which accelerates scale formation and corrosion in boilers.	
Potassium (K)	Feldspars, feldspathoids, some micas, and clay minerals.		
Boron (B)	Tourmaline, biotite, and amphiboles.	Many plants are damages by concentrations of 2.0 ppm.	
Bicarbonate (HCO_3)	Limestone and dolomite.	Upon heating of water to the boiling point, bicarbonate is changed to steam, carbonate, and carbon dioxide. Carbonate combines with alkaline earths (principally, calcium and magnesium) to form scale.	
Carbonate (CO_3)			
Sulfate (SO_4)	Gypsum, anhydrite, and oxidation of sulfide minerals	Combines with calcium to form scale. More than 500 ppm tastes bitter and may be a laxative.	250 ppm
Chloride (Cl)	Halite and sylvite.	In excess of 250 ppm may impart salty taste, greatly in excess may cause physiological distress. Food processing industries usually require less than 250 ppm.	250 ppm
Fluoride (F)	Amphiboles, apatite, fluorite, and mica.	Optimum concentration in drinking water has a beneficial effect on the structure and resistance to decay of children's teeth. Concentrations in excess of optimum may cause mottling of children's teeth.	Recommended limits depend on average of maximum daily temperatures. Limits range from 0.6 ppm at 90.5°F to 1.7 ppm at 50°F.
Nitrate (NO_3)	Nitrogenous fertilizers, animal exrement, legumes, and plant debris.	More than 100 ppm may cause a bitter taste and may cause physiological distress. Concentrations greatly in excess of 45 ppm have been reported to cause methemoglobinemia in infants.	45 ppm
Dissolved solids	Anything that is soluble.	More than 500 ppm is not desirable if better water is available. Less than 300 ppm is desirable for some manufacturing processes. Excessive dissolved solids restrict the use of water for irrigation.	500 ppm

1/ U.S. Public Health Service, 1962.

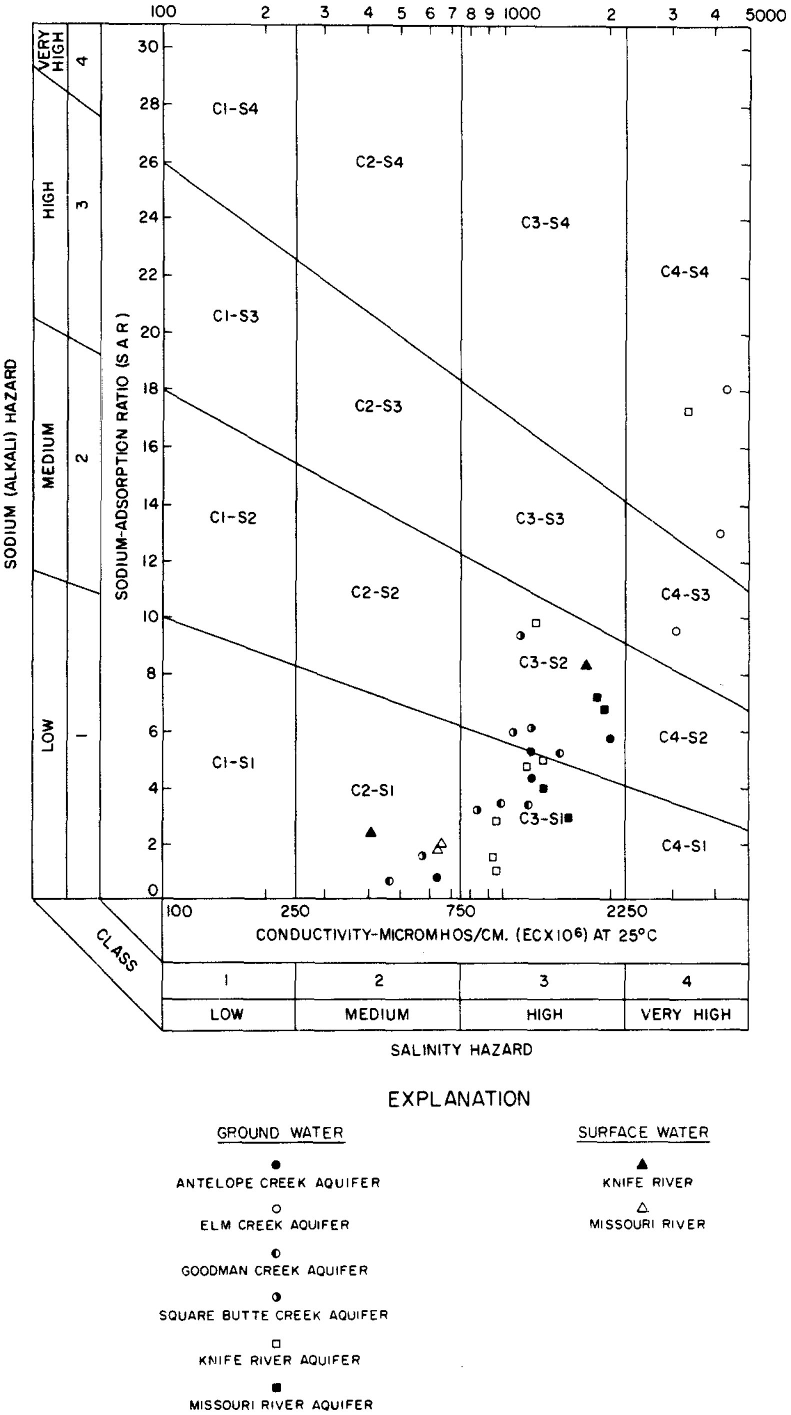


FIGURE 4.—Classification of selected water samples for irrigation purposes.

classifications of water as determined by the SAR and specific conductance. Numerical values of 3 or 4 indicate that the water is of marginal or unsuitable quality for irrigation. Water with a high sodium hazard has been used successfully for selected crops in some areas with the addition of chemical amendments. Water with a high salinity hazard has been used successfully for irrigation where coarse-textured soils occur and good drainage exists.

Another index used to evaluate irrigation water is the residual sodium carbonate. Residual sodium carbonate (RSC) is determined by subtracting the equivalents per million of calcium and magnesium from the sum of equivalents per million of bicarbonate and carbonate. If the RSC is between 1.25 and 2.5 epm, the water is considered marginal for irrigation. An RSC of more than 2.5 epm indicates that the water is not suitable for irrigation purposes. Good management practices might make it possible to use successfully some of the marginal RSC water for irrigation. For further information the reader is referred to "Diagnosis and Improvement of Saline and Alkali Soils" (U.S. Salinity Laboratory Staff, 1954).

Hardness

The hardness of water determines its usefulness for laundries and for some industries. The U.S. Geological Survey rates hardness as follows: Water having a hardness of 0 to 60 ppm calcium carbonate is soft, between 61 and 120 ppm is moderately hard, between 121 and 180 ppm is hard, and more than 180 ppm is very hard. Hardness does not seriously interfere with the use of water for most purposes, but it does increase the consumption of soap. Its removal by a softening process can be profitable for domestic uses, for laundries, and for some industries.

GEOLOGY OF THE GROUND–WATER RESERVOIR

Most of the usable ground water in Mercer and Oliver Counties is in the (1) consolidated rocks of Late Cretaceous age, (2) consolidated rocks of Tertiary age, and (3) unconsolidated deposits of Quaternary age. The Cretaceous and Tertiary rocks, which are partly capped by a veneer of glacial drift, form part of the southeast flank of the Williston basin (Denson and Gill, 1965, plate 5-H). These rocks were studied in detail with special reference to their water-bearing properties.

Rocks older than Late Cretaceous age, which occur at great depth, have been penetrated by oil and gas test holes and generally contain brackish or saline water. The Dakota Group, an important aquifer in eastern North Dakota, is at depths greater than 3,500 feet in Mercer and Oliver Counties. Calculations from the spontaneous potential (SP) curves of electric logs indicate the Dakota water has a conductivity of 7,000 to 10,000 micromhos, and is therefore too brackish for most uses.

Rocks of Late Cretaceous Age

Pierre Formation

The Pierre Formation is a marine deposit composed of olive-gray to dark-greenish-gray shale, and rarely a few thin beds of very fine grained sandstone. The formation, which underlies the Fox Hills Formation (plate 2, in pocket), is about 1,100 feet thick, as shown by logs of oil and gas test holes obtained from commercial suppliers of logs. No significant aquifers were found in the formation. For practical purposes, the formation forms the base of the fresh-water-bearing units in the report area.

Fox Hills Formation

The Fox Hills Formation, a sequence of alternating beds of marine sandstone and shale 205 to 334 feet thick, occurs at depths from 600 to more than 1,600 feet beneath the land surface (plate 2). Structural contours (figure 5) drawn on the base of the Fox Hills show that the beds dip to the northwest at 6 to 20 feet per mile. A thick bed of sandstone, the Colgate Member, forms the top of the formation. The lower part of the formation consists mainly of sandy siltstone and claystone.

Particle-size distribution curves (Croft, 1970, p. 257-258) were made from two samples cored from a coarse-grained part of the Colgate Member in well 142-84-24BBA at a depth between 961 and 964.5 feet. The results are summarized in table 2. The material from both cores consisted mainly of fine- to medium-grained sand. The sample from 961 to 962 feet had a median particle diameter of 0.25 millimeter, an effective diameter of 0.07 millimeter, and a coefficient of uniformity of 3.85. The sample from 964 to 964.5 feet had a median particle diameter of 0.22 millimeter and a coefficient of uniformity of about 6.0 if the effective-diameter value is extrapolated. The high values for the coefficient of uniformity indicate the sandstone is poorly sorted.

Hell Creek Formation

The top of the Hell Creek Formation is at depths between 270 and

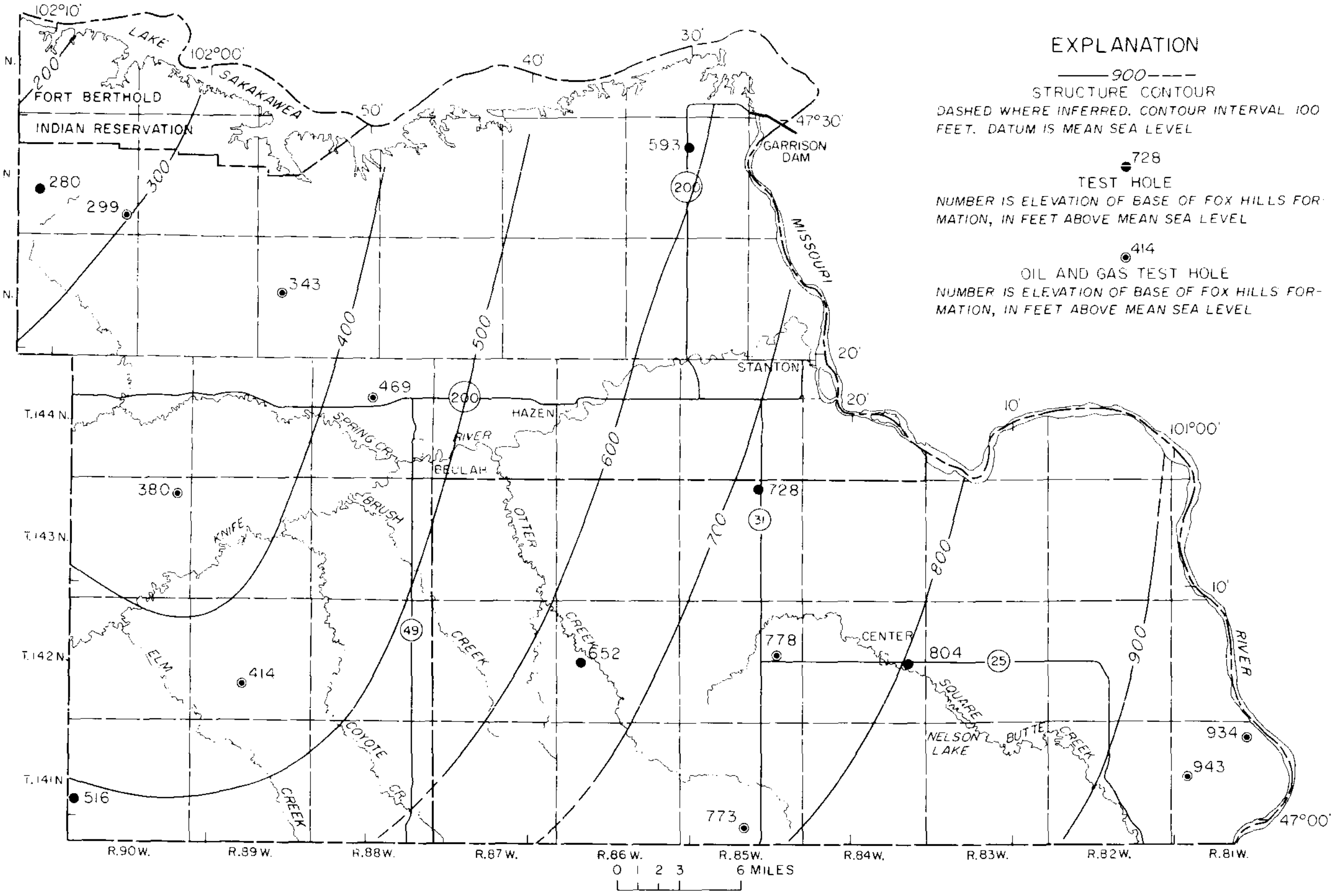


FIGURE 5.--Elevation of base of Fox Hills Formation.

TABLE 2.–Analysis of particle-size distribution curves

Well	Depth (feet)	Median particle diameter (D_{50}) (millimeter)	Effective particle diameter (D_{10}) (millimeter)	Coefficient of uniformity $(\frac{D_{60}}{D_{10}})$	Hydraulic conductivity (From Johnson, 1963, figs. 20-23) (gallons per day per square foot)	(feet per day)
141-90-19CCD	1,028	0.10			35	4.7
141-90-19CCD	1,180	.18			100	13.4
141-90-19CCD	1,190	.14			70	9.4
142-84-24BBA	360-361	.28	0.065	4.6	90	11.2
142-84-24BBA	368-369	.22	.08	2.8	100	13.4
142-84-24BBA	961-962	.25	.07	3.85	100	13.4
142-84-24BBA	964-964.5	.22	.04	6.0	40	5.4
142-86-20BBA	529-530	.30	.05	5.5	60	8.0

1,219 feet in test holes in the study area. The rocks overlie the Colgate Member of the Fox Hills Formation and consist of alternating beds of continental sandstone, siltstone, claystone, and a few thin beds of carbonaceous shale. The siltstone and claystone are generally light olive gray to dark greenish gray. The deposits of the Hell Creek, as shown on plate 2, are 228 to 357 feet thick.

Frye (1969, plate 2) has divided the formation into nine members from eastern Montana to central North Dakota. Although detailed subdivision of the Hell Creek was not practicable for this study, the following members of Frye are probably present: Marmarth, Bacon Creek, Huff, and Pretty Butte. Brown (1952, p. 92) recommended the Hell Creek and Ludlow contact be drawn at the base of the lowest coal bed. This was not practicable in Mercer and Oliver Counties because of insufficient data; therefore, the contact was arbitrarily drawn at the base of some unidentifiable beds that had a high resistivity in several electric logs. Lignite occurred near this arbitrary contact in several test holes, but rarely at greater depths.

Particle-size distribution curves were constructed from three samples cored from beds of fine-grained sandstone in well 141-90-19CCD (table 2). The curves indicate that the beds are largely fine-grained sandstone, siltstone, and claystone. The samples had a median particle diameter that ranged between 0.1 and 0.18 millimeters.

Rocks of Tertiary Age

Cannonball and Ludlow Formations, Undifferentiated

The oldest exposed rocks in the study area were mapped by Johnson and Kunkel (1959) as the Cannonball Formation of Paleocene age. The deposits of this formation are the youngest marine strata known in the northern Great Plains. They crop out beneath low rounded bluffs along the Missouri River and in Square Butte Creek in the southeastern part of Oliver County. Exposures of the Ludlow Formation, which consists of continental claystone, siltstone, sandstone, and lignite, have not been reported in Mercer and Oliver Counties. The rocks of the two formations are 218 to 405 feet thick along section A-A′ (plate 2). It was not practicable to separate the two formations in the subsurface in this report.

Where the Cannonball was mapped by Johnson and Kunkel (1959), it consists of light-olive-gray to dark-greenish-gray claystone, siltstone, and a few thin beds of fine-grained sandstone. The marine Cannonball beds thin westward in the subsurface and interfinger with the Ludlow.

Except for a few thin beds of sandstone at the base, most of the rocks forming this unit are relatively impermeable and for practical purposes are considered non-water-bearing.

Tongue River Formation

The Tongue River Formation consists of continental deposits of Paleocene age. The formation is well exposed in the bluffs above the Missouri River, in the valley of Square Butte Creek, and in the valley of the Knife River east of Hazen. Structural contours drawn on the base of the formation (figure 6) indicate the beds dip to the northwest into the Williston basin. The Tongue River Formation is as much as 500 feet thick along cross section A-A′ (plate 2).

The formation generally consists of interbedded light-olive-gray to dark-greenish-gray claystone, siltstone, fine-grained sandstone, and lignite. However, the lower part of the formation throughout most of Oliver County and in the southwestern corner of Mercer County consists mainly of permeable crossbedded friable sandstone that is interbedded with some siltstone and claystone. The sandstone commonly weathers yellowish brown. These beds of sandstone in the lower part of the formation have been described elsewhere by Pipiringos, Chisholm, and Kepferle (1965, p. A8) and Kume and Hansen (1965, p. 47). Lloyd and Hares (1915, p. 538-539) reported an unconformable contact between the basal sandstone of the Tongue River and Cannonball and Ludlow Formations. An unconformable (?) contact in Oliver County is shown on plate 2.

Ten particle-size distribution curves (Croft, 1970, p. 244-268) were constructed from three cores and from cuttings from numerous beds of sandstone in the lower part of the Tongue River Formation. The cores are from coarse beds of sandstone. Selected curves are summarized in figure 7, which shows that the median particle diameter of the sandstone samples ranges from very fine to medium grained. The median particle diameter of the core sample from well 142-86-20BBA (table 2) was 0.3 millimeter and the effective diameter was 0.05 millimeter. The coefficient of the uniformity was 5.5, indicating the sample was poorly sorted. The median particle diameter of the samples from well 142-84-24BBA was 0.22 millimeter from a depth of 368 to 369 feet and 0.28 millimeter from 360 to 361 feet. The effective particle diameter was 0.08 and 0.065 millimeter. They had coefficients of uniformity of 2.8 and 4.6, respectively, indicating the sandstone was moderately to poorly sorted.

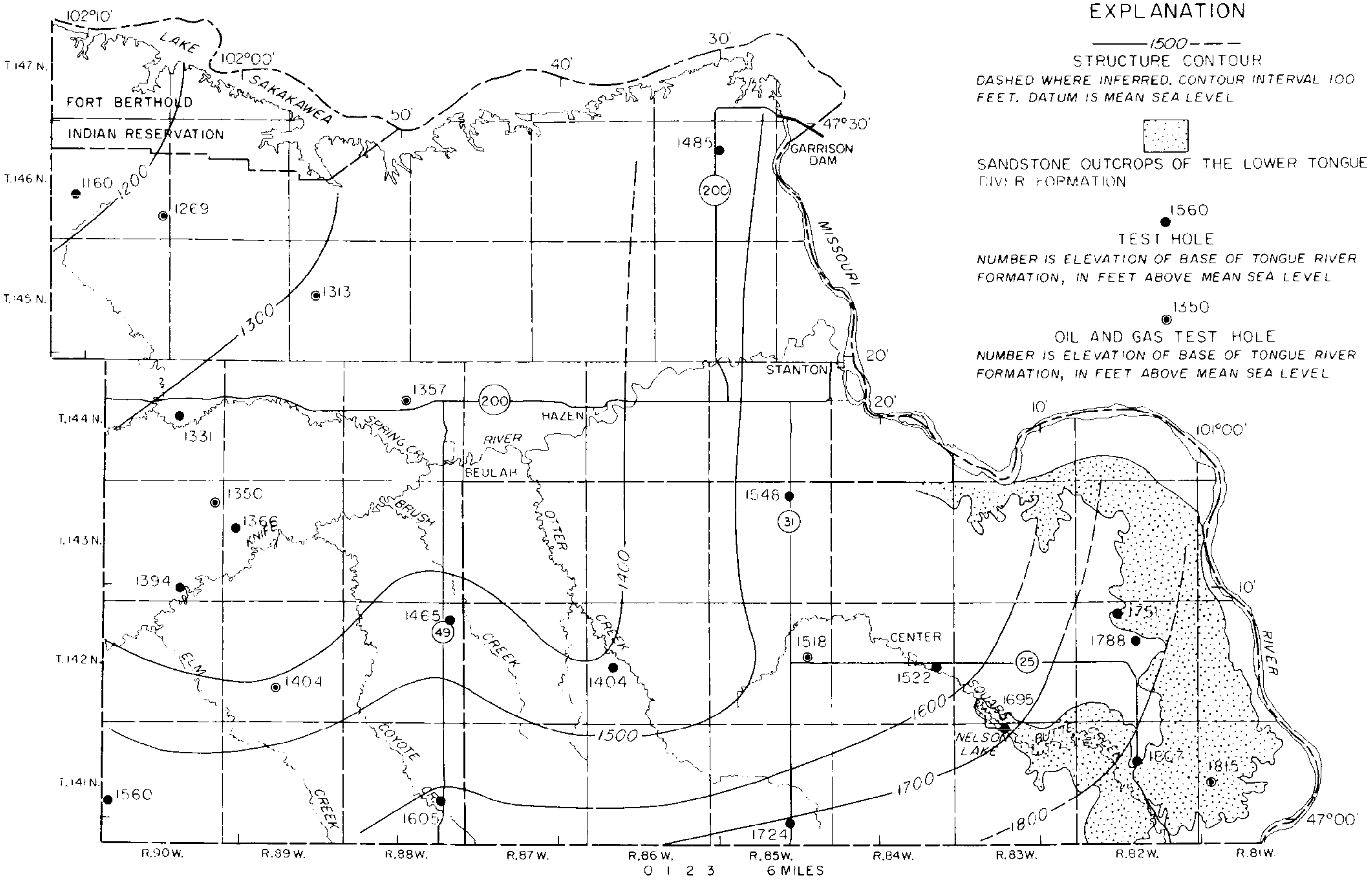


FIGURE 6.--Elevation of base of Tongue River Formation.

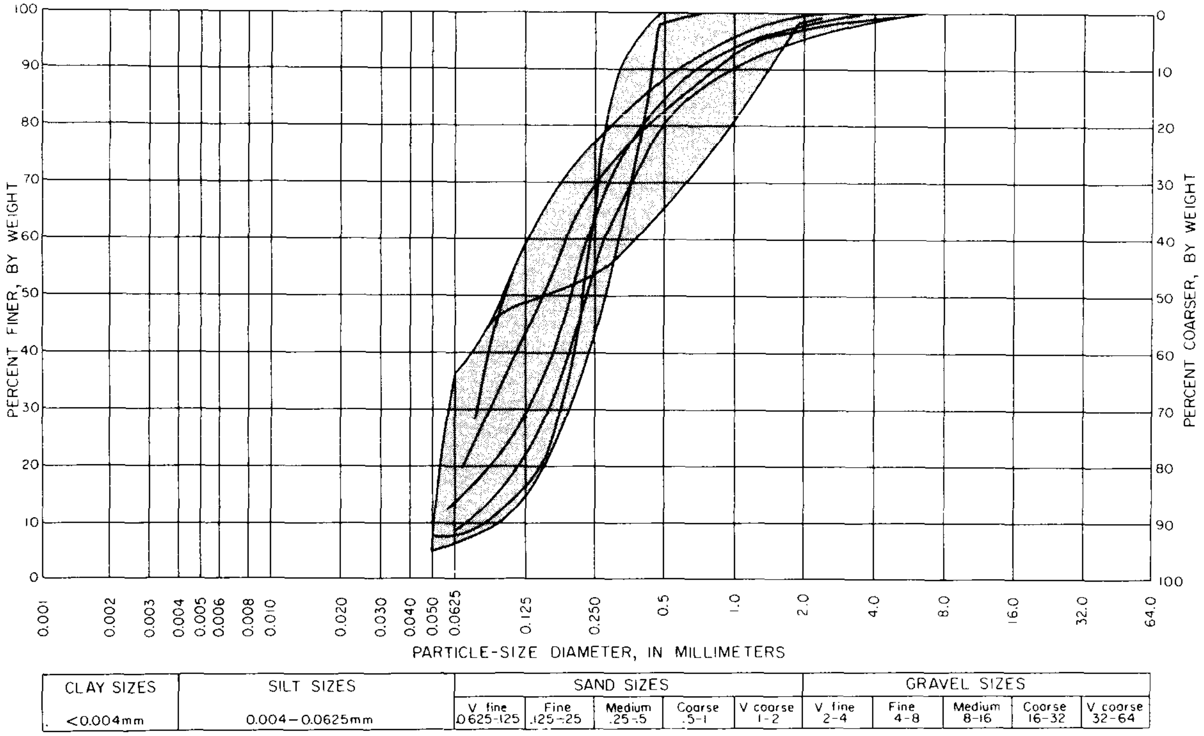


FIGURE 7.–Selected particle-size distribution curves of sandstone from the Tongue River Formation.

Sentinel Butte Formation

The Sentinel Butte Formation is a continental deposit of Paleocene age. The formation underlies much of Mercer County and the western part of Oliver County. The beds consist of bentonitic claystone, siltstone, sandstone, and lignite. The sandstone is thin bedded and is generally fine grained and silty. The more abundant fine-grained rocks, which are light olive gray to dark greenish gray, generally give the formation a darker appearance than the underlying Tongue River. The formation ranges from 0 to 510 feet in thickness (plate 2).

Although many farm and domestic wells obtain adequate water supplies from sandstone and lignite within the formation, no major aquifers were found in the Sentinel Butte.

Golden Valley Formation

The Golden Valley Formation of Eocene age caps many isolated buttes and hills in the western parts of Mercer and Oliver Counties. The rocks consist of light-olive-gray silty claystone and resistant fine-grained cross-bedded in Oliver County is shown on plate 2. sandy shale that weathers to a dark yellowish orange. Because of its topographic position, the formation is not a significant source of water in the study area.

Unconsolidated Deposits of Quaternary Age

A mantle of glacial drift deposited during the Pleistocene period overlies the Tertiary rocks of Mercer and Oliver Counties. The drift in the uplands consists of till composed of unsorted silt, clay, sand, and gravel. The till rarely exceeds 100 feet in thickness and yields little or no water. The drift in the stream valleys consists mainly of outwash composed of sand and gravel; however, thick beds of till are locally interbedded with the outwash. Much of the outwash sand and gravel was derived from granitic rocks.

Alluvium of Pleistocene (?) and Holocene ages overlies the deposits of drift in the stream valleys. Rarely is the alluvium more than 50 feet thick. Much of it consists of dark-gray sandy silt and clay eroded from the stratigraphically underlying fine-grained Sentinel Butte and Tongue River Formations. In the Missouri and Knife River valleys, part of Square Butte Creek valley, and locally in other drainages, part of the alluvium was eroded from coarse-grained arkosic glaciofluvial material. Therefore, some of the aquifers are composed of glaciofluvial material in the lower part and of alluvium in the upper part. Where the alluvium consists of reworked glaciofluvial material, it is difficult to distinguish from drift. A maximum thickness of 295 feet of alluvium and glacial-drift deposits was penetrated in well 144-88-2AAB.

MAJOR AQUIFERS

The availability of water for domestic, industrial, and irrigation supplies from principal aquifers in Mercer and Oliver Counties is summarized on plate 1. Information from test holes and private wells was utilized to determine the aquifer extent and productivity.

Important artesian aquifers occur in the consolidated rocks of the Fox Hills, Hell Creek, and Tongue River Formations that underlie the entire two-county area. Wells tapping these aquifers will generally yield less than 150 gpm (gallons per minute), and the water probably is not suitable for irrigation because of higher sodium content.

The largest yields and best quality water (figure 8) are obtainable from the relatively undeveloped glacial-drift and alluvial aquifers. These are generally 1 to 5 miles in width, have a maximum thickness of about 250 feet, and store about 2,640,000 acre-feet of ground water. In places the glacial-drift and alluvial aquifers will yield more than 500 gpm. About 1,215,000 acre-feet of water from these aquifers would be suitable for irrigation use.

Fox Hills and Basal Hell Creek Aquifer

Location and Development

Extensive beds of sandstone in the upper part of the Fox Hills and the lower part of the Hell Creek Formations form a major aquifer that underlies all of Mercer and Oliver Counties. These beds include the Colgate Member of the Fox Hills Formation and the beds that probably are the Little Beaver and Marmarth Members of the Hell Creek (Frye, 1969). The sandstone, which is fine to medium grained and has a low hydraulic conductivity, is generally interbedded with some siltstone and claystone. The aquifer is 150 to 370 feet thick. In some areas sandstone that occurs below the Colgate Member also forms part of the aquifer.

Numerous flowing wells drilled as much as 1,515 feet deep tap the aquifer for municipal, domestic, and livestock supplies. The flowing wells generally are restricted to stream valleys. Most are constructed with perforated 2-inch steel casing and are fitted with valves that control the flow of water. Although well owners generally allow only 5 to 10 gpm to flow, most wells were observed to flow 10 to 25 gpm when the valves were fully open. A few wells were observed to flow about 50 gpm.

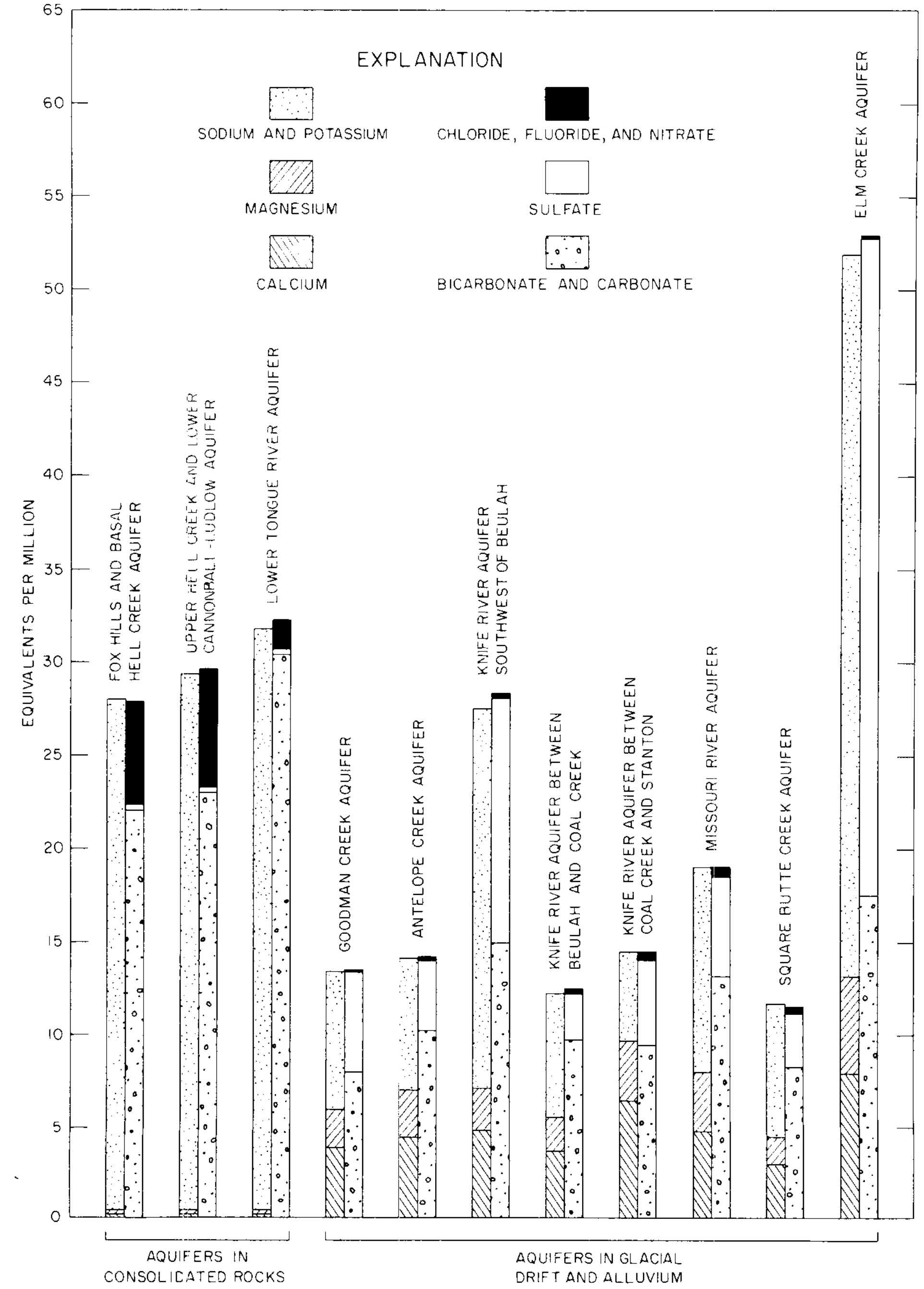


FIGURE 8.--Average values of major constituents in water in the principal aquifers.

Ground-Water Movement

A map of the potentiometric surface of the artesian aquifer in 1968 (figure 9) indicates that ground water in the aquifer generally moves from west to east. The hydraulic gradient ranges from about 3.5 feet per mile in the northern part of the area near Lake Sakakawea to 40 feet per mile in the southwestern corner of the area. However, in southwestern Mercer County, ground water is moving into a cone of depression centered beneath the Knife River, about 6 miles southwest of Beulah. The cone is caused by an estimated withdrawal of 0.5 mgd (million gallons per day) flowing from wells tapping the aquifer. A few of the water-level measurements used in construction of the map were made at a date later than 1968.

Hydrographs (figure 10) of two wells, 142-90-26ABB and 142-90-36AD, located within the cone and tapping the aquifer, show a general year-to-year decline in water levels during the period of record from 1967 to 1970. Well 142-90-36AD, which was observed flowing in 1968, had ceased to flow when visited in 1969. The rather large decline in the water level in the well may be due to an attempt to perforate the casing at a lower level after the well ceased flowing so water would flow into a tank located in a nearby draw. Well 142-90-26ABB had a head of +9.8 feet (lsd) on December 4, 1970, suggesting that water levels probably declined only 1 or 2 feet in the area during 1970.

Aquifer Constants

Croft and Wesolowski (1970), using the method described in a preceding section on obtaining hydraulic properties of aquifers in consolidated rocks, made 11 flow tests and 38 recovery tests of wells penetrating the Fox Hills and Hell Creek Formations. The values obtained for transmissivity (Croft and Wesolowski, 1970, table 1) ranged from 13 to 3,100 gpd (gallons per day) per foot (1.7 to 415 square feet per day) and averaged 510 gpd per foot (68 square feet per day). The values for hydraulic conductivity were obtained by dividing the thicknesses of the aquifer, obtained from drillers or electric logs, into the values for transmissivity. The hydraulic conductivity obtained by this method ranged from < 1 to 120 gpd per square foot (< 0.134 to 16 feet per day) and averaged 16 gpd per square foot (2.1 feet per day). A chart compiled by Johnson (1963, figure 22) suggests that the two core samples from well 142-84-24BBA (table 2) have hydraulic conductivities of 40 to 100 gpd per square foot (5.4 to 13.4 feet per

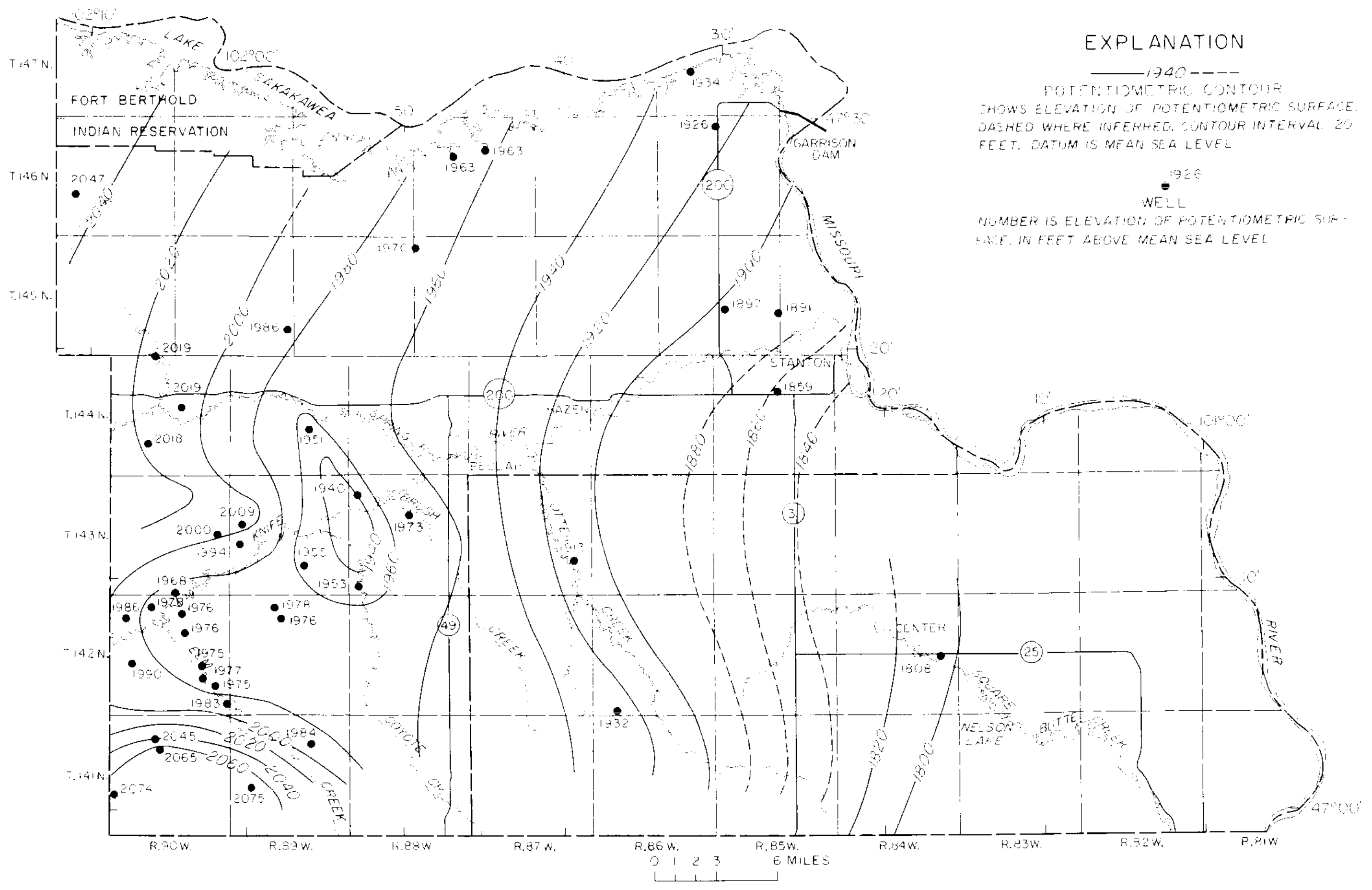


FIGURE 9.--Potentiometric surface of the Fox Hills and basal Hell Creek aquifer, 1968.

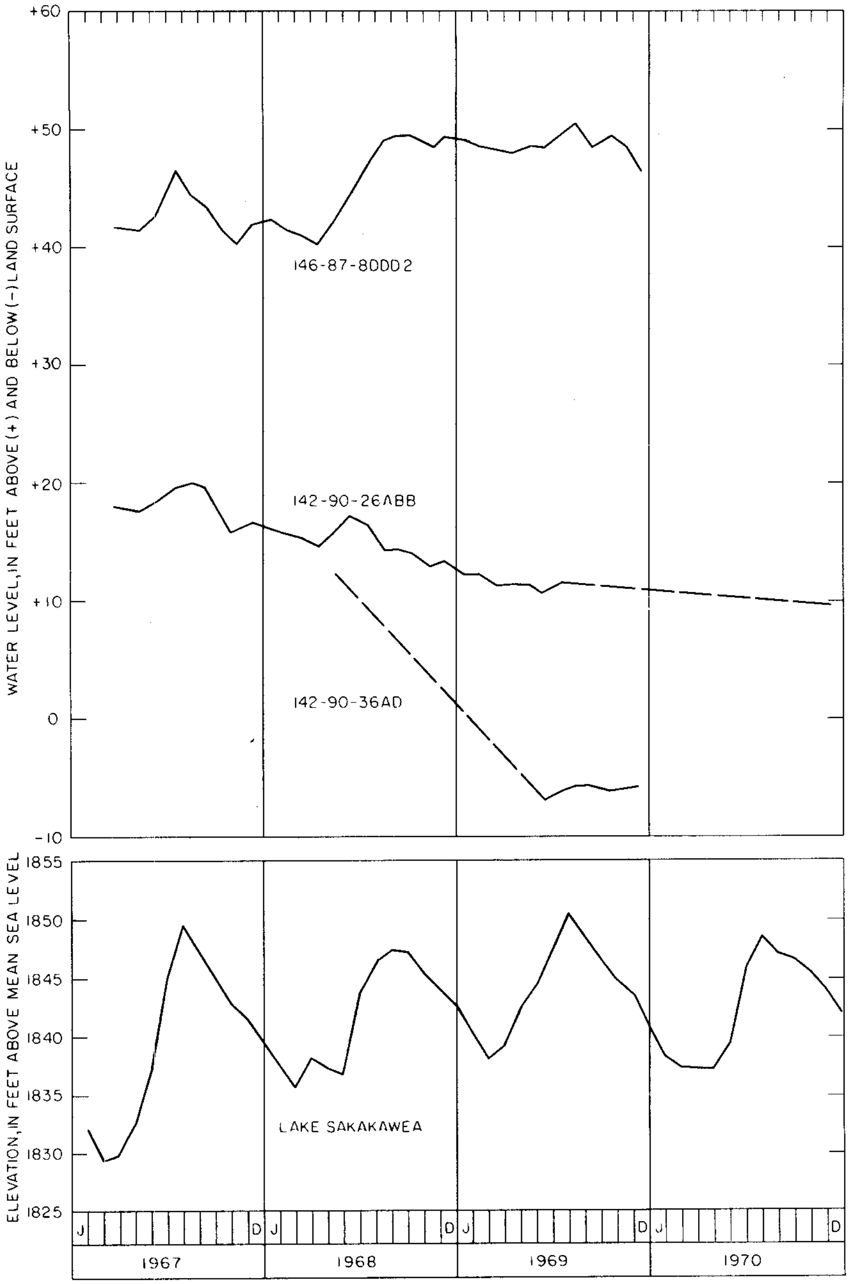


FIGURE 10.--Water-level fluctuations in the Fox Hills and basal Hell Creek aquifer and Lake Sakakawea.

day), assuming a porosity of 40 percent. The indicated hydraulic conductivities (Johnson, 1963, figure 20) for the samples from the Hell Creek in well 141-90-19CCD ranged from 35 to 100 gpd per square foot (4.7 to 13.4 feet per day).

Information obtained during the flow and recovery tests indicated that the wells and specific capacities that ranged from 0.1 to 0.6 gpm per foot and averaged 0.3 gpm per foot. The data from the flow tests suggested that values for storage coefficients of the aquifer ranged between 0.0001 to 0.00001.

The transmissivity of the aquifer southwest of Beulah was determined by ground-water flow analysis of the pumping depression, and was found to be 1,400 gpd per foot (187 square feet per day; Croft and Wesolowski, 1970, p. B194). Electric logs of oil and gas test holes in the area of flow analysis indicate that the several beds of sandstone in the Fox Hills and lower part of the Hell Creek have an average aggregate thickness of 90 feet. The aquifer, therefore, would have an average hydraulic conductivity of about $(\frac{1,400}{90})$ 16 gpd per square foot (2.1 feet per day), which corrobrates the value obtained from the flow and recovery tests.

A transmissivity map (figure 11) shows that the transmissivity of the aquifer ranges from less than 1,000 gpd per foot (133.7 square feet per day) in the southwestern corner of the study area to 5,950 gpd per foot (795.6 square feet per day) in the south-central part of the area. The map was constructed from values calculated from resistivity curves of electric logs of oil and gas test holes. The method is described by Alger (1966) and by Croft (1971). The values obtained from electric logs in the area of the pumping depression approximate the value of 1,400 gpd per foot (187 square feet per day) obtained from the ground-water flow analysis. The sandstone that forms the aquifer in the northern and eastern parts of the area commonly is better sorted and thicker than the sandstone in the southwestern corner of the area. Most of the transmissivity values obtained from the flow and recovery tests reported by Croft and Wesolowski (1970) are less than the values obtained from the electric logs because the wells do not fully penetrate the aquifer.

At any given location on the transmissivity map (figure 11), the yield in gallons per minute of an efficient, fully penetrating well with 50 feet of drawdown after 24 hours of pumping may be approximated by dividing the transmissivity by 40. Wells should yield 25 to 150 gpm.

Hydrographs of two flowing wells and the gage height of Lake Sakakawea (figure 10) show that artesian water levels and the lake level are roughly related. Changes in load on the aquifer cause compensating changes in water pressure and changes in stress in the aquifer skeleton.

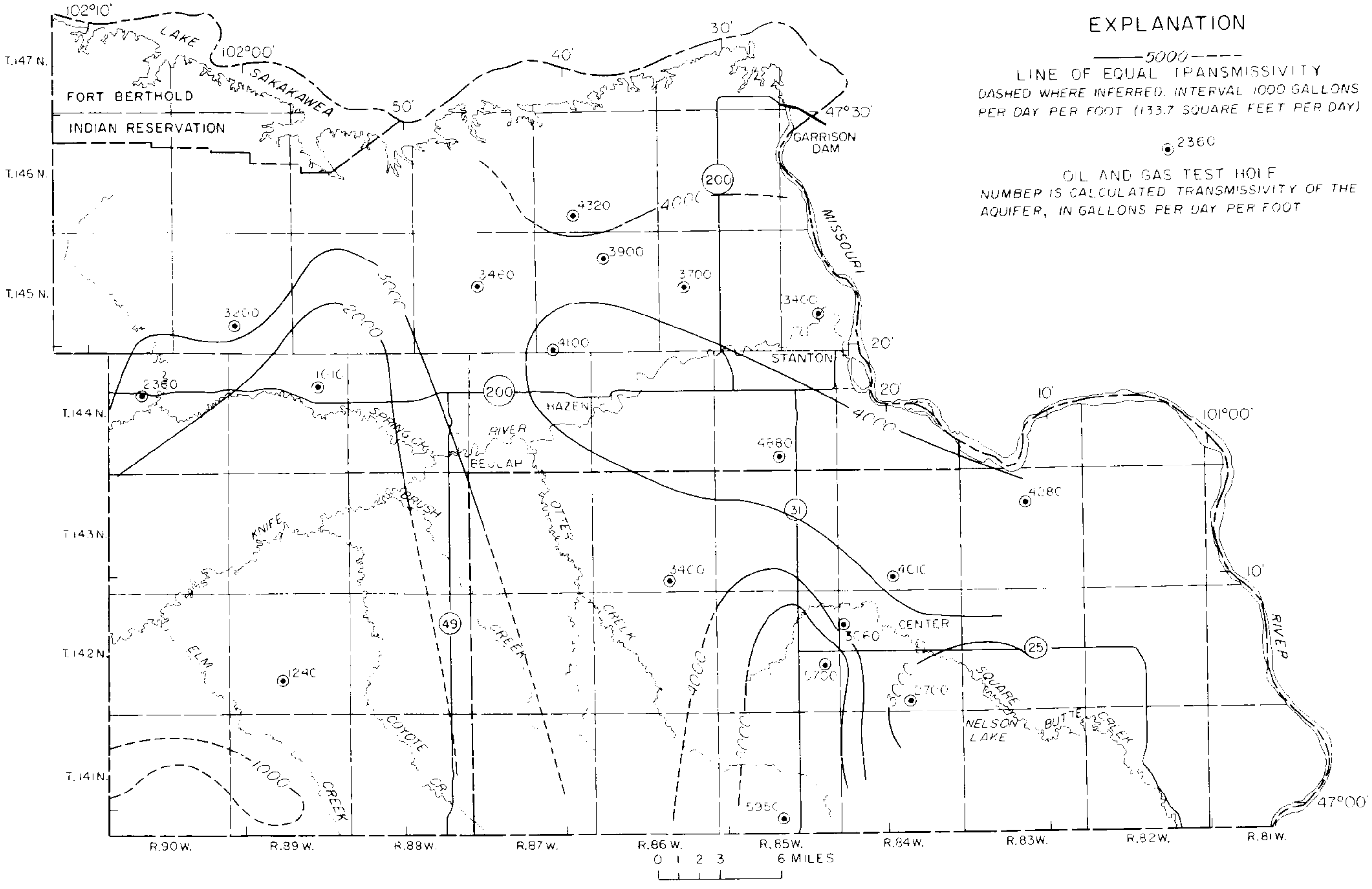


FIGURE 11.--Transmissivity of the Fox Hills and basal Hell Creek aquifer.

A better correlation between the lake level and the artesian water levels probably would exist if variation in flow from wells in the area had not occurred. Well 146-87-8DDD2 is several hundred yards from the lake. Well 142-90-26ABB, which is within the pumping depression in southwestern Mercer County, is about 30 miles from the reservoir. In general, the water levels rose in the two wells when the lake level rose, due to the increasing load on the aquifer. The water levels in these wells generally declined when the lake level fell. This correlation is shown best in 1967 and 1968.

The storage coefficient is related to barometric and tidal efficiency. Jacob (1940) showed mathematically that the sum of the barometric efficiency and tidal efficiency must equal unity (B.E.+T.E. = 1). He showed further that the storage coefficient is related to the barometric efficiency as follows:

$$S = (\gamma_o \theta m \beta) \left[\frac{1}{\text{B.E.}}\right] \qquad (5)$$

where

S is the storage coefficient;
γ_o is the specific weight of water, 0.0361 pound per cubic inch at the prevailing aquifer temperature;
θ is the porosity of the aquifer, expressed as a decimal fraction;
m is the thickness of the aquifer, in inches; and
β is the bulk modulus of compression of water, 0.0000033 square inch per pound.

The value for the storage coefficient of the Fox Hills and basal Hell Creek aquifer was caluclated with formula 5 using the following data. A rise in the lake level in 1967 of 20 feet produced a rise in the water level of about 5 feet in well 146-87-8DDD2 (figure 10). The well hydrograph and that of the lake level parallel closely during this period. The indicated tidal efficiency is (5/20x100) 25 percent. The drillers log of well 146-87-8DDD2 indicates the aquifer at the well site is 65 feet thick. A value of 0.75 (1-0.25) was used for barometric efficiency and 0.40 was used for the aquifer porosity. The storage coefficient, which approximates the values obtained by Croft and Wesolowski (1970), is:

$$S = (0.0361)\,(0.40)\,(65\text{x}12)\,(0.0000033)\,(1.34)$$
$$S = 0.00005$$

The small value for storage coefficient indicates that small withdrawals from the aquifer will cause large declines in water levels. Therefore, discharge from flowing wells should be restricted to 1 or 2 gpm of flow to prolong natural discharge. In most instances this amount of flow is sufficient to water large herds of cattle and to prevent freezing during the winter.

Drawdown of the Potentiometric Surface

Calculations suggest that the decline of the potentiometric surface of the aquifer (figure 12) from 1963 to 1968 was as much as 42 feet in the area southwest of Beulah, and about 10 feet near Hazen. The drawdown at the nodes on figure 12 was determined with the use of special drawdown scales. The use and construction of drawdown scales for predicting water-level declines for periods of heavy withdrawal are described by Conover and Reeder (1963, p. C38-C44). Values for the transmissivity of the aquifer at each well were obtained from figure 11 and a value of 0.001 was used for the storage coefficient. The calculations did not consider leakage into the overlying aquifer nor recharge into the pumping depression from adjacent areas.

Observation well 142-90-26ABB (figure 10) reportedly was the first well in the area to tap the aquifer. Figure 12 indicates that the drawdown in well 142-90-26ABB from 1963 to 1968 should be about 34 feet. The hydrograph (figure 10) suggests a drawdown of 34 feet is reasonable, if it is projected backwards in time, and slightly concave upwards for the unrecorded period from 1963 to 1967. Therefore, the total calculated drawdown is reasonable although several other factors were not considered in the calculations.

Water Quality

Thirty-one samples from 26 wells indicated that the water was a sodium bicarbonate type (figure 8) and generally contained from 1,230 to 1,990 ppm total dissolved solids. Chloride constituted 21 percent of the anions and ranged from 29 to 561 ppm. Sulfate content was low, possibly due to sulfate reduction by bacteria (Hem, 1959, p. 233-224). The water samples contained 0.7 to 6.0 ppm fluoride, and 1.7 to 3.5 ppm boron. The water was generally soft, and the concentrations of iron ranged from 0.04 to 14 ppm. Water from flowing wells generally had the lowest iron content. The water is suitable for livestock, most domestic purposes, and some industrial purposes The water is not recommended for irrigation because the

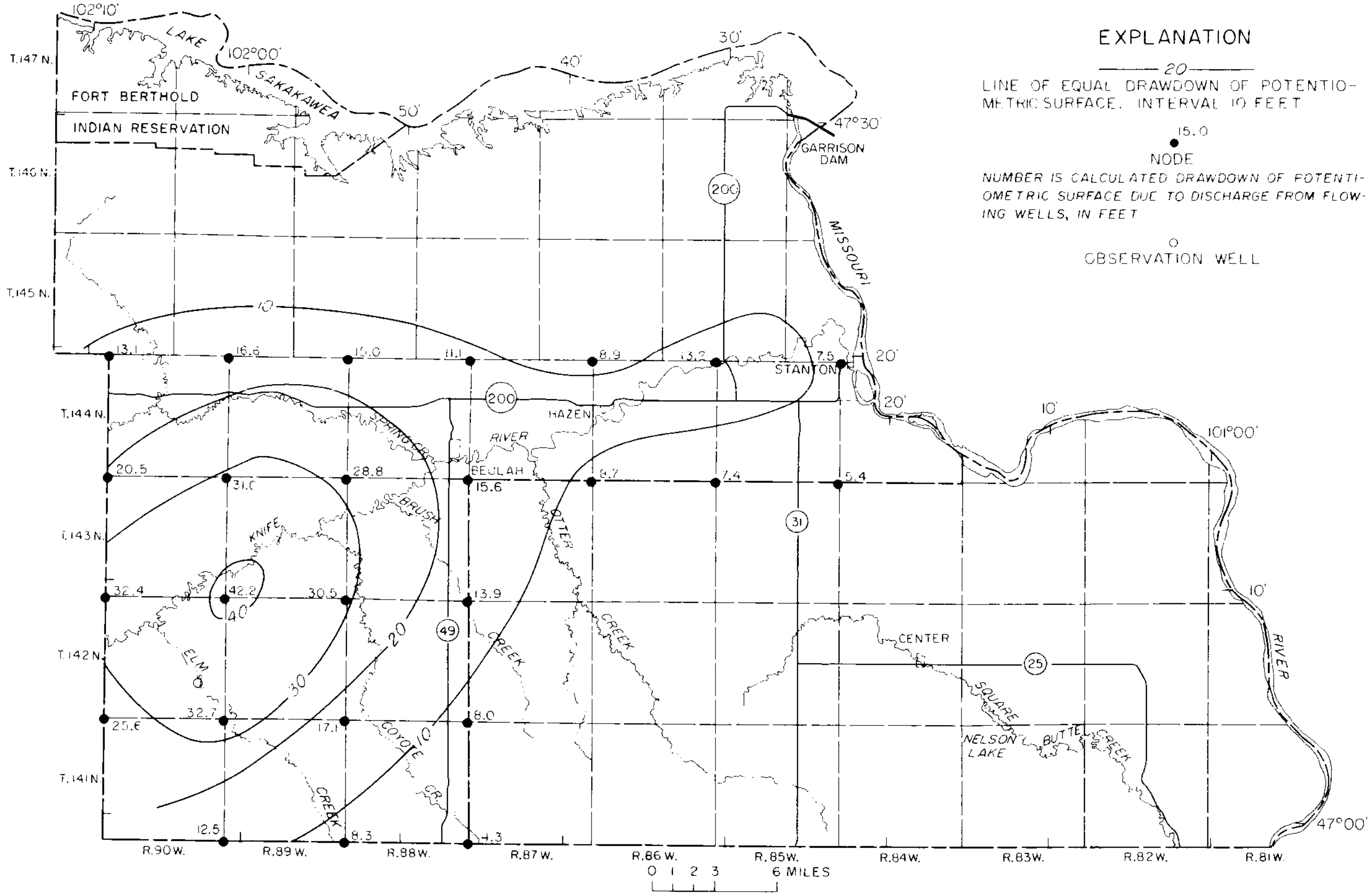


FIGURE 12.--Drawdown of the potentiometric surface of the Fox Hills and basal Hell Creek aquifer, 1963 to 1968.

sodium-adsorption ratios of most samples were generally higher than 70.

A water sample collected from well 144-86-11DAA for radiometric dating had an age of 16,900 years before present (B.P.), according to S. W. West, U.S. Geological Survey (written commun., January 1969). The well is 1,000 feet in depth. The age indicates that a large period of time is needed for natural recharge to reach the aquifer.

Upper Hell Creek and Lower Cannonball-Ludlow Aquifer

Location and Development

The upper Hell Creek and Lower Cannonball-Ludlow aquifer, which is 70 to 150 feet thick along section A-A' (plate 2), underlies all of Mercer and Oliver Counties. It consists of beds of fine- to medium-grained sandstone in the upper part of the Hell Creek Formation and beds of fine-grained sandstone at the base of the Cannonball and Ludlow Formations, undifferentiated (plate 2). The sandstone is interbedded with siltstone and claystone. That part of the aquifer that is in the Hell Creek Formation probably occurs within the Huff and Pretty Butte Members of Frye (1969). Thick beds of siltstone and claystone forming the middle and upper parts of the Cannonball and Ludlow Formations, undifferentiated, overlie the aquifer. Beds of siltstone and claystone, which probably represent the Bacon Creek Member of the Hell Creek Formation (Frye, 1969), separate the aquifer from the Fox Hills and basal Hell Creek aquifer.

Flowing wells, ranging in depth from 320 feet in the eastern part of the area to about 800 feet in the central part of the area tap the aquifer for domestic and livestock supplies. The flowing wells are located in stream valleys. Generally they are constructed with perforated 2-inch steel casing and are fitted with valves that control the flow of water. Maximum observed flows were about 25 gpm when the valves were fully opened.

Transmissivity

A transmissivity map (figure 13) of the aquifer in the northeastern part of the area shows that the transmissivity ranges from 180 to 4,200 gpd per foot (24.2 to 563 square feet per day). The values for transmissivity were calculated from resistivity curves of electric logs of oil and gas test holes. The yield in gallons per minute of an efficient, fully penetrating well with 50 feet of drawdown after 24 hours of pumping may be approximated by dividing the transmissivity by 40, at

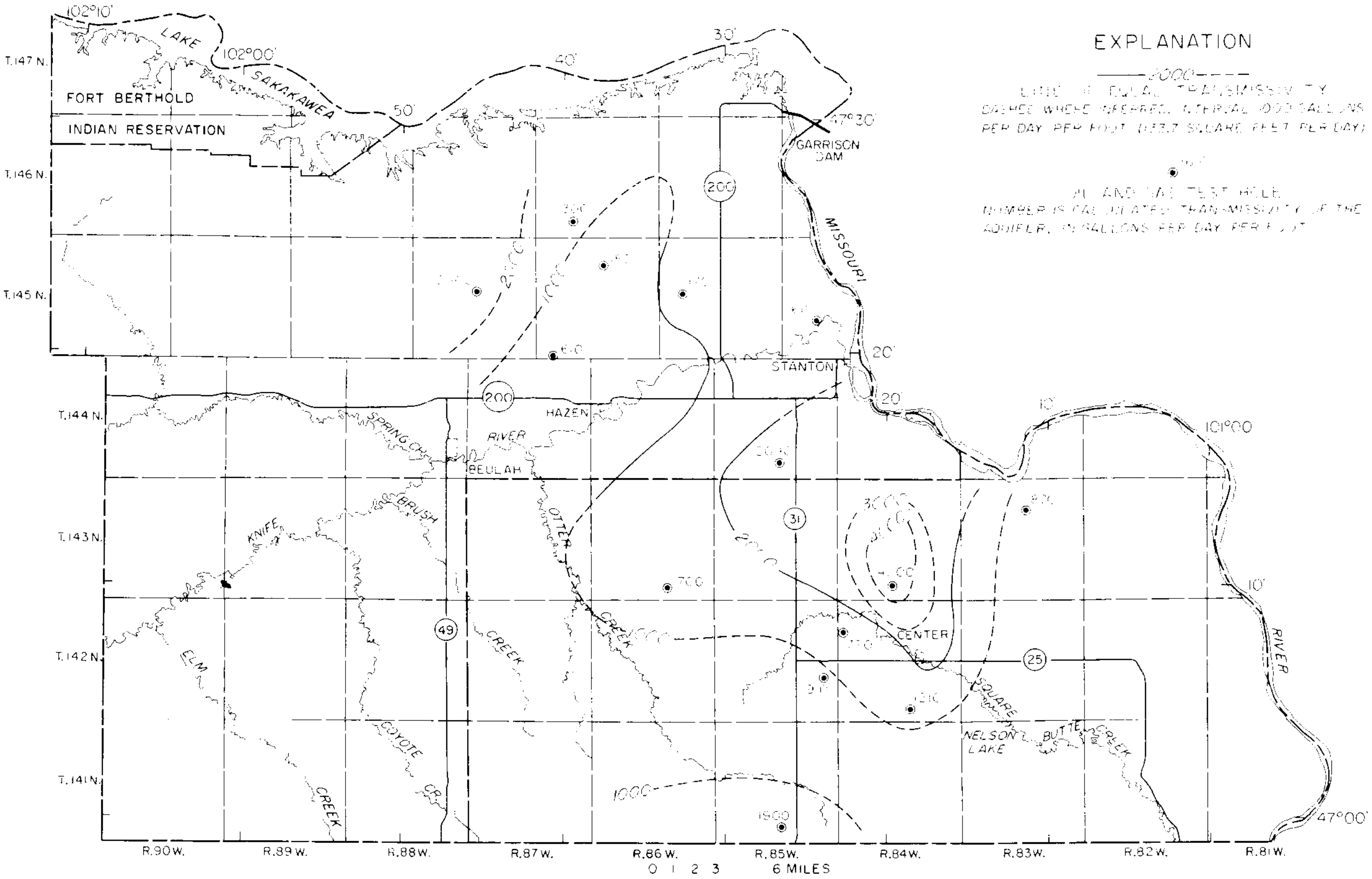


FIGURE 13.--Transmissivty of the upper Hell Creek and lower Cannonball-Ludlow aquifer.

any given location on the map. Wells tapping the aquifer should yield 5 to 100 gpm.

Ground-Water Movement

A map of the potentiometric surface of the aquifer (figure 14) in 1968 was constructed for Mercer and Oliver Counties. The contours indicate that ground water is moving from west to east. At Hazen the artesian head in the upper Hell Creek and lower Cannonball-Ludlow aquifer is about 100 feet lower than the head in the Fox Hills and basal Hell Creek aquifer (figures 9 and 14). This difference in head indicates that water is moving upward from the Fox Hills and basal Hell Creek aquifer to the upper Hell Creek and lower Cannonball-Ludlow aquifer.

Figure 15 shows the drawdown of the potentiometric surface of the upper Hell Creek and lower Cannonball-Ludlow aquifer from 1963 to 1968 in the northeastern part of the area. The decline in head is due mainly to discharge from flowing wells. At Stanton the decline was about 20 feet. The drawdown was calculated with special drawdown scales, using the transmissivity at each well site as shown by figure 13 and a storage coefficient of 0.0001.

Water Quality

Ten water samples were collected from the upper Hell Creek and lower Cannonball-Ludlow aquifer. The water was a sodium bicarbonate type (figure 8), and contained about 1,510 to 1,890 ppm total dissolved solids. Chloride constituted 22 percent of the anions and concentrations ranged from 119 to 381 ppm. Sulfate constituted less than 1 percent of the anions. Fluoride concentrations ranged from 0.8 to 2.2 ppm, and boron concentrations ranged from 1.3 to 2.4 ppm. The water generally is soft and is suitable for livestock and domestic purposes, but probably is not suitable for irrigation because of very high sodium-adsorption ratios.

Lower Tongue River Aquifer

Location and Development

The aquifer in the lower part of the Tongue River Formation, which underlies most of Oliver County and the southwest corner of Mercer County (plate 1), is fine- to medium-grained sandstone. The aquifer is less than 150 feet thick along section A-A′ (plate 2). Beds of siltstone

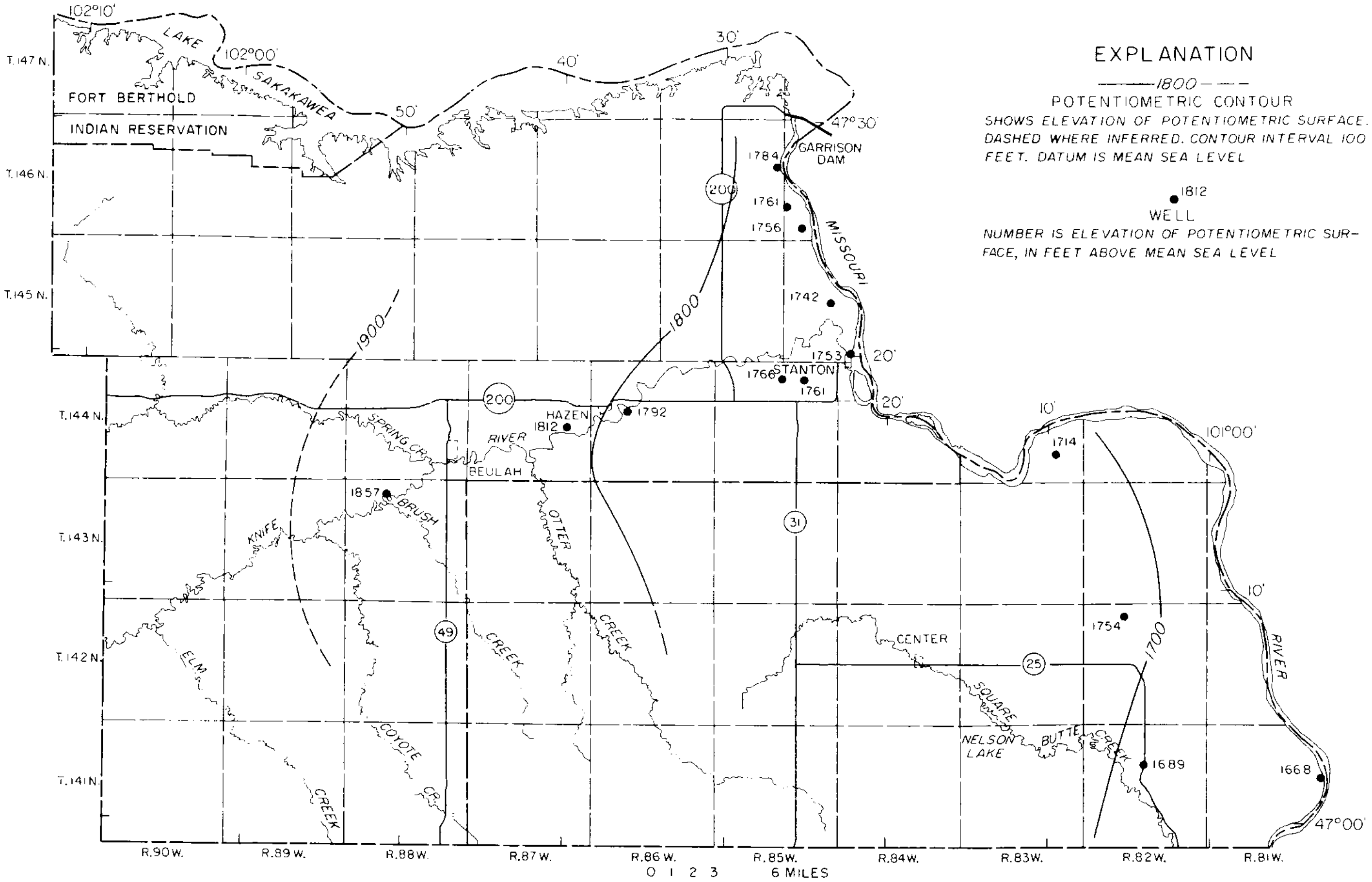


FIGURE 14.--Potentiometric surface of the upper Hell Creek and lower Cannonball-Ludlow aquifer, 1968.

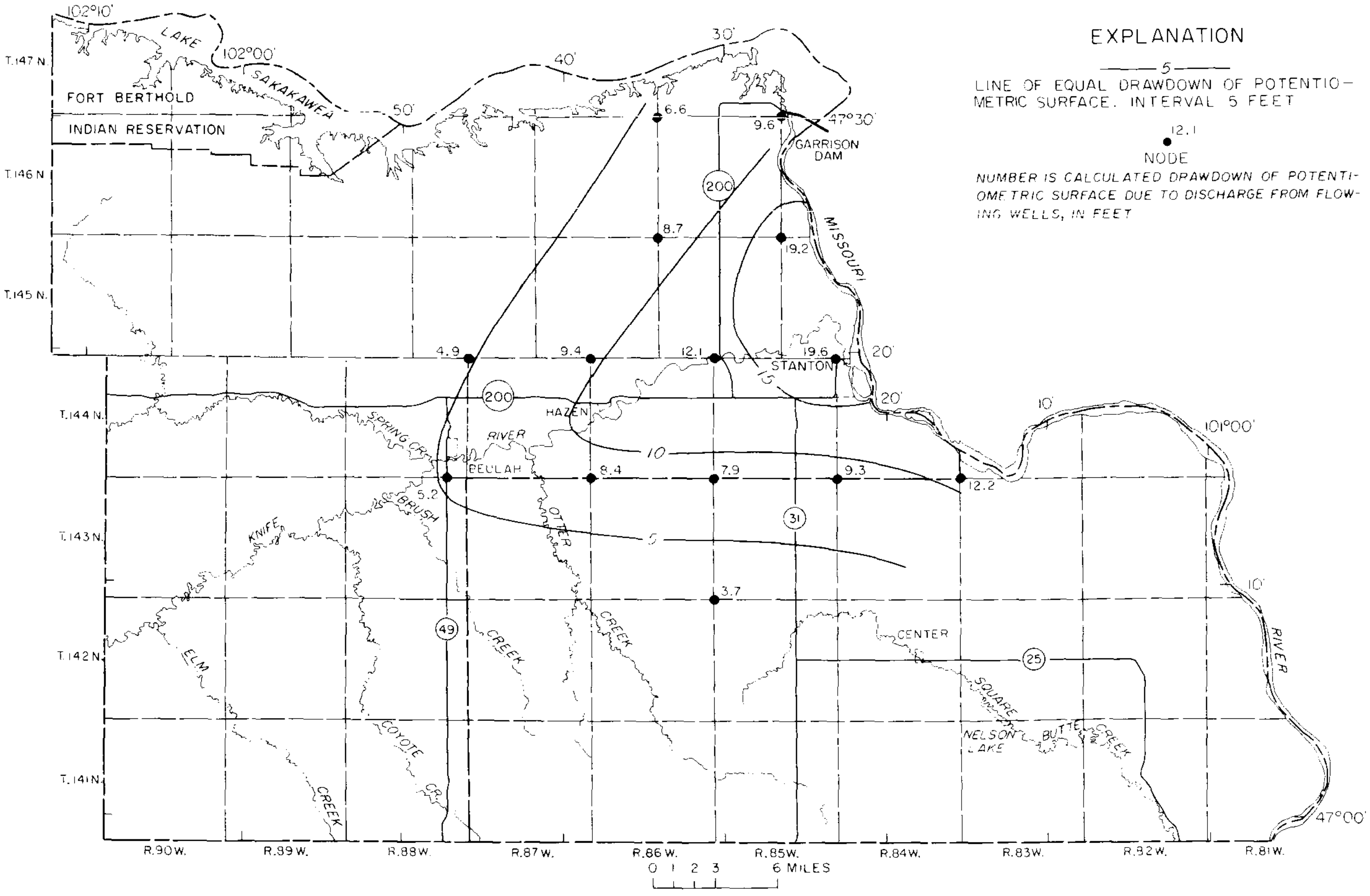


FIGURE 15.--Drawdown of the potentiometric surface of the upper Hell Creek and lower Cannonball-Ludlow aquifer, 1963 to 1968.

and claystone in the upper part of the Cannoball and Ludlow Formations undifferentiated separate the lower Tongue River aquifer from the upper Hell Creek and lower Cannonball-Ludlow aquifer.

The sandstone forming the aquifer has a low hydraulic conductivity and is interbedded with siltstone and claystone. The indicated hydraulic conductivity (table 2) for the three cores from wells 142-86-20BBA and 142-84-24BBA ranged from 60 to 100 gpd per square foot (8 to 13.4 feet per day). Wells tapping the sandstone should yield 5 to 50 gpm. In the southern part of Mercer County, in areas adjacent to Highway 49, the sandstone is very silty and wells probably would yield less than 5 gpm.

Only a few livestock and domestic wells tap the aquifer. Several flowing wells 280 to 680 feet in depth have been drilled in the valleys of Elm Creek and the Knife River.

Ground-Water Movement

A map of the potentiometric surface of the aquifer (figure 16) was constructed from water-level measurements made in 1968 in test holes drilled in Mercer and Oliver Counties. The contours indicate that ground water in the aquifer moves in a northerly to northeasterly direction under a hydraulic gradient of about 10 feet per mile. In much of Oliver County the head in this aquifer is more than 100 feet higher than the head in the upper Hell Creek and lower Cannonball-Ludlow aquifer. This difference in head indicates that water is moving downward from the lower Tongue River aquifer to the upper Hell Creek and lower Cannonball-Ludlow aquifer. Water is discharging where the aquifer crops out (figure 6) in bluffs along the Missouri River and Square Butte Creek. Many draws in the outcrop area contain springs and are lined with aspen, cottonwood, and other phreatic plants.

Water Quality

Seven water samples collected from the lower Tongue River aquifer indicated that the water was a sodium bicarbonate type (figure 8). The concentration of chloride, about 5 percent of the anions, was lower than the concentration of chloride in the Fox Hills and basal Hell Creek aquifer and in the upper Hell Creek aquifer. Water from the aquifer in the southwestern corner of Mercer County (plate 1) contained 1,810 to 1,930 ppm total dissolved solids, and water from the aquifer beneath Oliver County contained 1,440 to 1,700 ppm total dissolved solids. Samples generally contained 17 to 96 ppm chloride, 0.6 to 0.93 ppm boron, 0.9 to 1.8 ppm fluoride, and 0 to 6.8 ppm iron. The water is

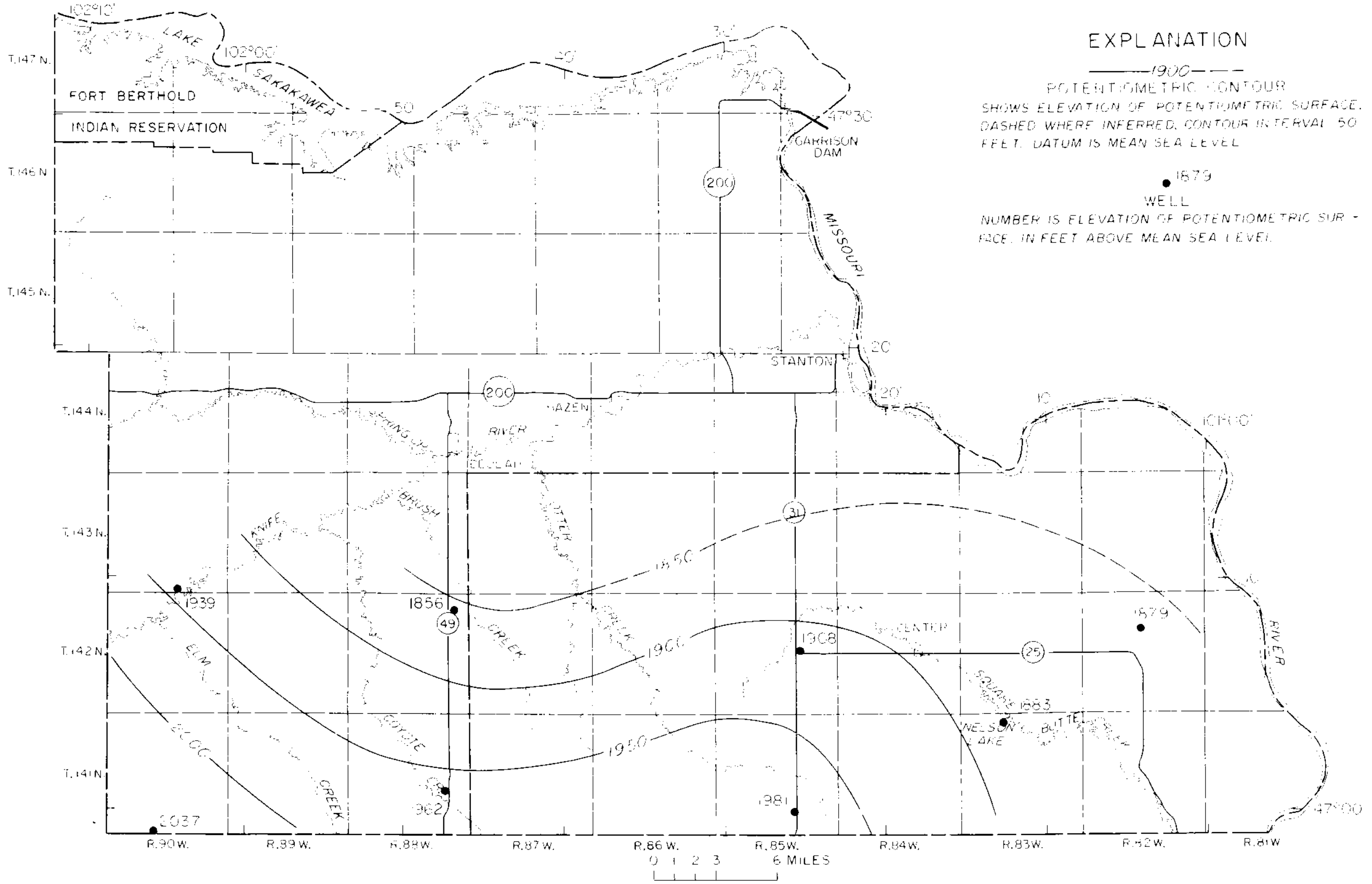


FIGURE 16.--Potentiometric surface of the lower Tongue River aquifer, 1968.

suitable for livestock and domestic use, but is not recommended for irrigation because of a very high sodium-absorption ratio.

Undifferentiated Lignite Aquifers in the Tongue River and Sentinel Butte Formations

Many livestock and domestic wells in the rural areas tap fractures and joints in undifferentiated beds of lignite for water supplies. The yield from most of these wells is probably less than 10 gpm, but is sufficient for the intended use.

Water-Level Fluctuations

The hydrograph of well 141-85-18DDA1 (figure 17), 25 feet deep, records about 2½ years of fluctuations of the water level in a bed of lignite southwest of Hannover. The water level in the well rose from October 1967 to April 1968 and from August 1968 to April 1969. It is generally highest in April because of recharge from snowmelt. The water level declined from April 1968 to August 1968 and from April 1969 to September 1969 because of evapotranspiration and discharge by springs. Well 145-86-11CDD, which is 100 feet deep, taps a bed of lignite north of Hazen. Although the well was pumped intermittently during the period of record, the hydrograph roughly parrallels the record for well 141-85-18DDA1.

Water Quality

Water from the lignite aquifers is highly variable in chemical quality. Conductivity measurements of several hundred water samples generally ranged from 500 to 7,000 micromhos per centimeter. Water samples from wells 145-86-11CDD and 146-88-10DDC were soft and very hard, respectively, and contained 1,050 and 1,810 ppm total dissolved solids. The samples contained 3.6 and 3.3 ppm iron and 0.2 and 0.4 ppm fluoride. The water was commonly reddish brown, because of organic compounds.

Glacial-Drift and Alluvial Aquifers

Goodman Creek Aquifer

The Goodman Creek aquifer is a long, narrow glaciofluvial deposit of sand and gravel that underlies Goodman Creek valley in western Mercer County (plate 1). The beds forming the aquifer probably extend

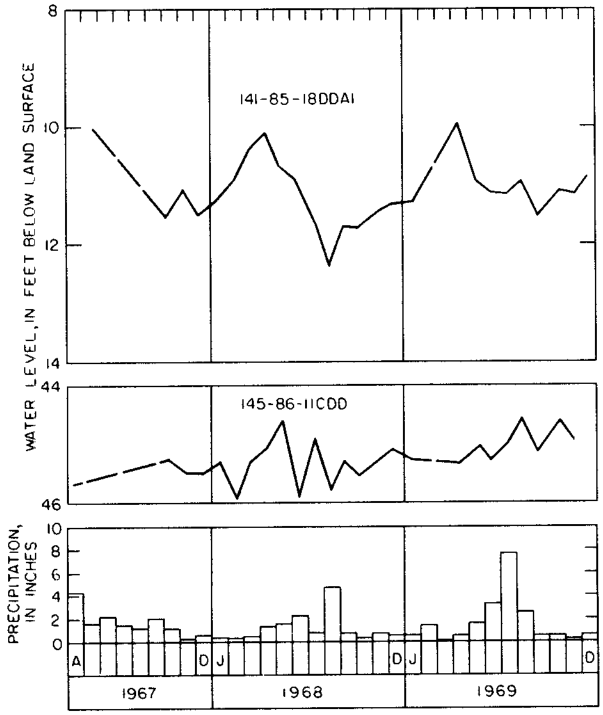


FIGURE 17.--Water-level fluctuations in lignite aquifers and precipitation at Beulah.

westward into Dunn County. The aquifer is 1 to 1½ miles wide and about 200 feet thick (figure 18). Test holes indicate that the coarsest and most permeable beds generally are near the base in that part of the aquifer north of Spring Creek. Overlying the sand and gravel is as much as 40 feet of alluvium, composed of sandy silt and clay. Two test holes in the aquifer south of Spring Creek penetrated mainly fine to medium sand. Wells in the central part of the aquifer (plate 1) should yield 100 to 500 gpm, which is adequate for irrigation. The aquifer stores about 530,000 acre-feet of ground water. Without recharge from precipitation, streams, and the adjoining consolidated rocks, about 265,000 acre-feet of water should be recoverable through wells.

Water-level fluctuations.--Observation well 145-90-8CBB (figure 19), 236 feet deep, records water-level fluctuations due to recharge to and discharge from the aquifer. The water level rose about 0.7 foot from February to July 1969, due principally to snowmelt and precipitation infiltrating through the overlying fine-grained alluvium. The water level shows a general decline from July to November, with most of the decline occurring from August to September. The decline in water levels resulted from subsurface outflow toward Spring Creek (plate 1), and discharge from evapotranspiration and springs exceeding the negligible precipitation and inflow from the adjoining bedrock.

Water quality.--The average results obtained from seven water samples from the Goodman Creek aquifer are shown in figure 8. The samples generally contained moderate amounts of mineral matter. The major constituents in the water are plotted in figure 20, which shows that water from the Goodman Creek aquifer is variable in quality and type with depth and location. Four test holes, 141 to 236 feet in depth and screened near the bottom of the aquifer, were drilled north of Spring Creek. They yielded water with 771 to 1,090 ppm total dissolved solids, 1.8 to 3.7 ppm iron, 254 to 465 ppm sulfate, and 275 to 373 ppm hardness. Sodium generally constituted about half of the cations and bicarbonate generally was the principal anion. In one sample, sulfate rather than bicarbonate was the principal anion. Water from the deeper wells in the aquifer was more highly mineralized and was similar to water from the lower Tongue River aquifer (figure 20). Water samples from the shallower wells generally contained less mineral matter. Well 145-90-21AAA2, 80 feet deep, contained water with 614 ppm total dissolved solids; sodium constituted about 50 percent of the cations. Well 145-90-6DB2, 54 feet deep, obtained water with 276 ppm total dissolved solids; calcium constituted 69 percent of the cations. Water from well 144-90-22DAD, which is 162 feet deep and taps the

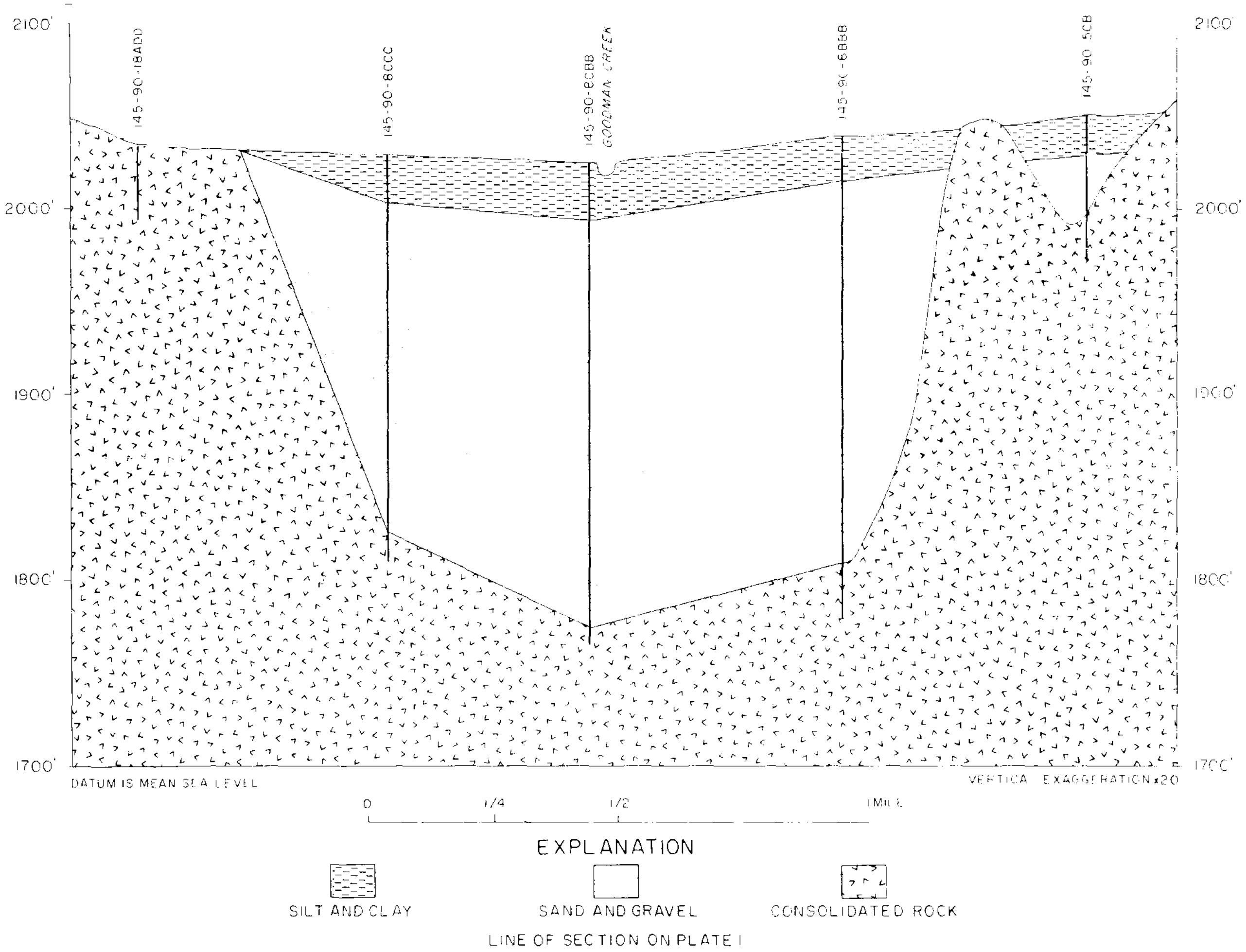


FIGURE 18.--Geologic section B-B′ through the Goodman Creek aquifer, Mercer County.

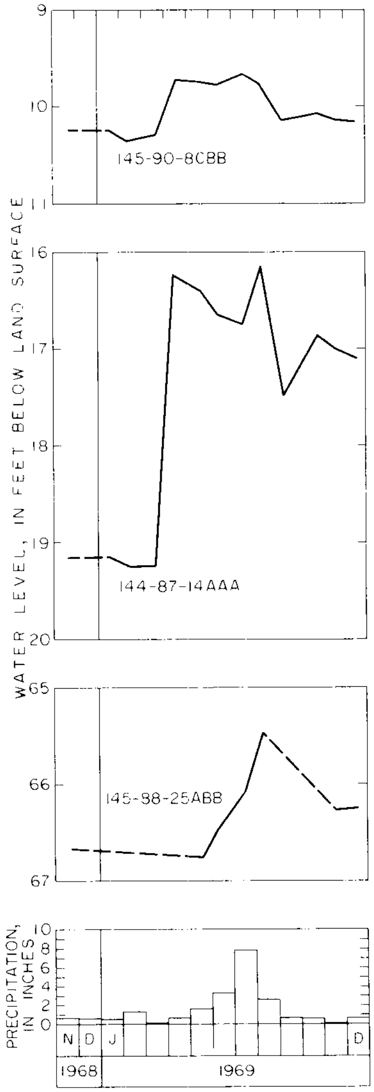
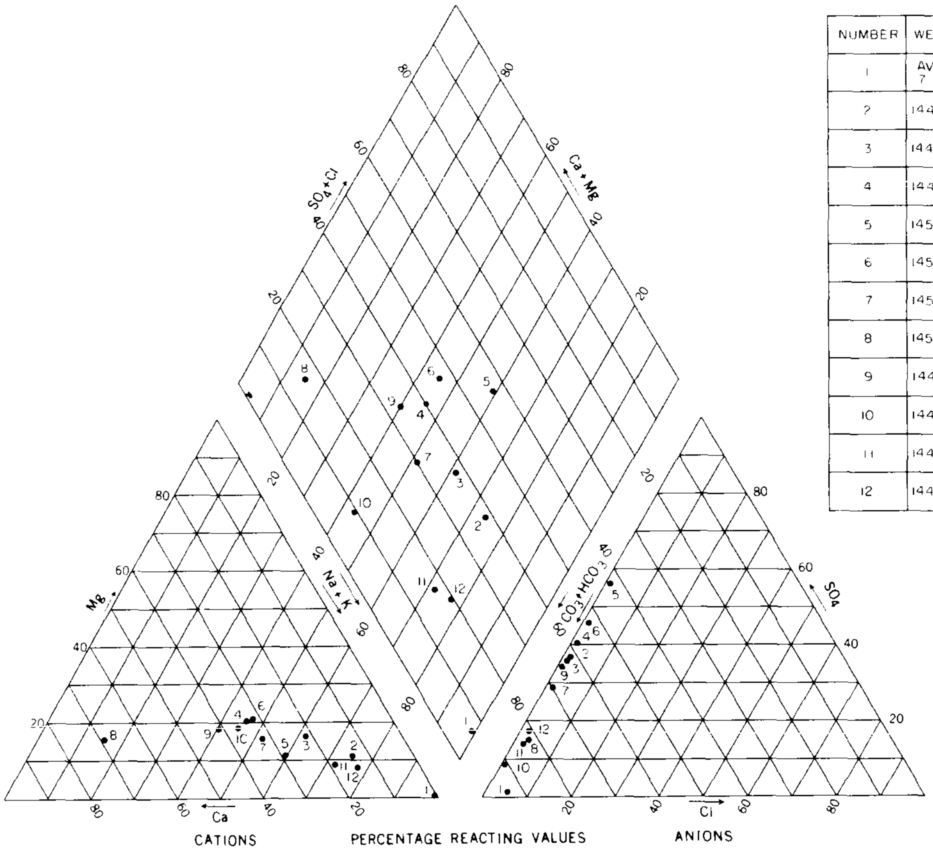


FIGURE 19.--Water-level fluctuations in the Goodman and Antelope Creek aquifers and precipitation at Beulah, Mercer County.



NUMBER	WELL NUMBER	DEPTH	DISSOLVED SOLIDS (PPM)	AQUIFER
1	AVERAGE OF 7 ANALYSES	-	1760	LOWER TONGUE RIVER
2	144-90-22DAD	162	1010	GOODMAN CREEK
3	144-90-16ABC	141	771	GOODMAN CREEK
4	144-90-4DDC	160	802	GOODMAN CREEK
5	145-90-8CBB	236	1090	GOODMAN CREEK
6	145-90-21AAA1	200	1000	GOODMAN CREEK
7	145-90-21AAA2	80	614	GOODMAN CREEK
8	145-90-6DB2	54	276	GOODMAN CREEK
9	144-86-18DDC3	53	511	KNIFE RIVER
10	144-86-18ADC2	63	539	KNIFE RIVER
11	144-86-18DDC4	203	742	KNIFE RIVER
12	144-86-19ABA	224	1040	KNIFE RIVER

FIGURE 20.--Major constituents in water from the Goodman Creek, Knife River, and lower Tongue River aquifers.

aquifer south of Spring Creek, contained 1,010 ppm total dissolved solids. Sodium and bicarbonate were the main cations and anions. The water samples were classified C2-S1 to C3-S2 (figure 4) for irrigation purposes.

Antelope Creek Aquifer

The Antelope Creek aquifer (plate 1) underlies a narrow valley that extends from Lake Sakakawea to the Knife River. The valley divides about 4 miles north of Beulah. The deposits forming the aquifer consist of glaciofluvial sand and gravel interbedded with silt and clay, are less than 1 mile in width, and are about 250 feet thick (figure 21). Overlying the sand and gravel is about 20 feet of alluvium composed of dark sandy silt and clay. Wells in the central part of the aquifer from Spring Creek to Lake Sakakawea (plate 1) should yield 100 to 500 gpm, which is adequate for irrigation. The aquifer contains about 260,000 acre-feet of ground water. Without recharge, about 130,000 acre-feet should be recoverable through wells.

Water-level fluctuations, recharge, and discharge.--Water levels in wells 145-88-25ABB and 144-87-14AAA (figure 19) reflect the aquifer response to seasonal changes in recharge and discharge. In 1969 the water level rose more than 1 foot in well 145-88-25ABB from infiltration of precipitation. The water level rose about 3 feet in March and April 1969 in well 144-87-14AAA from infiltration of melting snow and about 0.6 foot in July and August during a period of heavy rain. The water level declined from August to November in well 145-88-25ABB when subsurface outflow towards the Knife River and discharge from evapotranspiration and springs exceeded precipitation and inflow from the adjoining bedrock.

The coarse deposits of the aquifer form a highly permeable conduit connecting Lake Sakakawea and the Knife River valley. The direction of ground-water movement in the aquifer (plate 1), suggested by water-level measurements in several test holes, indicates that water enters the aquifer when the lake is at a maximum elevation (1,850 feet), and percolates southward toward the Knife River valley near Hazen (elev. 1,750 feet), a distance of 18 to 20 miles.

Water quality.--Five water samples obtained from wells tapping mainly the lower part of the Antelope Creek aquifer contained moderate amounts of dissolved mineral matter (figure 8). Three of the water samples were of the sodium bicarbonate type. Sodium in the other two samples constituted 16 and 47 percent of the cations. Total dissolved solids ranged from 423 to 1,460 ppm. Hardness ranged from 264 to 576 ppm, and the water contained 2.0 to 8.6 ppm iron. The

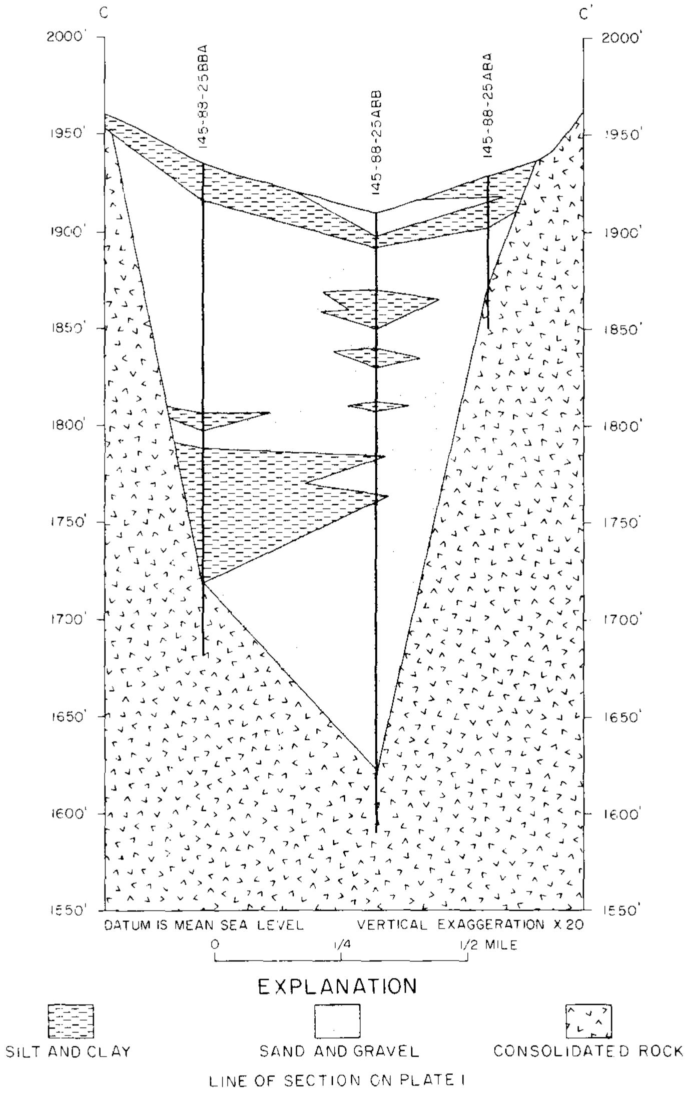


FIGURE 21.--Geologic section C-C′ through the Antelope Creek aquifer, Mercer County.

water contained 0.3 to 0.5 ppm fluoride and was classified as C2-S1 to C3-S2 (figure 4) for irrigation purposes.

Knife River Aquifer

The Knife River aquifer underlies the flood plain and terraces of the Knife River valley from the southwestern corner of Mercer County to Stanton, near the Missouri River (plate 1). It ranges from half a mile to about 5 miles in width and underlies approximately 70 square miles. Glaciofluvial sand and gravel (figures 22-24) deposits forming the aquifer have a maximum thickness of about 60 feet southwest of Beulah (figure 22) and a maximum thickness of about 240 feet east of Beulah (figures 23 and 24). Alluvium consisting of 0 to 45 feet of dark sandy silt and clay partly overlies the sand and gravel.

Wells in the central part of the aquifer from the Dunn County line to Stanton (plate 1) should yield 100 to 500 gpm. Yields greater than 500 gpm probably can be obtained from a 2-square-mile area west of Stanton. The yield in these areas should be adequate for irrigation. The aquifer contains about 920,000 acre-feet of ground water. Without recharge, about 460,000 acre-feet of water should be recoverable through wells.

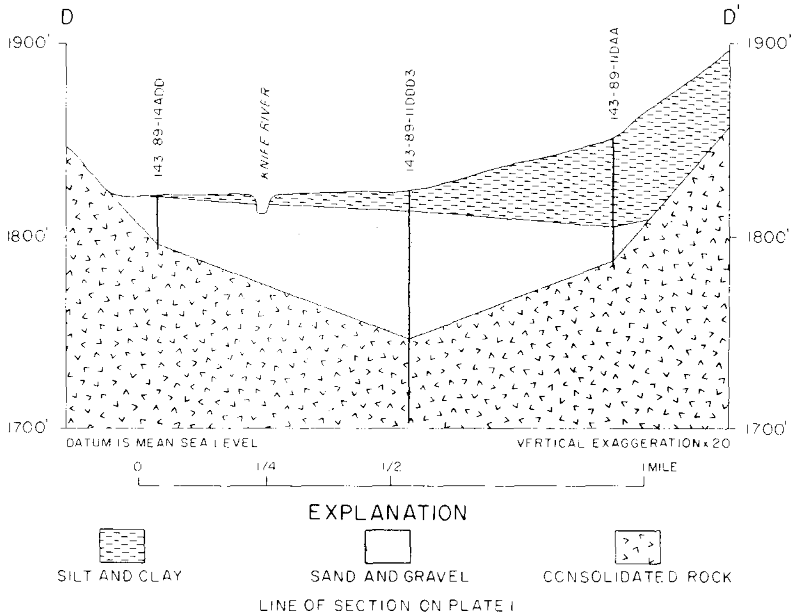


FIGURE 22.--Geologic section D-D' through the Knife River aquifer, Mercer County.

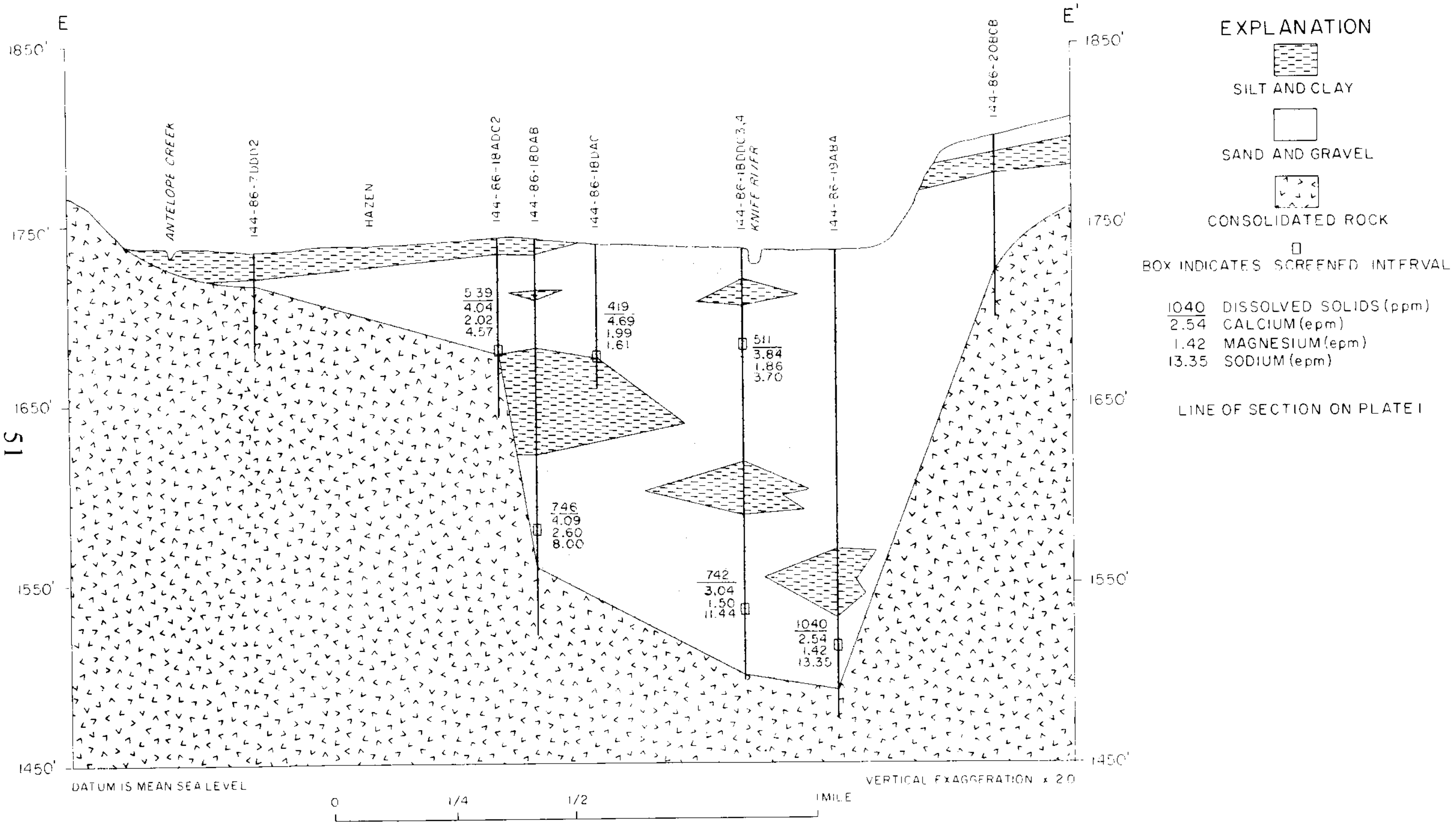


FIGURE 23.--Geologic section E-E′ through the Knife River aquifer, Mercer County, showing quality-of-water relationships.

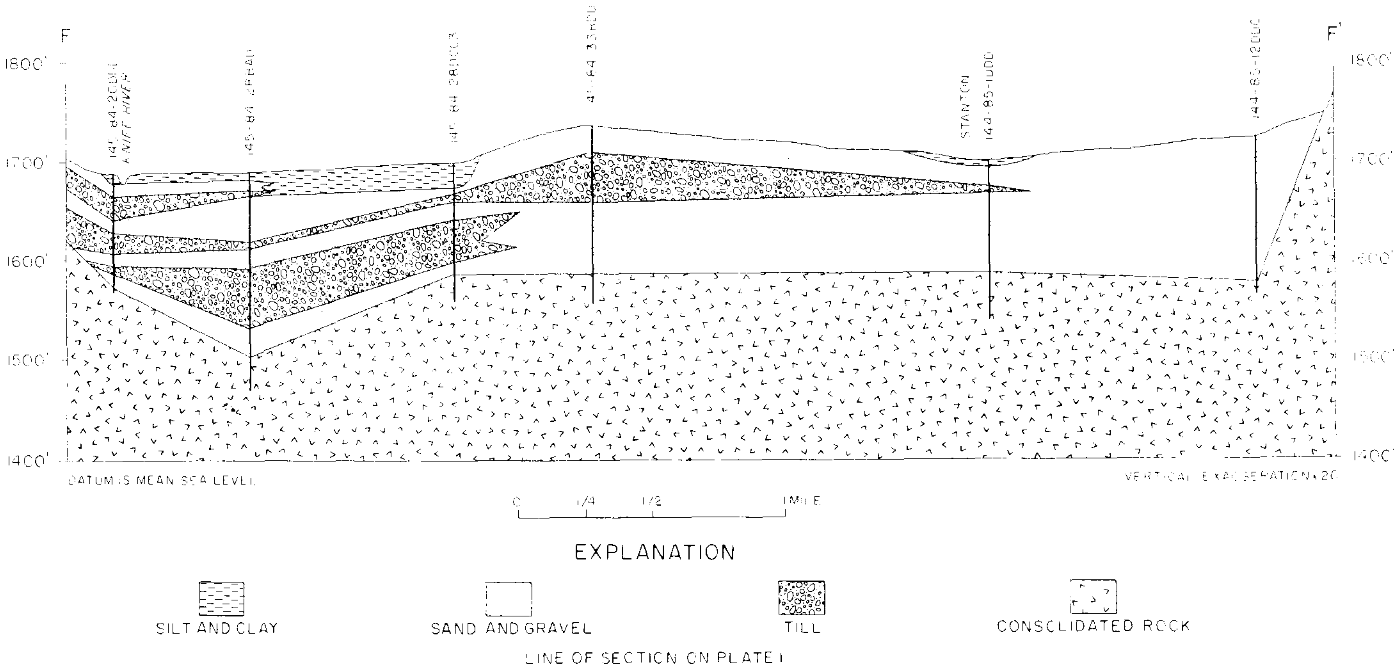


FIGURE 24.--Geologic section F-F' through the Knife River aquifer, Mercer County.

Water-level fluctuations.–Hydrographs of wells 145-84-28BAD and 144-86-18ADC2 (figure 25) show the water-level fluctuations in the Knife River aquifer. The water level in well 145-84-28BAD, which taps a confined part of the aquifer, generally rose from November to March or April and declined from March or April to October or November. In April 1969 the water level in well 144-86-18ADC2, which taps a water-table part of the aquifer, rose almost 5 feet when a heavy snow cover melted rapidly and flooded much of the Knife River valley. The flood water came within several feet of the well casing. The area was again flooded in July 1969 following heavy rains. The water level in the water-table well declined to December 1969 because subsurface outflow, discharge by springs, and evapotranspiration exceeded the recharge by precipitation and inflow from the adjoining bedrock.

Aquifer constants.--An aquifer test was performed during July 1969 about 2 miles west of Stanton (R. W. Schmid, written commun., July 1969). The production well (figure 26), 144-85-2BCB6, was screened from 110 to 130 feet in sand and gravel of the Knife River aquifer. It was pumped at a rate of 800 gpm for 4,500 minutes. Six observation wells were spaced at distances of 53, 100, 200, 475, 540, and 1,060 feet from the production well. They were equipped with continuous water-level recorders and electric water-level sensing devices to monitor water-level changes. In addition, several other nearby observation wells were measured periodically. Well logs indicate the aquifer at this site is overlain and confined by thick beds of till.

A plot of the distance-drawdown data from the observation wells for 100 minutes and 1,000 minutes aligns with a segment of the Theis (1935) curve (figure 27). The coordinates of a match point for both graphs are recorded and substituted into the Theis equation in the form:

$$T = \frac{114.6\, Q\, W(u)}{s} \qquad (6)$$

where:

T = transmissivity, in gallons per day per foot;
Q = discharge of a well, in gallons per minute;
$W(u)$= well function of u, coordinate of type curve;
s = drawdown in feet;
$u = \frac{1.87\, r2\, S}{Tt}$;
r = distance, in feet, from discharge point to observation well;
S = storage coefficient; and
t = time in days (t expressed in minutes, $u = \frac{2{,}693\, r^2\, S}{Tt}$).

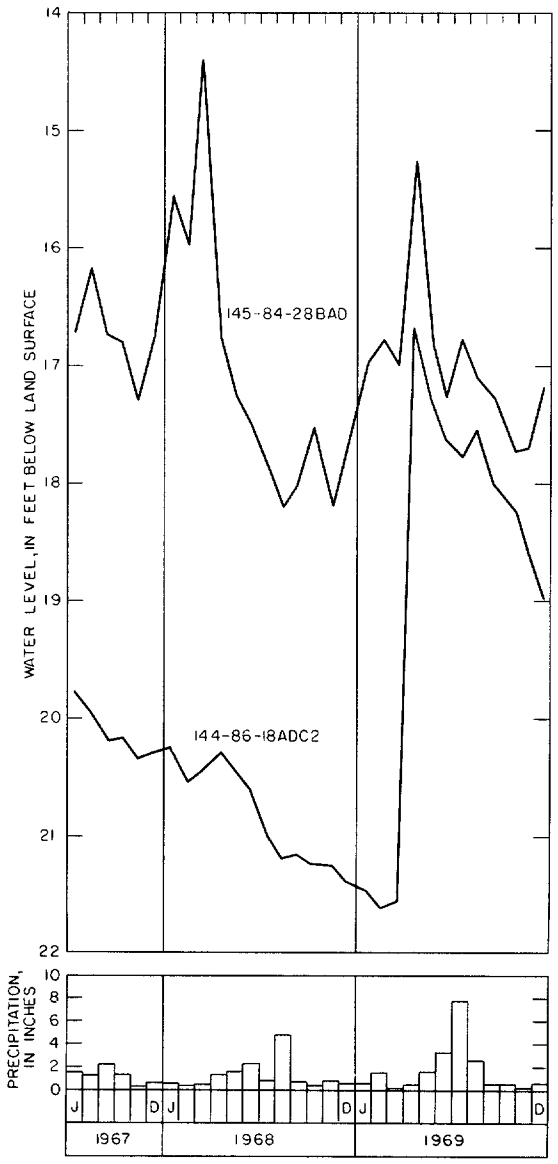


FIGURE 25.–Water-level fluctuations in the Knife River aquifer and precipitation at Beulah, Mercer County.

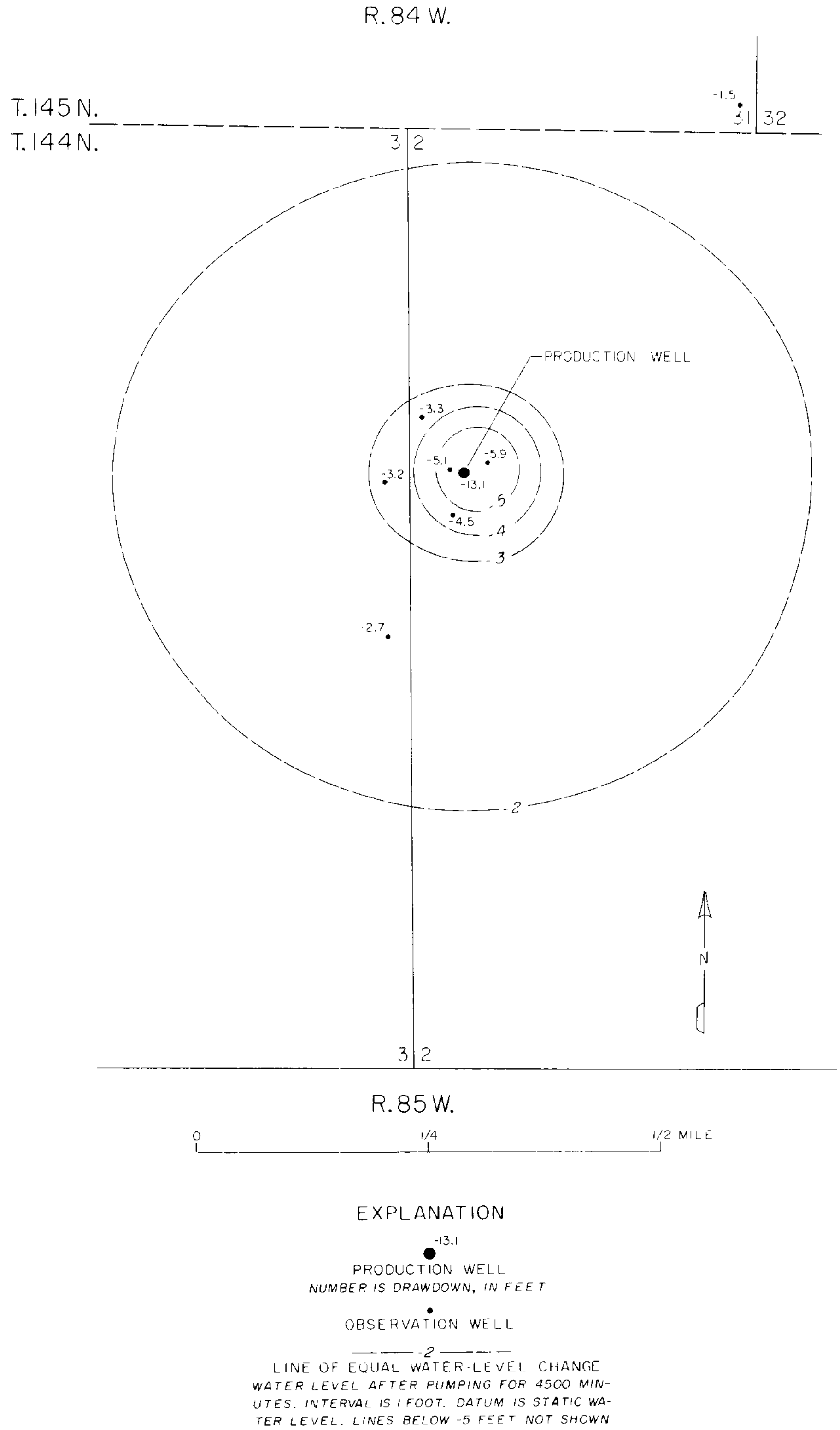


FIGURE 26.--Locations of wells and area of influence for aquifer test near Stanton.

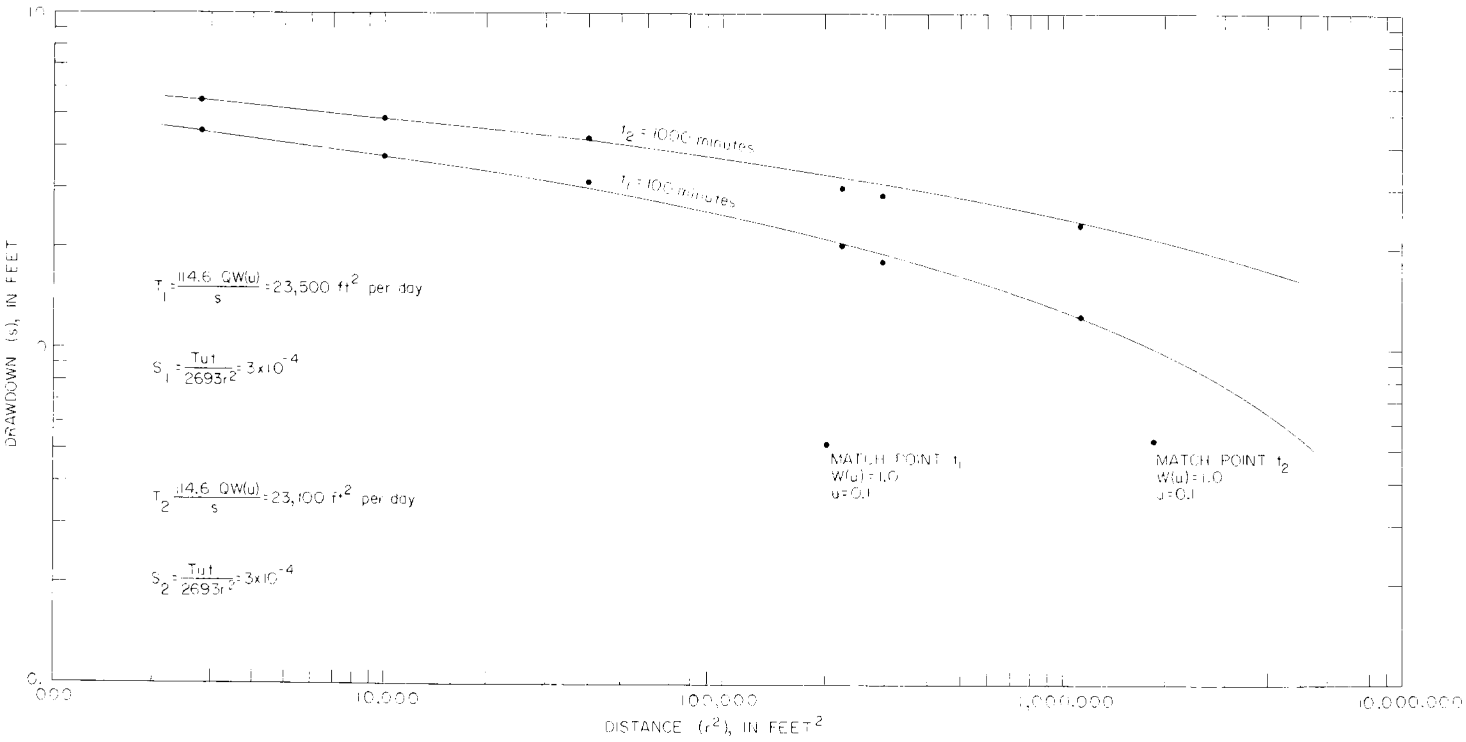


FIGURE 27.--Logarithmic plots of distance-drawdown data for observation wells 144-85-2BCB2, 2BCB3, 2BCB1, 2BCC, 3ADA, and 3DAA.

After solving for transmissivity, the storage coefficient is derived by means of the equation defining "u." The value for transmissivity in gallons per day per foot can be converted to transmissivity in square feet per day by multiplying by 0.134.

Solution of the equations indicates that the transmissivity at the site is about 176,000 gpd per foot (23,500 square feet per day) for the 100-minute curve, and is about 173,000 gpd per foot (23,100 square feet per day) for the 1,000-minute curve. The storage coefficient has a value of 0.0003. The pumped well had a specific capacity of 66 gpm per foot.

P. D. Akin and J. E. Powell (written commun., 1953) conducted an aquifer test in February 1953 on well 144-88-25CCA, owned by the city of Beulah. The well was pumped at a rate of 120 gpm and had a maximum drawdown of about 16.5 feet. The recovery data from the pumped well suggested an approximate transmissivity at the site of 50,000 gpd per foot (6,700 square feet per day).

An aquifer test was made by North Central Consultants, Jamestown, North Dakota (written commun., 1967), near Beulah city well 144-88-25CA. The well was pumped at a rate of 310 gpm and had a drawdown of about 14.5 feet after 1,000 minutes. The transmissivity at the site was about 60,000 gpd per foot (8,000 square feet per day).

Water quality.--Thirty-nine water samples were collected from 36 wells and test holes tapping the Knife River aquifer from the southwest corner of Mercer County to Stanton. Water from the aquifer southwest of Beulah (figure 8) is more highly mineralized and higher in sulfate than water from the aquifer between Beulah and Coal Creek and from the aquifer between Coal Creek and Stanton.

Three water samples were collected from the Knife River aquifer southwest of Beulah. Water from well 143-90-34DAC1 contained 1,390 ppm dissolved solids, 678 ppm sulfate, 1.9 ppm iron, and had a hardness of 351 ppm. Water from well 143-90-34DAC2 contained 1,980 ppm total dissolved solids and water from well 143-89-11DDD2 contained 1,130 ppm total dissolved solids. In the three samples sodium (figure 8) constituted 71 percent of the cations; bicarbonate constituted 53 percent of the anions, and sulfate 47 percent.

Fourteen analyses of water from the aquifer between Beulah and Coal Creek indicated that water in this area was low in dissolved constituents (figure 8), but varied in quality and type with depth, as illustrated in figures 20 and 23. Water in the upper part of the aquifer contained 419 to 539 ppm total dissolved solids and generally was of the calcium bicarbonate type. Water in the lower part contained 742 to

1,040 ppm total dissolved solids and was of the sodium bicarbonate type. Total dissolved solids in the 14 analyses ranged from 419 to 1,040 ppm.

Twenty-two analyses of water collected from the aquifer between Coal Creek and Stanton indicated that the water was of the calcium magnesium bicarbonate type and low in dissolved constituents (figure 8). Total dissolved solids ranged from 503 to 1,740 ppm. Boron ranged from 0.04 to 0.52 ppm, excepting one sample that contained 3.4 ppm. Fluoride generally ranged from 0.1 to 0.6 ppm, excepting one sample that contained 5.0 ppm.

Most of the water samples from the Knife River aquifer east of Beulah were classified C3-S1 to C3-S2 for irrigation purposes (figure 4). Water from well 143-90-34DAC2, southwest of Beulah, was classified C4-S4. In comparison, water from the Knife River had an irrigation classification of C2-S1 during periods of high discharge and of C3-S2 during periods of low discharge.

Ground-water discharge to the Knife River.--The chemical composition of water in the Knife River varies with discharge (figure 28), as shown by data collected in 1964 at a gaging station near Golden Valley. When flow in the river consisted mainly of runoff during periods of heavy precipitation in the spring, summer, and early fall, the dissolved-solids concentration of the water was low. Discharge is least and dissolved-solids concentration is greatest when precipitation is light during late fall and winter. The high dissolved-solids concentration during the late fall and winter suggests that the flow during these periods is ground water released from storage in the Knife River aquifer and the underlying bedrock.

Missouri River Aquifer

The Missouri River aquifer underlies the terraces (Johnson and Kunkel, 1959, plate 1) and flood plains of the Missouri River valley from Garrison Dam to the southeast corner of Oliver County (plate 1). It consists of coarse glaciofluvial sand and gravel beneath the terraces and coarse glaciofluvial and alluvial deposits beneath the flood plains. The aquifer generally ranges from a quarter of a mile to 2½ miles in width and is more than 200 feet thick in a buried valley that passes through the Stanton, Fort Clark, and Hensler areas (figure 29). Yields of more than 500 gpm can be expected from the aquifer north of Hensler. The aquifer contains about 470,000 acre-feet of ground water. Without recharge, about 235,000 acre-feet of water should be recoverable through wells.

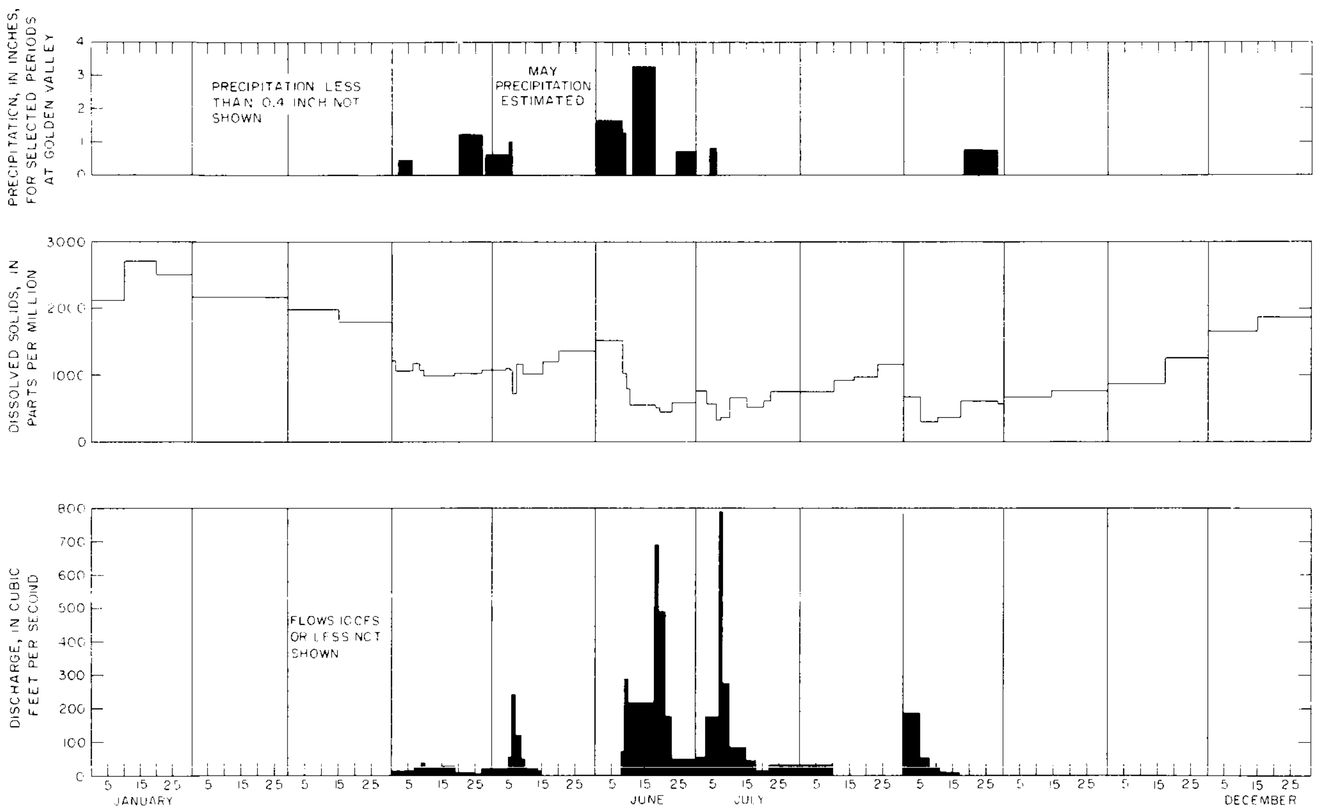


FIGURE 28.--Composite mean discharge and dissolved solids of the Knife River near Golden Valley, N. Dak., for selected periods, 1964.

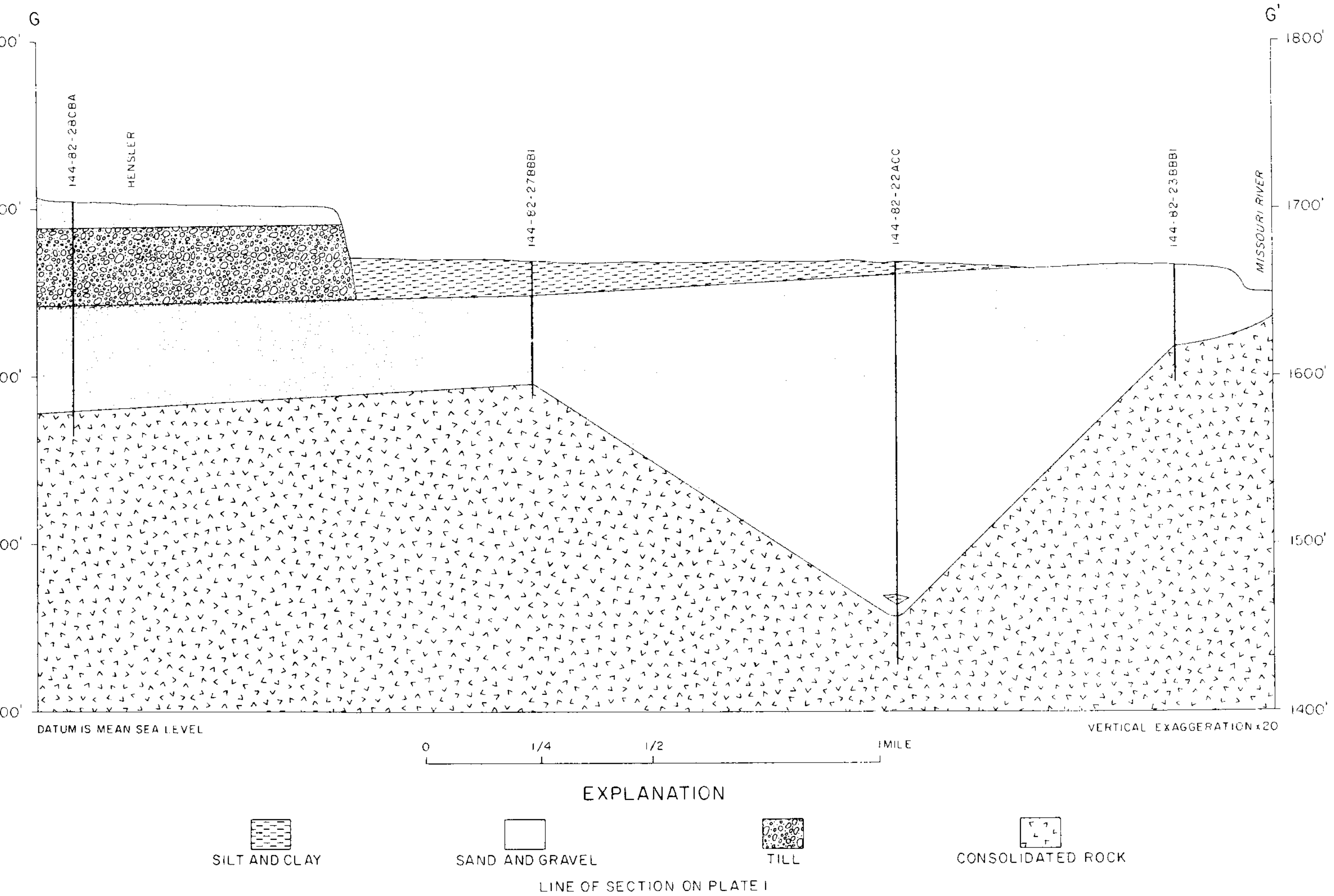


FIGURE 29.–Geologic section G-G′ through the Missouri River aquifer, Oli

Ground-water movement.--A water-level contour map (figure 30) of part of the Missouri River aquifer near Hensler shows that the ground water moves toward the Missouri River. The gradient varies from about 10 feet per mile near the terrace to about 5 feet per mile or less near the river.

Todd (1959, p. 68) indicated that for the special case of nearly parallel flow lines, hydraulic conductivity and the hydraulic gradient are related by the following expression, where K is the hydraulic conductivity and i is the hydraulic gradient:

$$\frac{K_1}{K_2} = \frac{i_2}{i_1} \tag{7}$$

Therefore, the water-level contour lines shown on the map suggest that the deposits underlying the area where the hydraulic gradient is about 10 feet per mile have hydraulic conductivities of approximately the same magnitude as those at the site of the aquifer text, which is discussed in the following section. The deposits underlying the area where the hydraulic gradient is 5 feet per mile or less probably have a hydraulic conductivity that is twice the value obtained at the site of the aquifer test.

Aquifer constants.--An aquifer test was performed 2 miles north of Hensler by R. W. Schmid (written commun., 1969) in October 1968. The production well, 144-82-17CDD1, was screened from 97 to 111 feet in sand and gravel, and was pumped at a rate of 243 gpm for 3,000 minutes. Three observation wells were spaced at distances of 100, 200, and 400 feet from the production well. The observation wells were equipped with continuous water-level recorders and electric water-level sensing devices to monitor water-level changes.

A plot of distance-drawdown data obtained from the observation wells for 10 minutes, 30 minutes, and 3,000 minutes aligns with a segment of the Theis-type (1935) curve (figure 31). Solution of the Theis equation for the three curves gives values for transmissivity at the site of 103,000 gpd per foot (13,800 square feet per day) at 10 minutes, 90,000 gpd per foot (12,000 square feet per day) at 30 minutes, and 89,000 gpd per foot (11,900 square feet per day) at the end of the test. The storage coefficient ranged from 0.0008 at the beginning of the test to 0.05 at the end of the test. The results indicate leaky artesian or water-table conditions.

Walton (1962, p. 6) and Prickett (1965) emphasized that under water-table conditions, water is derived largely from storage by the gravity drainage of the interstices in the portion of the aquifer

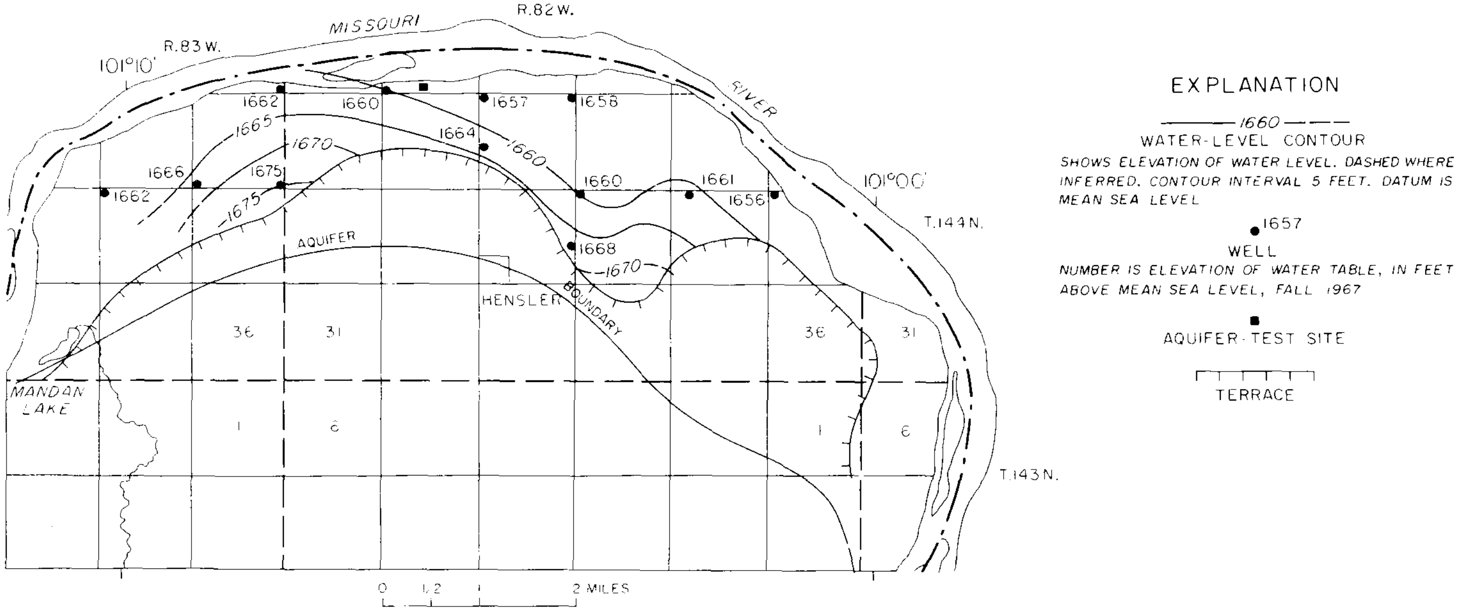


FIGURE 30.--Elevation of the water table of the Missouri River aquifer near Hensler, Oliver County.

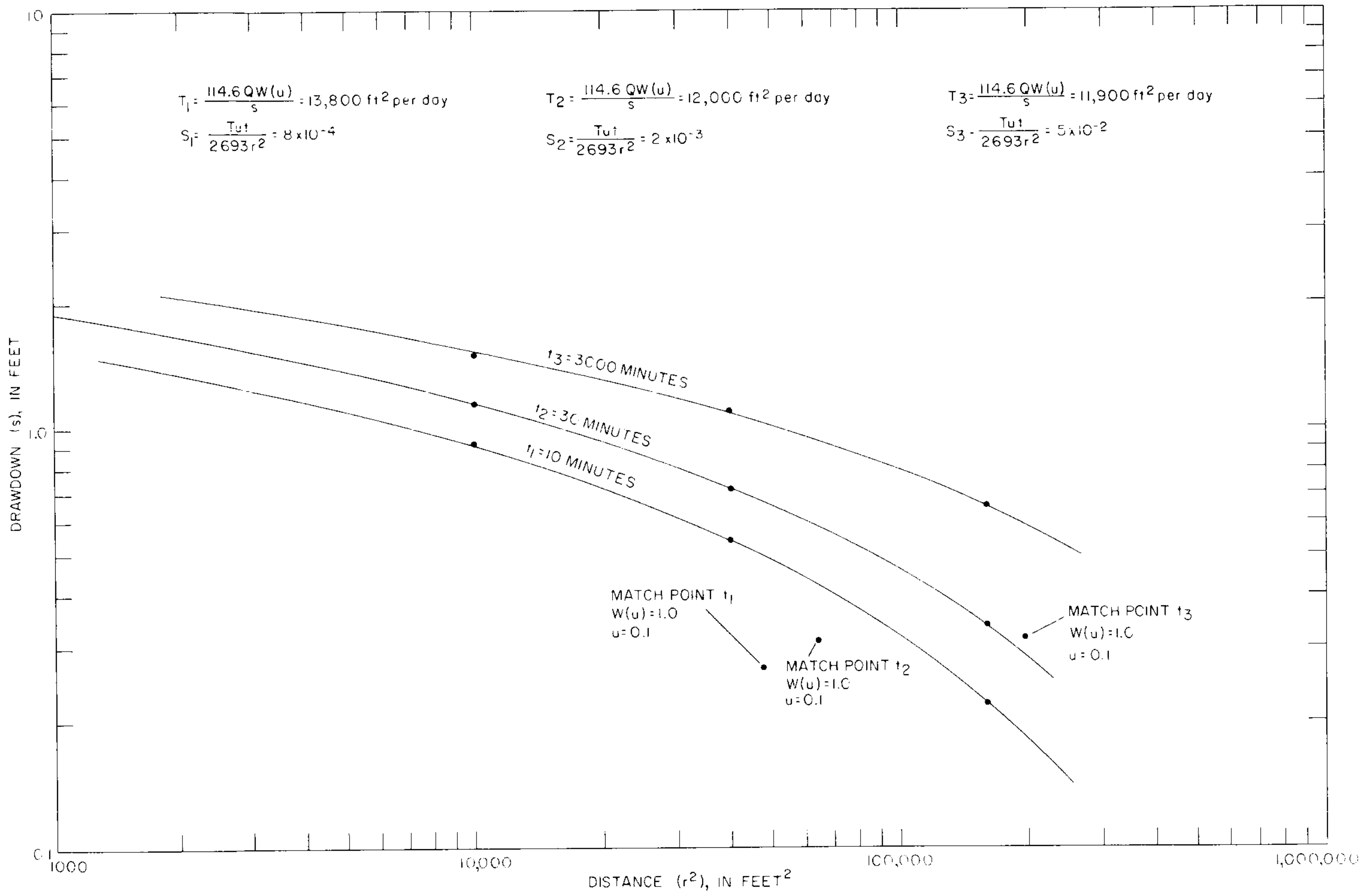


FIGURE 31.--Logarithmic plots of distance-drawdown data for observation wells 144-82-17CDD2, 17CDD3, and 20ABB.

dewatered by the pumping. The gravity drainage of water through stratified sediments is not immediate and the nonsteady flow of water towards a well in an unconfined aquifer is characterized by slow drainage of the interstices. Thus, the storage coefficient varies and increases at a diminishing rate with the time of pumping. Also, they stated that under water-table conditions the nonequilibrium artesian formula for determining transmissivity is applicable only under favorable conditions at the beginning of the test.

Time-drawdown data for observation well 144-82-17CDD3 are shown in figure 32, and are analyzed by methods described by Prickett (1965) for water-table conditions. The transmissivity for the A curves was 121,000 gpd per foot (16,200 square feet per day) and for the Y curves was 107,000 gpd per foot (14,300 square feet per day). These values are comparable to the value of 103,000 gpd per foot (13,800 square feet per day) obtained from the 10-minute distance-drawdown data (figure 31). The storage coefficient value obtained from the 3,000-minute distance-drawdown data is comparable to the 0.02 obtained from the Y curves. The time when delayed gravity drainage ceases to influence drawdown, determined with the delay index (Prickett, 1965, figure 6), is 6,000 minutes. Therefore, the test was not long enough to completely dewater the overlying beds. However, the storage coefficient of 0.02 is probably sufficiently accurate so that it can be used to approximate the long-term effects of pumping.

A particle-size distribution curve was made from a bailer sample obtained from a depth of 101 to 103 feet in well 144-82-17CDD1. The sample had an effective particle size of 0.16 millimeter, a median diameter of 0.47 millimeter, and a coefficient of uniformity of 8.75. If a porosity of 35 percent is assumed for the sample, the hydraulic conductivity would be 300 to 400 gpd per square foot (Johnson, 1963, figures 22-23). The transmissivity estimated by this method would be 60,000 to 80,000 gpd per foot (8,000 to 11,000 square feet per day); a value smaller than that obtained from the aquifer tests.

Water-level fluctuations.–Hydrographs of three wells (figure 33) show water-level fluctuations in the Missouri River aquifer. The water level in well 144-82-27BBB1 rose from January to March 1968 and from November 1968 to April 1969. The large rise in April 1969 accompanied the melting of an excessively large cover of snow. The water level also rose sharply in August 1969 due to infiltration from excessive precipitation. The water level declined from April to November in well 144-82-28CBA when subsurface outflow and discharge by evapotranspiration and springs exceeded the recharge by precipitation and inflow from the adjoining bedrock.

Well 144-82-23BBB2 is about 150 feet from the Missouri River, and

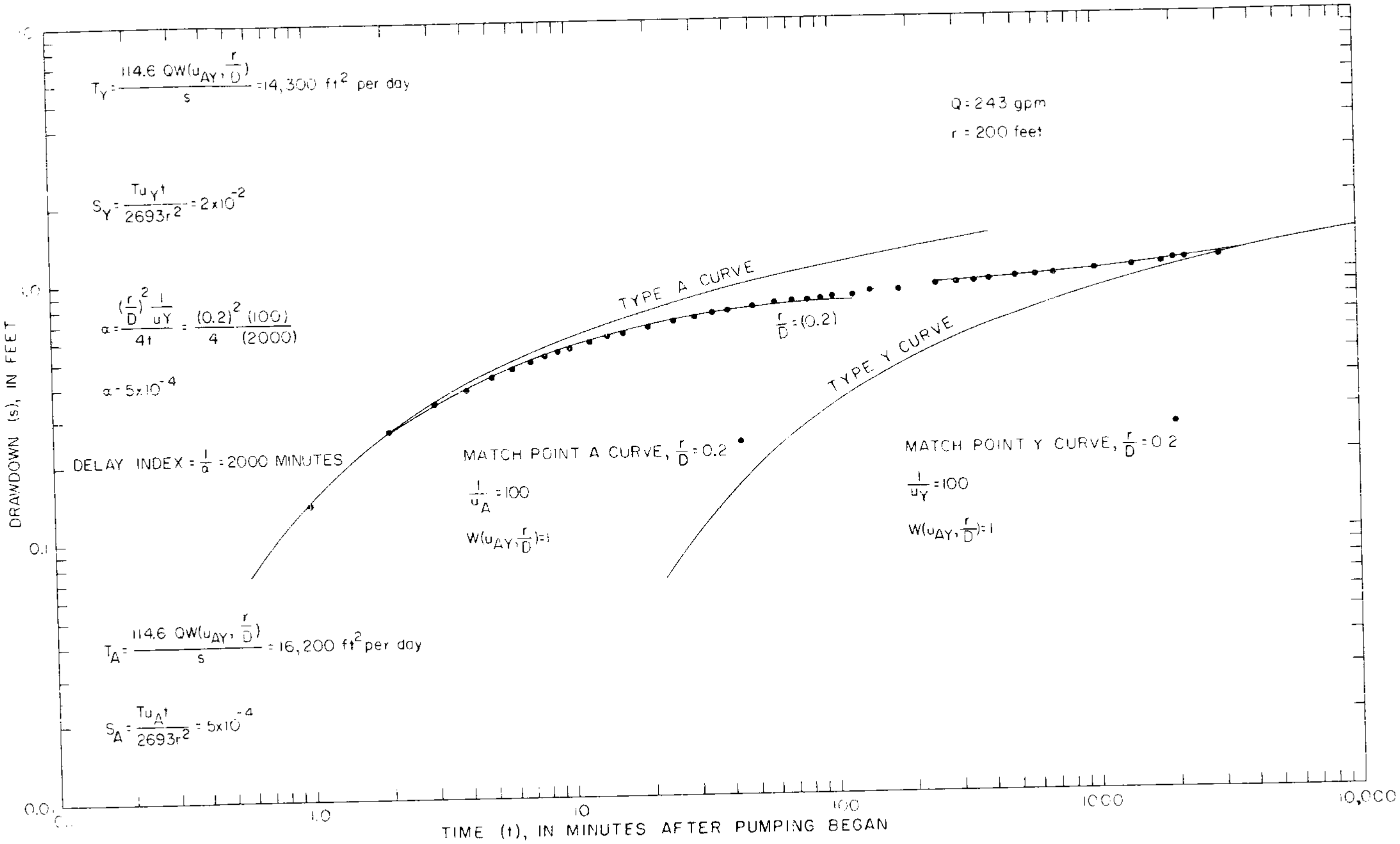


FIGURE 32.--Time-drawdown data for observation well 144-82-17CDD3.

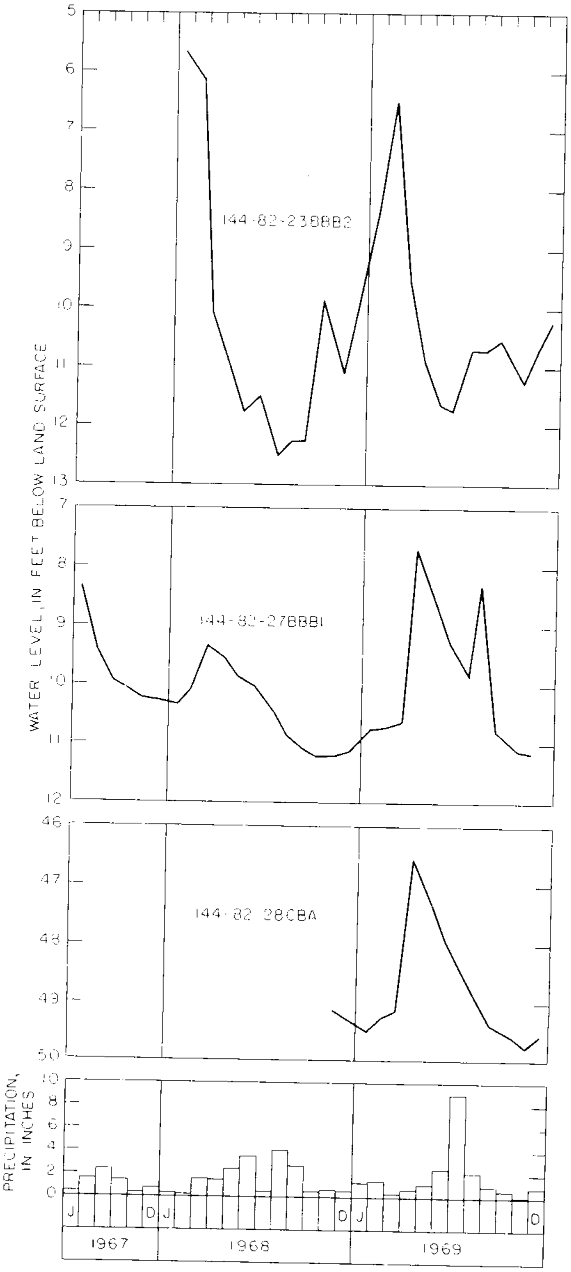


FIGURE 33.--Water-level fluctuations in the Missouri River aquifer and precipitation at Center, Oliver County.

the water level in the well fluctuates according to the river level, which is controlled by releases from Lake Sakakawea.

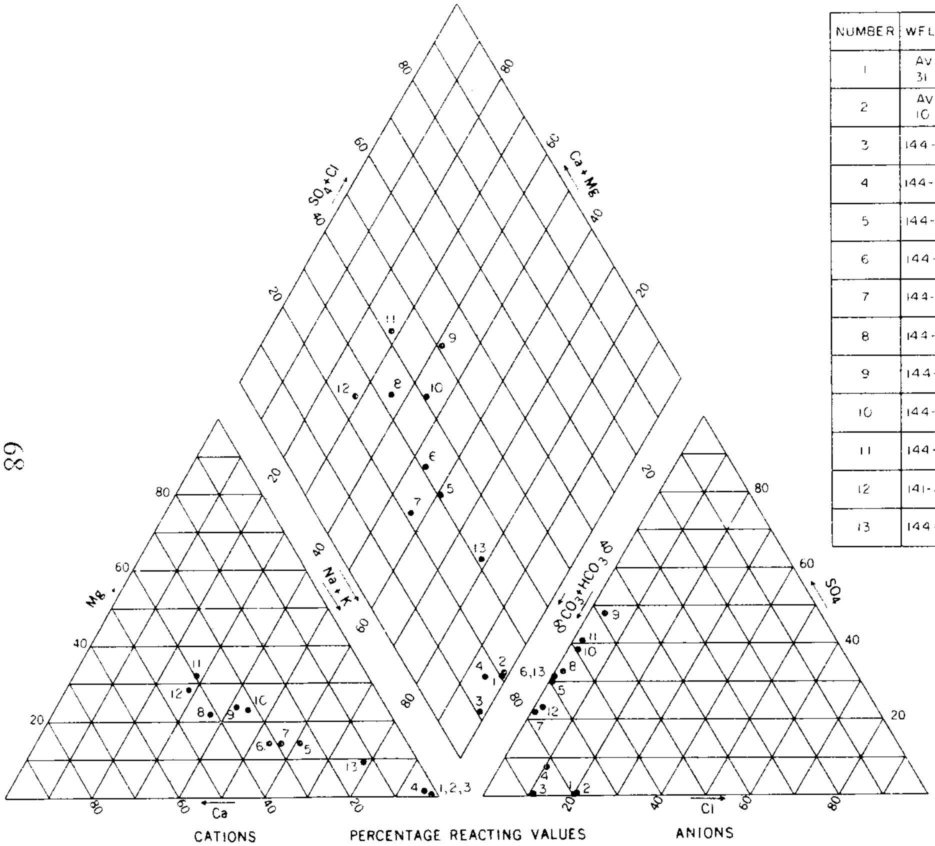
Water quality.--Twenty-five water samples were collected from 23 wells tapping the Missouri River aquifer. Most of the samples were from the aquifer near Hesler. They indicate that the water contains moderate amounts of dissolved mineral constituents (figure 8). Sodium and bicarbonate were the principal cations and anions in the average sample; however, the composition of the water in selected samples (figure 34) was variable in quality and type. Total dissolved solids ranged from 585 ppm to 1,660 ppm, fluoride ranged from 0.1 to 0.9 ppm, and boron ranged from 0.05 to 1.3 ppm. Water from the deeper wells generally was similar to water from aquifers in the consolidated rocks. The water was classified C3-S1 to C3-S2 for irrigation purposes (figure 4).

Two water samples from the Missouri River about 1,500 feet south of Garrison Dam indicate that the river water contains less dissolved mineral matter than the water in the Missouri River aquifer. The river water contained 420 to 427 ppm total dissolved solids, and sodium constituted 34 to 37 percent of the cations. The concentration of iron was 0 to 0.12 ppm and the concentration of boron was 0 to 0.34 ppm. The river water was classified C2-S1 for irrigation purposes (figure 4).

Square Butte Creek Aquifer

The Square Butte Creek aquifer, which consists of alluvial and glaciofluvial deposits beneath Kineman and Square Butte Creeks, extends from the vicinity of Hazen to the southeast corner of Oliver County (plate 1). The aquifer is as much as 130 feet thick (figure 35) in test holes 3 miles northwest of Center, and about 82 feet thick in well 143-85-3DAD near the Mercer-Oliver county line. Erosion by Square Butte Creek southeast of Center has thinned the deposits of sand and gravel and created four terrace levels (Johnson and Kunkel, 1959, p. 26-27). Four holes were augered near Nelson Lake and the thickest deposit of sand and gravel, about 72 feet, was found in test hole 141-83-4BAD. At sites 7 miles southeast of Nelson Lake near the Morton-Oliver county line, the thickest section, 39 feet, was found in well 141-82-22CDA. Wells in the central part of the aquifer northwest of Center should yield 100 to 500 gpm (plate 1). Wells in the aquifer southeast of Center will probably yield 10 to 100 gpm. The aquifer contains about 250,000 acre-feet of ground water. Without recharge, about 125,000 acre-feet of water should be recoverable through wells.

Water-level fluctuations.--The hydrograph of well 141-83-4ADD (figure 36), which is about half a mile downstream from Nelson Lake,



NUMBER	WELL NUMBER	DEPTH	DISSOLVED SOLIDS (PPM)	AQUIFER
1	AVERAGE OF 31 ANALYSES	-	1547	FOX HILLS AND BASAL HELL CREEK
2	AVERAGE OF 10 ANALYSES	-	1630	UPPER HELL CREEK AND LOWER CANNONBALL-LUDLOW
3	144-83-26DB	-	1590	UPPER HELL CREEK AND LOWER CANNONBALL-LUDLOW
4	144-82-23DDD	200	1480	MISSOURI RIVER
5	144-82-17CDD4	103	1290	MISSOURI RIVER
6	144-82-20ABB	101	1200	MISSOURI RIVER
7	144-82-20DCD	85	687	MISSOURI RIVER
8	144-82-27BBB1	50	985	MISSOURI RIVER
9	144-82-26ADD	26	1520	MISSOURI RIVER
10	144-82-21DAA	70	1150	MISSOURI RIVER
11	144-83-13DDD	19	741	MISSOURI RIVER
12	141-81-13CCC	54	547	MISSOURI RIVER
13	144-83-24DBA	100	1660	MISSOURI RIVER

FIGURE 34.--Major constituents in water from the Missouri River aquifer and selected aquifers in the consolidated rocks.

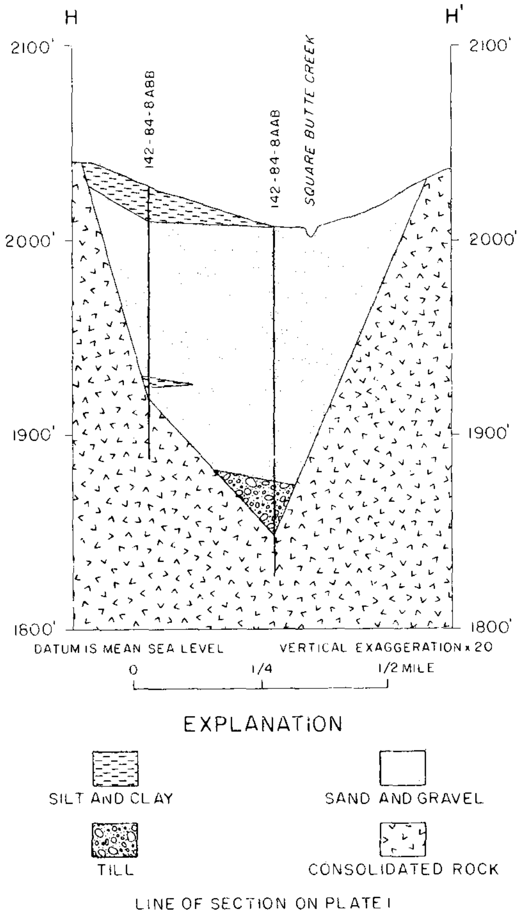


FIGURE 35.--Geologic section H-H' through the Square Butte Creek aquifer, Oliver County.

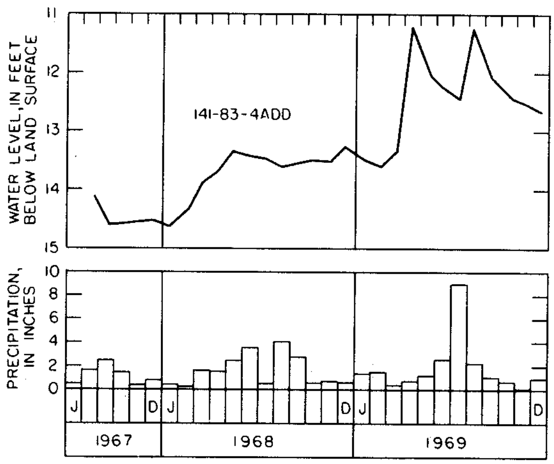


FIGURE 36.–Water-level fluctuations in the Square Butte Creek aquifer and precipitation at Center, Oliver County.

shows the aquifer response to Nelson Lake and seasonal changes in recharge and discharge. Underflow from the lake, which was created in late 1967 and early 1968, is indicated by the general year-to-year rise in water levels. Infiltration of snowmelt and precipitation caused the water level to rise sharply in April 1969 when a heavy snow cover melted rapidly, and in July 1969 following a period of heavy thundershowers. The water level generally declined during summer and fall months when subsurface outflow, discharge by springs, and evapotranspiration exceeded the recharge by precipitation and inflow from the adjoining bedrock and underflow from the lake.

Water Quality.–Eight water samples collected from the Square Butte Creek aquifer contained moderate amounts of dissolved mineral matter (figure 8). The analyses indicated that sodium and bicarbonate generally were the principal cations and anions present. Total dissolved solids ranged from 374 to 863 ppm. Iron ranged from 0.40 to 6.1 ppm, boron ranged from 0.11 to 0.39 ppm, and fluoride ranged from 0.1 to

0.4 ppm. The water was classified C2-S1 to C3-S2 for irrigation purposes (figure 4).

Elm Creek Aquifer

The Elm Creek aquifer underlies the valley of Elm Creek in the southwest corner of Mercer County (plate 1). The aquifer consists of glaciofluvial sand and gravel, and varies from less than a quarter of a mile to 2 miles in width. In test well 142-90-23DCC2, the sand and gravel is 152 feet thick and is overlain by 38 feet of alluvium, consisting of gray sandy silt and clay. Three miles north of the Morton-Mercer county line (figure 37), the sand and gravel is less than 100 feet thick and is overlain by 46 to 256 feet of silt and clay. Wells will probably yield 100 to 500 gpm in two small areas in the central part of the aquifer (plate 1). Yields of 10 to 100 gpm are expected elsewhere from the aquifer. The aquifer contains about 210,000 acre-feet of ground water. Without recharge, about 105,000 acre-feet of water should be recoverable through wells.

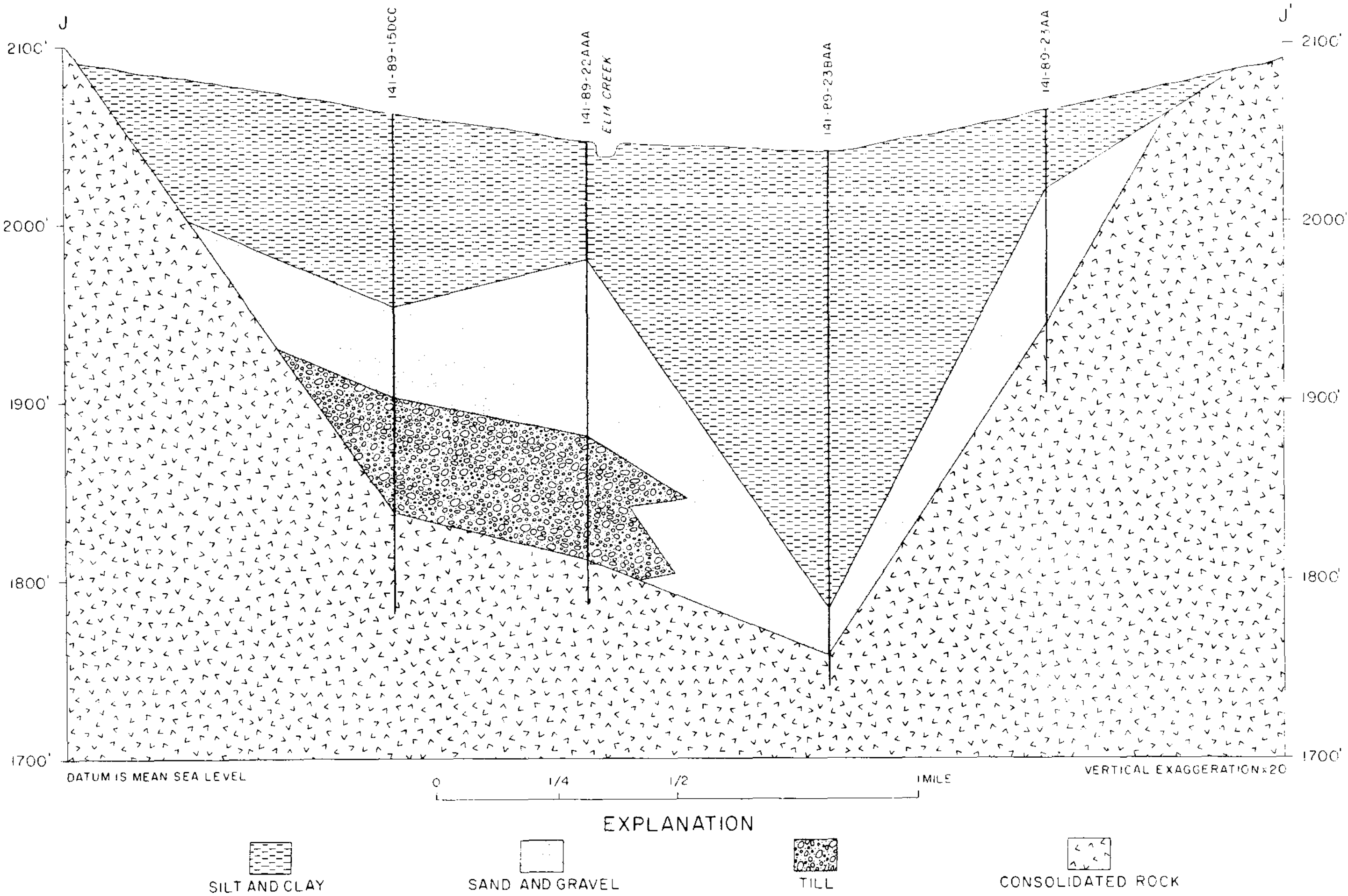
Water quality. Four water samples collected from the aquifer were high in dissolved constituents (figure 8), and were of the sodium sulfate type. Sodium constituted 65 to 80 percent of the cations. Total dissolved solids ranged from 2,320 to 4,650 ppm. Iron ranged from 0.3 to 18 ppm, and fluoride ranged from 0.1 to 0.4 ppm. The water was classified C4-S3 to C4-S4 and should not be used for irrigation purposes without special management practices.

USE OF WATER IN MERCER AND OLIVER COUNTIES

Approximately 137,000 acre-feet of water (table 3) from rivers, streams, and ground-water reservoirs was used in Mercer and Oliver Counties in 1968. About 135,000 acre-feet of this amount was obtained from surface sources and about 2,270 acre-feet of this amount was obtained from ground-water sources.

An estimated 129,000 acre-feet was pumped from the Missouri River for cooling purposes by two lignite-burning electric-generating plants south of Stanton. The water used for cooling is returned to the river. The production of electrical power by lignite-burning plants is expected to quadruple in the next decade.

Water from the Missouri River has been appropriated for irrigation of 9,300 acres adjacent to the river. During years of normal precipitation, about 0.5 acre-foot of water per acre of land is needed in addition to precipitation for irrigated crops. Therefore, an estimated 4,600



LINE OF SECTION ON PLATE I

FIGURE 37.--Geologic section J-J′ through the Elm Creek aquifer, Mercer County.

TABLE 3.–Water use for 1968, in acre-feet

Surface-water sources	
Use	
Electric powerplants	129,000
Irrigation	4,600
Farm and livestock	1,000
Ground-water sources	
Use	
Industrial	300
Municipal	292
Artesian flow	1,100
Irrigation	18
Farm and livestock	560
Total	136,870

acre-feet was pumped from the Missouri River in 1968 for irrigation adjacent to the river. The demand for irrigation water from rivers and streams will probably increase greatly in the next 10 years.

An estimated 300 acre-feet of water per year was pumped from ground-water reservoirs in the study area for cooling purposes in electric-generating plants and for gravel washing. Industrial use of ground water will probably increase greatly in the next 10 years. The cities of Beulah, Hazen, and Center pumped approximately 292 acre-feet of water per year for municipal purposes. An estimated 18 acre-feet of ground water per year was pumped from two irrigation wells near Hensler. Because of the large available supplies of ground water suitable for irrigation, pumpage of ground water for irrigation could increase greatly in the next decade. About 1 mgd (1,100 acre-feet per year) of water was withdrawn from the artesian aquifers for livestock and domestic use. Much of the flow from the artesian aquifers was not used.

Water for farm and livestock use, obtained from both surface and shallow ground-water sources, was estimated at 1,560 acre-feet per year from data published by the North Dakota State University (1968).

SUMMARY

Most of the usable ground water in Mercer and Oliver Counties is obtained from (1) consolidated rocks of Late Cretaceous age, (2) consolidated rocks of Tertiary age, and (3) unconsolidated deposits of Quaternary age. Rocks older than Late Cretaceous age generally contain brackish of saline water. The availability of water from the major aquifers in the unconsolidated deposits and the consolidated rocks of Late Cretaceous and Tertiary ages is summarized on plate 1.

Important artesian aquifers occur within the consolidated rocks of the Fox Hills, Hell Creek, and Tongue River Formations. The aquifers in these formations consist mainly of fine- to medium-grained sandstone, and potential well yields generally will not exceed 150 gpm. Existing wells have specific capacities that range from 0.1 to 0.6 gpm per foot. Flowing wells tapping these aquifers are as much as 1,480 feet deep and are mainly in stream valleys. The total withdrawal from the artesian aquifers is about 1 mgd, and the water is used mainly for domestic and livestock purposes. The water is a sodium bicarbonate type that is high in dissolved constituents and is not suitable for irrigation.

Much of the water for domestic and livestock supplies in the rural areas is obtained from wells tapping beds of lignite. The yield from most of the lignite aquifers is probably less than 10 gpm, but is sufficient for the intended purpose. The water is highly variable in chemical quality. Conductivity measurements of several hundred water samples ranged from 500 to 7,000 micromhos per centimeter. Two water samples contained 1,050 and 1,810 ppm total dissolved solids. Iron in the samples was 3.3 and 3.6 ppm. Commonly the water is reddish brown.

Unconsolidated deposits of sand and gravel form important aquifers in the valleys of Goodman, Antelope, Elm, and Square Butte Creeks and the Knife and Missouri Rivers. These are the most productive aquifers in Mercer and Oliver Counties and contain about 2,640,000 acre-feet of ground water. Only 1,215,000 acre-feet is suitable for irrigation because the water in the Elm Creek aquifer is not usable for this purpose without special management practices.

The Goodman and Antelope Creek aquifers are in northwestern Mercer County. They are less than 1 mile to 1-1/2 miles in width and 200 to 250 feet thick. The water varies in quality and type with depth and location. Test holes screened near the bottom of the Goodman Creek aquifer north of Spring Creek obtained water that ranged from 771 to 1,090 ppm total dissolved solids. A shallower well, 80 feet in depth, contained 614 ppm total dissolved solids. Wells tapping the lower part of the Antelope Creek aquifer obtained water containing 423 to 1,460 ppm total dissolved solids.

The Knife River aquifer underlies the flood plain and terraces of the Knife River valley from the southwest corner of Mercer County to Stanton. It varies from half a mile to about 5 miles in width, and has a maximum thickness of about 240 feet east of Beulah. An aquifer test near Stanton indicated a transmissivity of 176,000 gpd per foot (23,500 square feet per day) at that site. The storage coefficient had a value of 0.0003. Water from the aquifer southwest of Beulah was high in dissolved constituents and sulfate constituted 47 percent of the anions. Analyses of water from the aquifer between Beulah and Coal Creek indicated that the water was low in dissolved constituents, but varied in quality and type with depth. Total dissolved solids ranged from 419 to 1,040 ppm. Total dissolved solids ranged from 503 to 1,740 ppm in analyses of water from the aquifer between Coal Creek and Stanton.

The Missouri River aquifer underlies the terraces and flood plains of the Missouri River from Garrison Dam to the southeast corner of Oliver County. The aquifer ranges from less than a quarter of a mile to 2 1/2 miles in width and is as much as 203 feet thick northeast of Hensler. Time-drawdown data for an aquifer test made 2 miles north of Hensler indicated that the aquifer at that site had a transmissivity of 107,000 to 121,000 gpd per foot (14,300 to 16,200 square feet per day) and a storage coefficient of about 0.02. The water contains moderate amounts of dissolved mineral constituents. Sodium and bicarbonate were the principal cations and anions in the samples. Total dissolved solids ranged from 585 to 1,660 ppm.

The Square Butte Creek aquifer occurs beneath the valleys of Kineman and Square Butte Creeks from the vicinity of Hazen to the southeast corner of Oliver County. The aquifer is as much as 130 feet thick 3 miles northwest of Center. Water samples collected from wells tapping the aquifer contained 374 to 863 ppm total dissolved solids.

The Elm Creek aquifer underlies the valley of Elm Creek in the southwestern corner of Mercer County. The sand and gravel forming the aquifer is as much as 152 feet thick. Water samples collected from the aquifer were of a sodium sulfate type. Total dissolved solids ranged from 2,320 to 4,650 ppm.

About 137,000 acre-feet of water was used in Mercer and Oliver Counties in 1968. About 134,000 acre-feet of water was taken from the Missouri River for cooling purposes in electric-generating plants and for irrigation. About 2,270 acre-feet of water was obtained from ground-water sources for industrial, livestock, and domestic use.

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DEFINITION OF TERMS

Amendment – a substance that aids plant growth by improving the condition of the soil.

Aquifer – a group of permeable saturated deposits.

Area of influence – the area affected by a discharging well.

Artesian water -- ground water that is under sufficient pressure to rise above the top of the aquifer.

Bank storage – Water absorbed and stored in the permeable bed and banks of a stream or lake and returned in whole or in part as the level of the surface-water body falls.

Barometric efficiency (B.E.) – equals the change in water level resulting from a change in atmospheric pressure, in feet, divided by the change in atmospheric pressure, in feet of water.

Bedrock -- consolidated rocks underlying glacial and alluvial deposits of Pleistocene and Holocene age.

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

Discharge -- the removal or loss of water from an aquifer or the flow of water into a stream.

Drawdown -- decline of the water level in a cone of depression caused by a discharging well.

Evapotranspiration – water returned to the air through direct evaporation from water or land surface and by transpiration of vegetation.

Flowing well – a well in an artesian aquifer having sufficient head to discharge water at the land surface.

Glaciofluvial deposits – sediments deposited by streams flowing from a glacier.

Ground water – water in the zone of saturation.

Ground-water divide – a line on a water table on each side of which the water table slopes downward from the line.

Ground-water movement -- the movement of ground water in the zone saturation.

Head -- the hydraulic pressure of water in a well.

Hydraulic conductivity (K) -- the rate at which water of the prevailing viscosity will move through a unit cross section of the material in unit time under a unit hydraulic gradient. The units for K are cubic feet per day per square foot ($ft^3/day/ft^2$), which reduces to ft/day. The term hydraulic conductivity is replacing the term field coefficient of permeability, which was formerly used by the U.S. Geological Survey and which was reported in units of gallons per day per square foot. The value for hydraulic conductivity is given in both units in this report. To convert a value for field coefficient of permeability to the equivalent value of hydraulic conductivity, multiply by 0.134; to convert from hydraulic conductivity to coefficient of permeability, multiply by 7.48.

Hydraulic gradient (i) – slope of the water table or potentiometric surface in either feet per foot or in feet per mile.

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

Hydrologic system – a series of interconnected aquifers and streams.

Infiltration – the movement of water from the surface towards the zone of saturation.

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

Irrigation -- the controlled application of water for crops.

Lacustrine deposits -- sediments formed in a lake environment.

Logarithm (log) -- the exponent of the power to which a fixed number (the base, usually 10) must be raised in order to produce a given number. Logarithmic scale enables large numbers to be plotted on a graph within a short distance.

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

Observation well -- a well from which hydrologic data are measured and recorded.

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

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

Porosity (θ) -- the ratio (expressed as a percentage)of the volume of voids in the rock to the total volume of the rock.

Potentiometric surface -- the imaginary horizon formed by the head in an artesian aquifer.

Radius of influence -- the distance between a discharging well and the edge of the cone of depression.

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

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

Specific capacity – the discharge from a well, generally expressed as gallons per minute per foot of drawdown.

Static water level -- the water level in a well that is outside the area influenced by pumping.

Storage – the quantity of water contained in openings in the zone of saturation.

Storage coefficient (S) – the volume of water released from or taken into storage per unit surface area of the aquifer per unit change in head. S is a dimensionless number. Under confined conditions, S is typically small, generally between 0.00001 and 0.001. Under unconfined conditions, S is much larger, typically from 0.001 to 0.20.

Tidal efficiency (T.E.) – equals the change in water level resulting from a change in surface-water stage, in feet, divided by the change in surface-water stage, in feet.

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

Transmissivity (T) – the rate at which water of the prevailing viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The units for T are cubic feet per day per foot (ft^3/day/ft), which reduces to ft^2/day. The term transmissivity is replacing the term coefficient of transmissibility, which was used by the U.S. Geological Survey and which was reported in units of gallons per day per foot. The value for transmissivity is given in both units in this report. To convert a value for coefficient of transmissibility to the equivalent value of transmissivity, multiply by 0.134; to convert from transmissivity to coefficient of transmissibility, multiply by 7.48.

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

Water table – the water table is the upper surface of the zone of saturation where the hydrostatic pressure is equal to atmospheric pressure. The configuration of the water table commonly is a subdued replica of the land surface.

Zone of saturation – the zone below the water table.