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COUNTY GROUND WATER STUDIES 9

NORTH DAKOTA STATE WATER CONSERVATION COMMISSION

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GEOLOGY AND GROUND WATER RESOURCES WILLIAMS COUNTY, NORTH DAKOTA

PART III -- HYDROLOGY

by
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Prepared by the United States Geological Survey in cooperation with the North Dakota State Water Commission, North Dakota Geological Survey, and Williams County Board of Commissioners.

GRAND FORKS, NORTH DAKOTA
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GEOLOGY AND
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of Williams County, North Dakota

Part III - Ground Water Resources

By C. A. Armstrong

ABSTRACT

Ground water in Williams County, North Dakota, is obtained from aquifers in the glacial drift of Quaternary age, the Fort Union Group of Tertiary age, and the Dakota Group of Cretaceous age. Three of the more productive aquifers are the Little Muddy, Ray, and Grenora; these aquifers are composed of sand and gravel that was deposited in the ancestral Yellowstone, Little Missouri, and Missouri River valleys, respectively. Properly constructed wells in the more permeable parts of these glacial aquifers can be expected to yield more than 500 gallons per minute. Yields of more than 500 gallons per minute are also obtainable from the more permeable parts of the Trenton and Hoffland aquifers in the proglacial Yellowstone and Missouri River valleys. Yields of 50 to 500 gallons per minute are obtainable from some outwash and buried glaciofluvial deposits in the northern part of the county and from some of the finer sand deposits in the five major aquifers.

Water from the glacial drift aquifers differs greatly in quality. Generally it is very hard and of a calcium bicarbonate type. Water in the Fort Union Group consists of two types; a soft sodium bicarbonate water, and a hard sodium sulfate bicarbonate water. Generally it is too saline for human consumption or irrigation. Water from the Dakota is used for pressure maintenance in oil fields, but is too saline for most other uses.

INTRODUCTION

Williams County, an area of about 2,100 square miles, is in the northwestern part of North Dakota (fig. 1). The county is bounded on the west by Montana, on the south by the Missouri River, on the north by Divide County, and on the east by Burke and Mountrail Counties.

The study of the geology and ground-water resources of Williams County has been a cooperative investigation made by the U. S. Geological Survey, the North Dakota State Water Commission, the North Dakota Geological Survey, and the Williams County Board of Commissioners. The geologic 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. The North Dakota Geological Survey mapped the geology of the county and will publish the results as Part I of this series. The basic data have been published as Part II of this series (Armstrong, 1967a).

Purpose and Scope

The purpose of the investigation was to evaluate the quantity and quality of ground water in Williams County. The principal objective was to locate moderate to large supplies of ground water that could be used for irrigation, industrial, or municipal supplies. Another objective was to locate dependable ground-water supplies that could be used for domestic and stock supplies.

Fieldwork was begun by E. A. Ackroyd during the summer of 1963 and continued under his leadership until 1965. The fieldwork consisted of inventorying wells and springs to obtain information about existing water supplies from water users in the county. Test holes were drilled to supplement the information gathered during the inventory. Water levels were measured periodically in selected wells to evaluate recharge to and discharge from the aquifers. Two aquifer tests in the Hofflund aquifer and one in the Little Muddy aquifer were made to determine the coefficients of storage and transmissibility and to establish a basis for estimating coefficients of transmissibility elsewhere in the county. Water samples were obtained from selected wells to determine the chemical characteristics of water in the county.

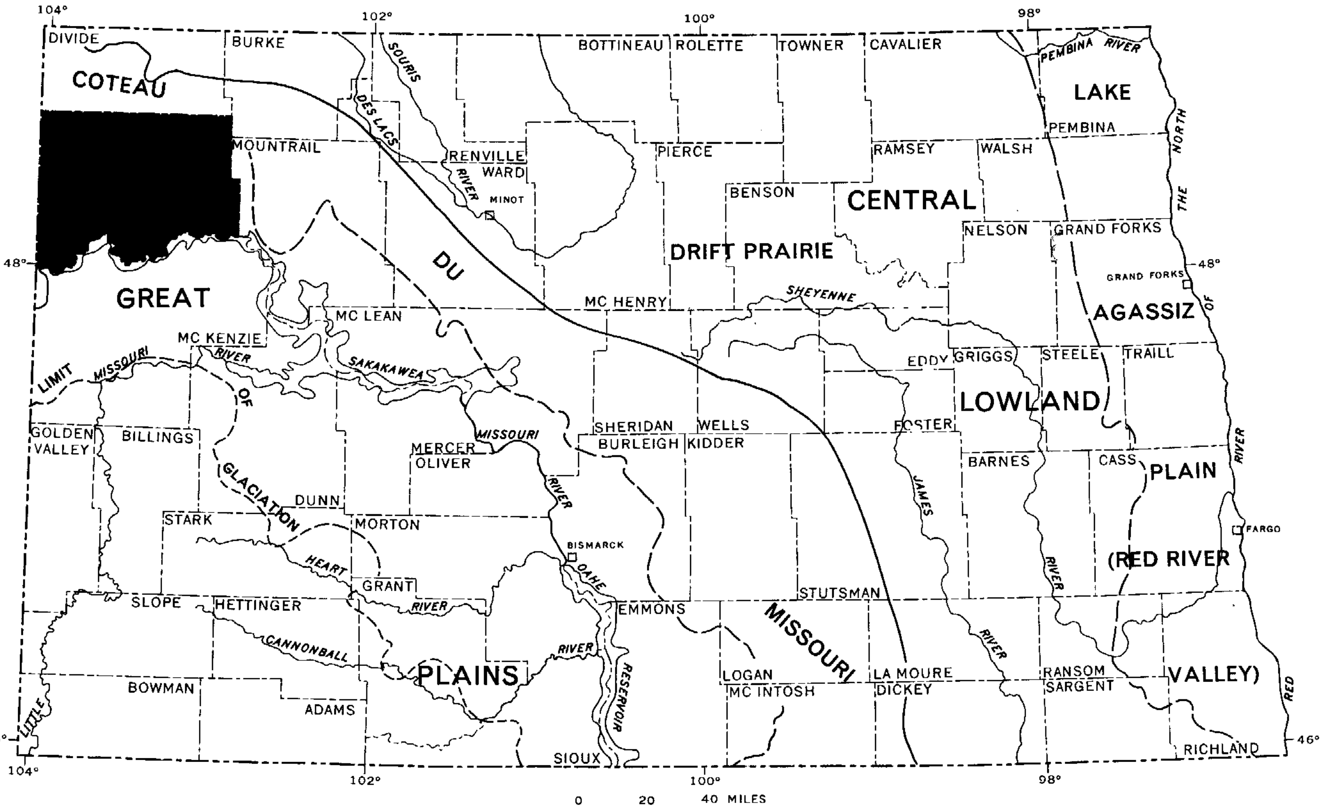


Figure 1. Map showing physiographic divisions in North Dakota and location of report area.

Well-Numbering System

The well-numbering system used in this report (fig. 2) is based on the federal system of rectangular surveys of the public lands. The first numeral denotes the township, the second denotes the range, and the third denotes the section in which the well, spring, or test hole 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). Thus, well 157-95-15add would be located in the SE¼SE¼NE¼ sec. 15, T. 157 N., R. 95 W. The numbering system also is used in this report for the location of small areas.

Previous Investigations

Williams County ground-water data were included by Simpson (1929) in a report on the ground-water resources of North Dakota. Simpson (1935) mapped a small area of artesian flow in the northeastern part of Williams County near Wildrose, and also discussed the changes in ground-water levels due to the drought of 1929-34 (Simpson, 1937). Abbott and Voedisch (1938) discussed the municipal ground-water supplies of Williams County and tabulated chemical analyses of water from the cities and villages using ground water. Water resources in approximately four townships in the northwestern part of the county were described in an investigation by Vorhis (1949). Witkind (1959), included a brief section on water resources in his report "Quaternary Geology of the Smoke Creek-Medicine Lake-Grenora Area, Montana and North Dakota." Schmid and Hoisveen (1961) investigated the ground-water potential for irrigation in the Little Muddy valley area, and Paulson and Powell (1962) made an investigation of the "Geology and Ground Water Resources of Tioga and Hofflund Flat Areas, Williams and Mountrail Counties, North Dakota." The North Dakota State Department of Health (1964) published analyses of water used in Williams County municipal supplies. Armstrong (1966) constructed a preliminary ground-water availability map of Williams County and Ackroyd (1967) constructed a preliminary map showing the potential yield of ground water from the Little Muddy aquifer. Several geologic and special mineral investigations have included at least part of Williams County.

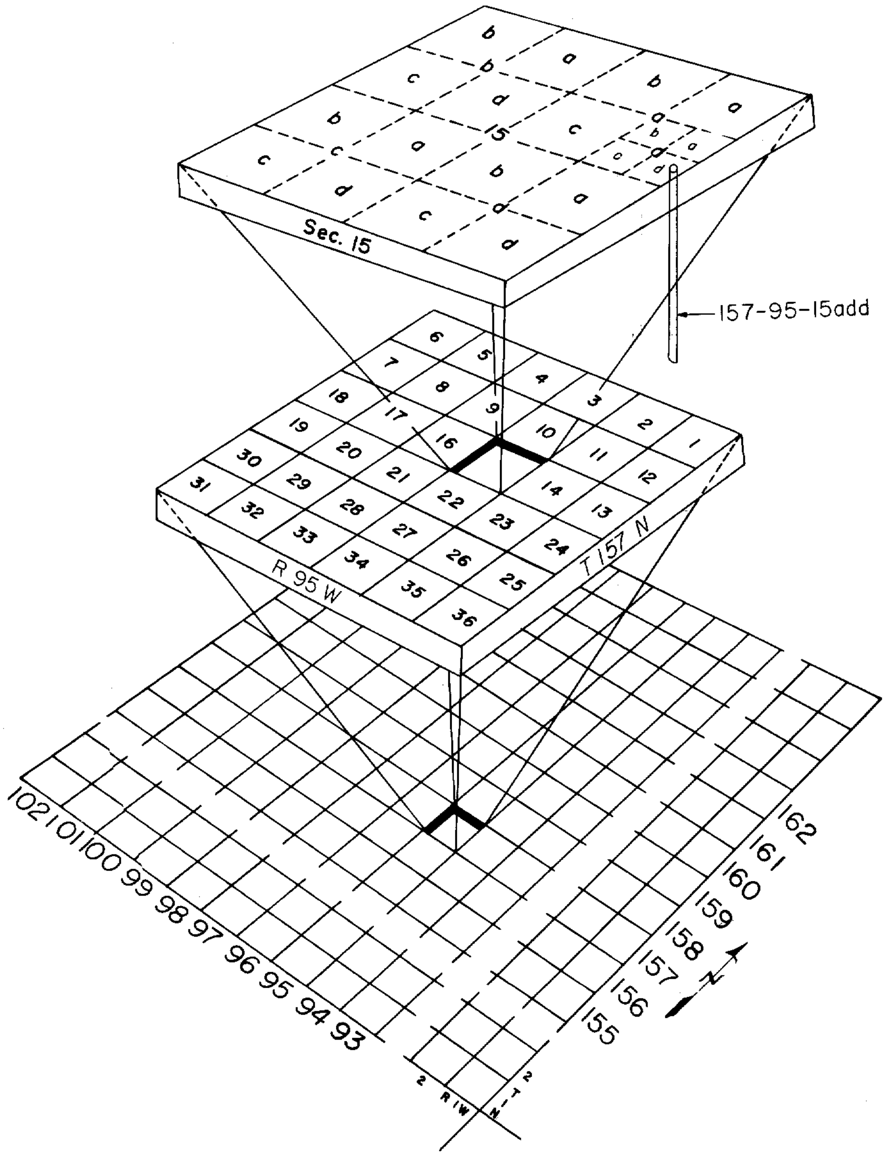


Figure 2. Diagram showing system of numbering wells, springs, and test holes.

Acknowledgments

Appreciation is expressed to the Williams County Commissioners, other county officials, the Williston Herald, and the Plains Reporter for aid and publicity that made it possible to complete the fieldwork without unnecessary delays. Particular recognition is due M. O. Lindvig and R. W. Schmid of the North Dakota State Water Commission for their aid during aquifer tests, and to the well drillers who furnished well logs. Recognition is also due to the Skelly Oil Co. for contributing drillers' logs of seismograph holes, and to the Amerada Petroleum Corp. for furnishing ground-water data on some of the deeper bedrock aquifers. Appreciation also is expressed to the farmers and ranchers of Williams County for giving free access to their lands and for their records of wells.

Population and Economy

The population of Williams County in 1960 was 22,051 (U. S. Bureau of Census, 1960). Williston, the county seat and largest city, had a population of 11,866. Except for Ray and Tioga, with populations of 1,049 and 2,087, respectively, all other cities have less than 500 inhabitants.

The county is served from the east and west by the Great Northern Railway, which connects all the cities and villages. U. S. Highway 2 crosses the county in an east-west direction and U. S. Highway 85 crosses in a north-south direction. Many state and county roads make all parts of the county accessible by motor vehicles, except in the winter and after heavy rains.

The economy of the county is based largely on agriculture. Small grains, flax, sugar beets, and hay are the principal crops. Cattle and sheep are other important sources of farm income. Petroleum production, refining, and services also make up a significant part of the economy.

Climate

The climate of Williams County is semi-arid. Figure 3 shows the monthly precipitation at the U. S. Weather Bureau stations at Grenora

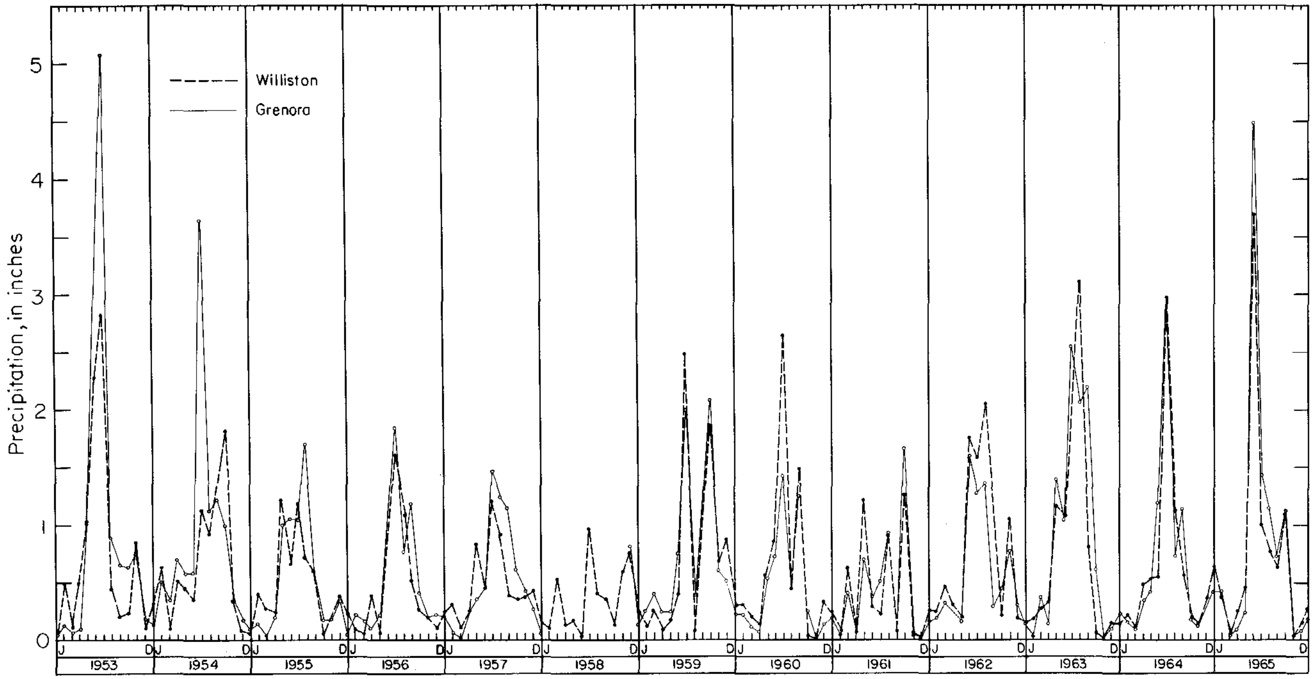


Figure 3. Graph showing monthly precipitation from 1953 through 1965 at Grenora and Williston.

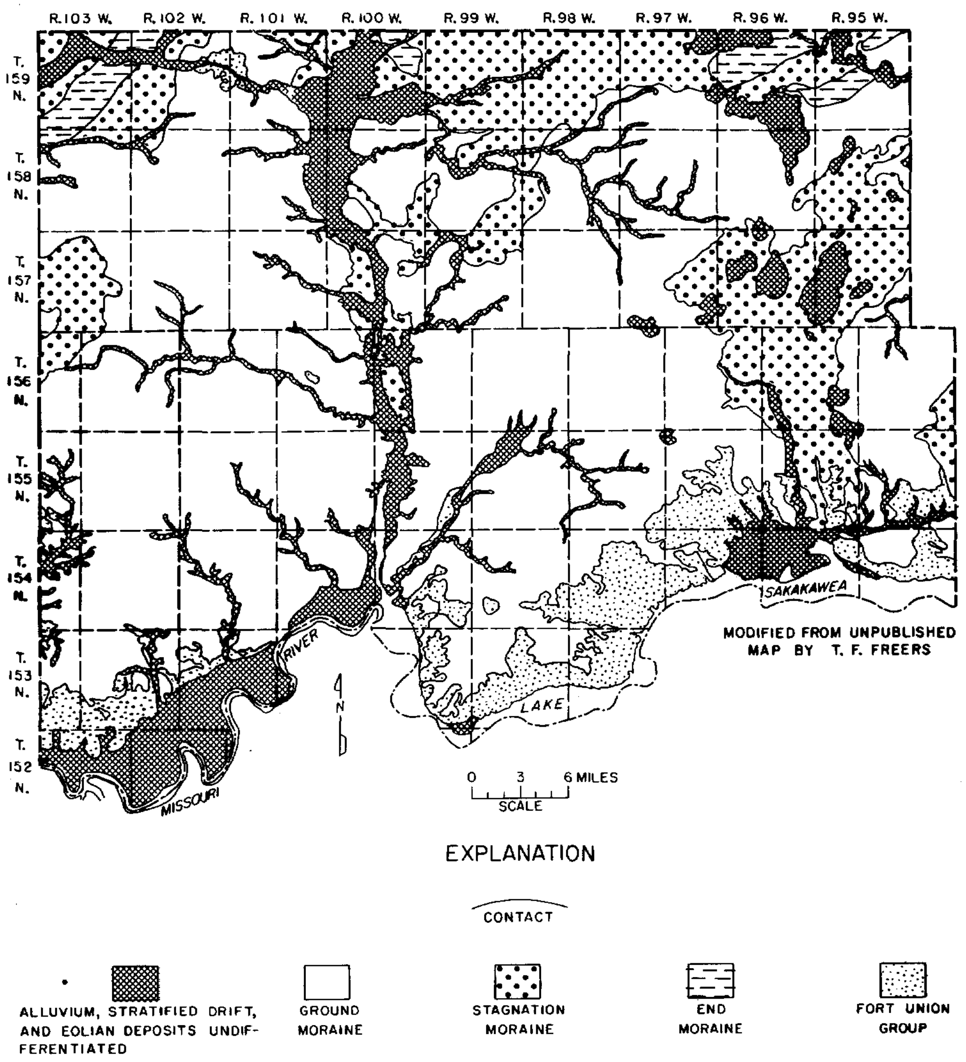
and Williston (U. S. Weather Bureau, 1954-66). The average annual precipitation is 13.70 inches at Williston and 14.21 inches at Grenora. About 75 percent of the precipitation falls during the growing season from May into September. The growing season from 1950 through 1965 averaged 132 days at Williston and 115 days at Grenora. Most of the summer precipitation is extremely variable from month to month and place to place within the county. It is not uncommon for a part of the county to receive an inch (or more) of rain during a thunderstorm while another part receives very little or none. Over a period of many years, precipitation in one area of the county probably is similar to that of a nearby area, but within any one growing season there can be an appreciable difference. For example: 16.82, 17.66, 15.94, 19.80, and 14.36 inches of rain fell at Epping, Grenora, Tioga, Wildrose, and Williston, respectively, during the period May through September 1965.

The minimum temperature in the county since 1949 was -41°F at Tioga and Williston on February 28, 1962. The summers are usually warm, generally ranging from 78° to 84°F. However, temperatures exceeding 90°F are not uncommon. The maximum recorded temperature in the county since 1949 was 107°F at Tioga on August 9, 1958.

Physiography and Drainage

Williams County lies within the glaciated area of the Missouri Plateau (fig. 1). The northern 3 to 8 miles of the county lie within an area of stagnation moraine and end moraine (fig. 4) called the Coteau du Missouri, which contains tracts of steep-sided hills and depressions. Most of the remainder of the county lies within an area of ground moraine, which is characterized by low to moderately undulating topography except where stream valleys dissect the surface.

Maximum topographic relief in the county exceeds 700 feet. The highest altitude is approximately 2,545 feet on the summit of a broad hill at 158-95-21aa. The lowest altitude was less than 1,800 feet in the Missouri River valley in the southeastern part of the county; however, since the spring of 1965, Lake Sakakawea has flooded much of the low land and the minimum altitude in the county is now represented by the lake level. Local relief generally is less than 100 feet per mile, but exceeds this in the area of end moraine.



MODIFIED FROM UNPUBLISHED MAP BY T. F. FREERS

Figure 4. Map showing landforms and surficial deposits.

Drainage in the report area is of two types: integrated and interior. The integrated drainage flows toward the Missouri River through tributaries such as Beaver Creek or indirectly through Little Muddy Creek. Little Muddy Creek drains slightly more than 45 percent of the county; however, drainageways are poorly developed in some of the higher areas. Flow from these areas occurs only during spring thaws following above normal winter precipitation. Figure 5 is a hydrograph of the monthly mean flow of Little Muddy Creek at 155-100-5ba (U. S. Geological Survey, 1954-65). The peak flows generally occur in March or April, but may be as late as May. The maximum discharge recorded at this site was 6,910 cfs (cubic feet per second) on March 27, 1960. The secondary peaks, such as occurred in June 1962 and July 1963, are caused by heavy rainfalls of short duration. Most of the low flows, usually from May or June through February, are caused by ground-water discharge. The minimum flow during the period of record from July 1954 to September 1965 was 0.2 cfs in November 1960 and February 1963. The increase in flow, which generally occurs in September or October, results from the decreased transpiration of plants following the killing frosts in the fall.

The interior drainage is most common in areas of high relief in the northern part of the county. These areas are characterized by undrained depressions, which commonly are called sloughs or prairie potholes. Most depressions are part of a small drainage basin, but some fill up and spill over into lower potholes or into the Missouri River drainage system. Most of the depressions contain water for only a few months during the spring and early summer; although some have drainage areas of several hundred acres or more and generally contain water throughout the year.

PRINCIPLES OF GROUND-WATER OCCURRENCE

All ground water of economic importance is derived from precipitation. After precipitation falls on the earth's surface, part is returned to the atmosphere by evaporation, some of the precipitation runs off to the streams, and the remainder sinks into the ground. Much of the water that sinks into the ground is held temporarily in the soil

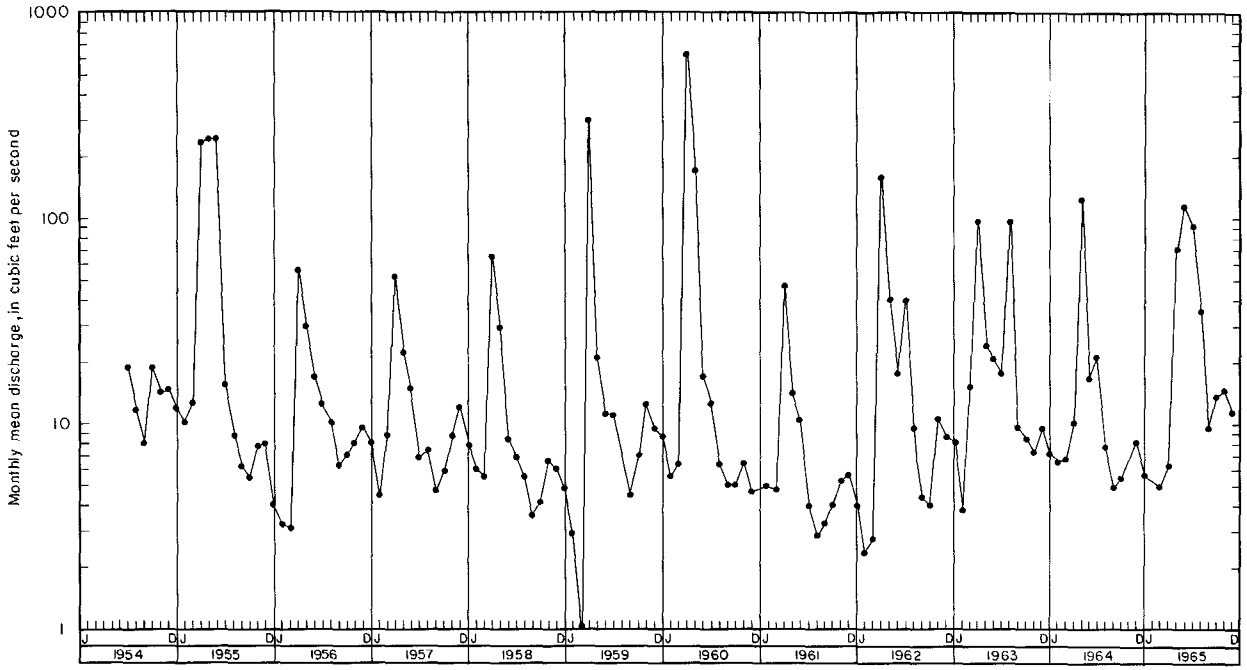


Figure 5. Hydrograph showing monthly mean flow of Little Muddy Creek at 155-100-5ba

and then is returned to the atmosphere either by evaporation or by transpiration. The water that infiltrates downward to a saturated zone (zone of saturation) becomes ground water.

Ground water moves under the influence of gravity from areas where water enters the ground (recharge) to areas where water leaves the aquifer (discharge). The rate of ground-water movement is generally very slow; it may be only a few feet per year. This rate of movement is governed by the permeability of the deposits through which it moves and by the hydraulic gradient or slope of the water table or piezometric surface.

Porosity is the ratio of the volume of the open or pore space in a rock to its total volume and is an index of the storage capacity of the material.

Permeability refers to the ease with which a fluid will pass through porous material. The degree of permeability is determined by the size and shape of the pore spaces in the rock and the extent of their interconnections. Gravel, well-sorted medium or coarse sand, and fractured lignite beds generally are highly permeable. Well-cemented deposits and fine-grained materials such as silt, clay, and shale usually have a low permeability, and may act as barriers that impede the movement of water into or out of more permeable rocks.

The coefficient of transmissibility is a measure of the rate of flow through porous material. It is expressed as the number of gallons of water that will move in 1 day under a unit hydraulic gradient (1 foot per foot) through a vertical strip of the aquifer 1-foot wide extending the full saturated height of the aquifer.

The coefficient of permeability is the rate of flow in gallons per day through 1 square foot of the aquifer under a unit hydraulic gradient. Thus, the field coefficient of permeability is equal to the coefficient of transmissibility divided by the thickness of the aquifer. The field coefficient of permeability is measured at the prevailing water temperature.

The coefficient of storage is the volume of water released from or taken into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface. Under water-table conditions, the coefficient of storage is practically equal to the specific yield, which is the volume of water released by gravity drainage divided by the volume of the material drained. The specific yield may be equal to only about half of the total porosity, and the coefficient of storage only a very small fraction of the porosity.

The upper surface of the zone of saturation is called the water table. This surface is irregular and is controlled by the topography, geology, and hydrology of the area. Water-table conditions refer to a ground-water environment that is not confined by overlying impermeable beds, and the water is free to move in response to gravity. If an aquifer is overlain by relatively impermeable beds, the water is confined and is under pressure exerted by water at higher elevations and by the confining beds. The water level will rise above the level at which it is first encountered; wells supplied from this type of aquifer are said to be artesian. The piezometric surface is that level to which artesian water would rise in an open column.

The water level in a well fluctuates in response to recharge to and discharge from the aquifer. Atmospheric pressure changes and land surface loadings also cause minor water-level fluctuations in artesian aquifers. The static level is the water level in the well when it is not being pumped. When water is withdrawn from a well, the water level near the well is lowered; the piezometric surface resembles a cone around the well, which is called the cone of depression. The amount of water-level drawdown, or the difference between the static level and the pumping level, is controlled by the capacity of the aquifer, the physical characteristics of the well, and the rate and duration of pumping. During constant and uniform discharge from a well, the water level declines rapidly at first and then continues to lower at a decreasing rate as the cone of depression broadens.

Specific capacity, which is a measure of well performance, is determined by dividing the rate of pumping, in gallons per minute, by the drawdown, in feet. Specific capacity is expressed as gallons per minute per foot of drawdown.

The water level in a pumping well necessarily must decline in order that water may flow from the aquifer to the well. However, the amount of water-level decline becomes serious only if (1) it causes water of undesirable quality to move into the aquifer, (2) if the yield of the well decreases because of interference from other wells or from aquifer boundaries, (3) if the pumping lift increases to the point where pumping becomes uneconomical, or (4) if the water level declines below the top of the screen. When pumping is stopped, the water level rises in the well and its vicinity at a decreasing rate until the water level again approaches the static level.

Under natural conditions, over a long period of time, the rate of discharge from an aquifer approximately equals the rate of recharge. When equilibrium exists, the amount of water in storage remains essentially the same. However, some water-level fluctuations may occur when periods of peak recharge and discharge are at different times.

Withdrawal of water from an aquifer causes one or a combination of the following: (1) a decrease in the rate of natural discharge, (2) an increase in the rate of recharge, or (3) a reduction in the volume of water in storage. If ground-water withdrawal plus natural discharge does not exceed recharge to an aquifer, the water level will approach equilibrium. If they exceed recharge, the excess will be withdrawn from storage. When water is taken from storage, the water level continues to decline as long as water is discharged.

The maximum rate of ground-water withdrawal that can be maintained indefinitely is related directly to the rate of recharge. However, recharge is regulated largely by climate and geologic controls and is impossible to evaluate quantitatively without large amounts of data.

QUALITY OF WATER

All natural water contains dissolved solids. Rainfall begins to dissolve mineral matter as it falls to the earth and continues to dissolve it as the water infiltrates through the earth. The amount and kind of mineral matter dissolved depend upon the solubility and types of rocks or other mineral matter encountered, the length of time the water is in contact with them, and the amount of carbon dioxide and soil acids in the water. Water that has been underground a long time, or has traveled a long distance from the recharge area, generally is more highly mineralized than water that has been in transit for only a short time and is withdrawn near the recharge area. Ground water usually contains more dissolved minerals than water from streams.

The dissolved mineral constituents in water are usually reported in parts per million (ppm) or grains per U. S. gallon. A part per million is a unit weight of a constituent in a million unit weights of water. Parts per million can be converted to grains per gallon by dividing the parts per million value 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 necessary to calculate percent sodium, the sodium-adsorption 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.

The chemical analyses of water in Williams County were listed by Armstrong (1967a, table 4). The data in the table are summarized in the discussion of the major aquifers described in this report.

Table 1 was modified from Durfor and Becker (1964, table 2). It shows the major constituents in water, their major sources in Williams County, and their effects upon usability. Most, if not all, of the minerals shown in the major source column are present in the glacial drift or the Fort Union Group in Williams County.

The chemical properties and constituents most likely to be of concern to residents of Williams County are: (1) dissolved solids and the related specific conductance, (2) sodium-adsorption 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.--Major chemical constituents in water--their sources, concentrations, and effects upon usability
(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)	Feldspar, ferromagnesium, and clay minerals.	In presence of calcium and magnesium, silica forms a scale in boilers and on steam turbines that retards heat.	
Iron (Fe)	Natural sources: Amphiboles, ferromagnesium minerals, ferrous and ferric sulfides, oxides, and carbonates, and clay minerals. Manmade sources: well casings, pump parts, 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 action of soap. High concentrations of magnesium have a laxative effect.	
Magnesium (Mg)	Amphiboles, olivine, pyroxenes, dolomite, magnesite, and clay minerals.		
Sodium (Na)	Feldspars, clay minerals, 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 damaged by concentrations of 2.0 ppm.	
Bicarbonate (HCO_3)	Limestone and dolomite.	Upon heating, bicarbonate is changed to steam, carbonate, and carbon dioxide. Carbonate combines with alkaline earth (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 temperature. Limits range from 0.6 ppm at 90.5°F to 1.7 ppm at 50°F.
Nitrate (NO_3)	Nitrogenous fertilizers, animal excrement, 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.

Dissolved Solids and Specfic 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 10,000 ppm. However, growth and reproduction of livestock may be affected by water containing more than 3,000 ppm of dissolved solids.

The specific conductance of water is a measure of the water's ability to conduct an electrical current: it is a function of the amount and kind of dissolved mineral matter. Specific conductance usually is reported in micromhos. An estimate of the total dissolved solids in parts per million can be obtained by multiplying specific conductance by 0.65; however, the conversion factor may range from 0.55 to 0.75, depending upon the type and amount of dissolved minerals. For example: water from well 152-100-3bbb has a specific conductance of 3,050 micromhos; the analysis shows that there are 2,010 ppm dissolved solids, which is a factor of 0.66.

Irrigation Indices

Two indices used to show 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. The hazards increase as the numerical values of these indices increase. Figure 6 shows the SAR versus the specific conductance of analyzed water from Williams County. The analyses are plotted in order to show the general range of sodium and salinity hazards of water from the glacial drift, the Fort Union Group, and surface sources. The figure indicates that some of the water in Williams County should not be used for irrigation. It also indicates that much of the water is of marginal quality for irrigation, but high sodium and high salinity hazard waters can be used successfully with ideal soil conditions and drainage in conjunction with proper water management.

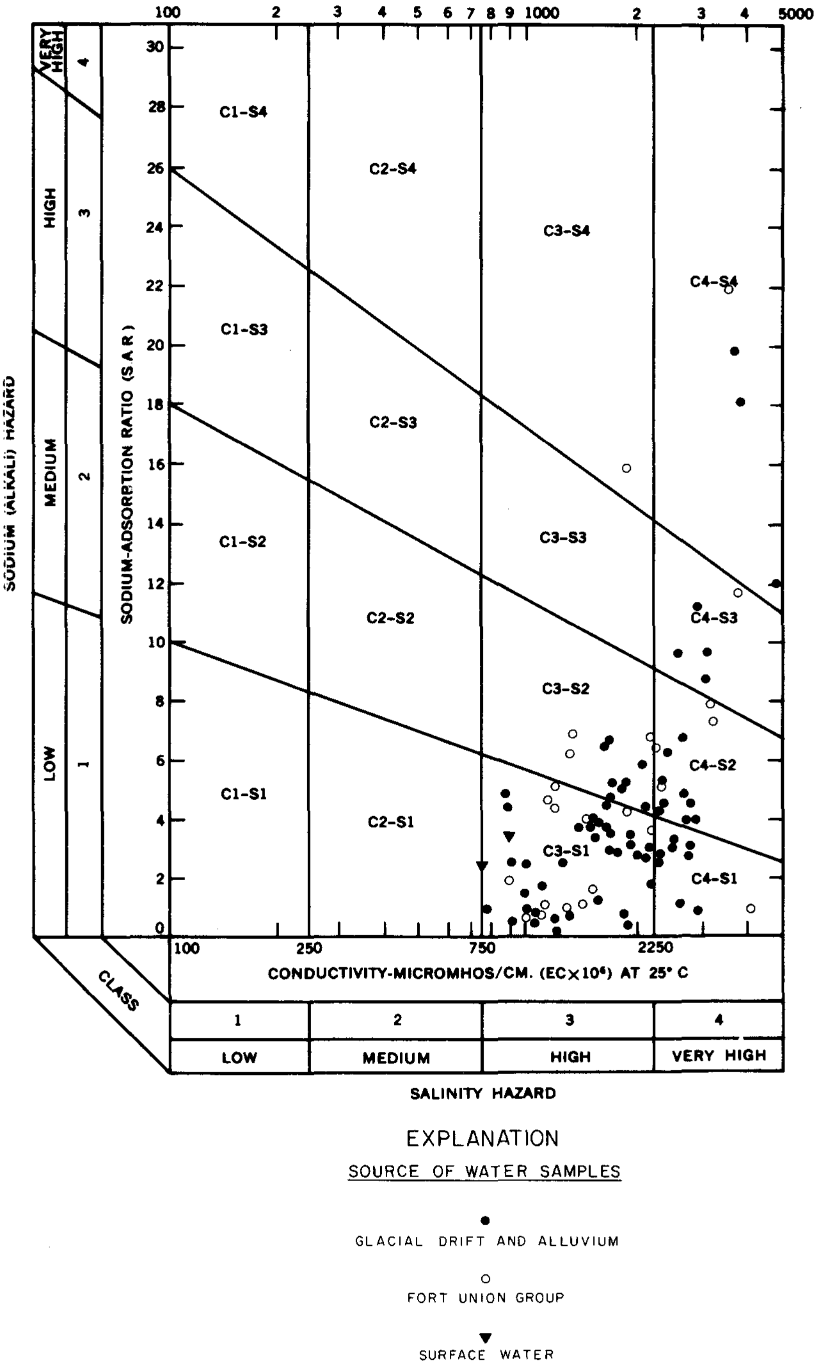


Figure 6. Graph showing salinity and sodium hazard classifications of selected water samples.

Another index used to rate irrigation water is the residual sodium carbonate (RSC). This quantity 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 marginal for irrigation. An RSC of more than 2.5 epm indicates that the water is not suitable for irrigation purposes. Generally the water in Williams County has an RSC index of less than 2.5 epm. Good management practices and the proper use of amendments 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 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. Water from the glacial drift in Williams County is generally very hard. Water from the upper part of the Fort Union Group generally is very hard also, but the water from the lower part of the Fort Union Group, above the Cannonball Formation, generally is soft.

THE ROCKS AND THEIR WATER-BEARING PROPERTIES

The sedimentary rocks of Williams County that contain aquifers are divided into the following units: (1) rocks of pre-Cretaceous age, (2) Dakota Group of Cretaceous age, (3) Fox Hills and Hell Creek Formations of Cretaceous age, (4) Fort Union Group of Tertiary age, and (5) glacial drift of Quaternary age. The Dakota Group, Fort Union Group, and the glacial drift contain the only aquifers that are presently of economic importance. Consequently, these are described in the greatest detail. The Fox Hills and Hell Creek Formations are included in the aquifer-bearing units of Williams County even though there is a scarcity of data. They probably contain some water of economic value as they do elsewhere in North Dakota.

In western North Dakota, pre-Quaternary sedimentary rocks were deposited in the large, sporadically sinking Williston basin. Williams County is located over the north-central part of this basin; consequently, the rocks generally dip to the south in the western part of the county. The eastern part of the county generally overlies the axis and western flank of the Nesson anticline, a north-south-trending fold within the basin; hence the beds dip westward in this part of the county. The total structural effect is a somewhat asymmetrical trough-like structure that dips southward. The axis of this trough extends through the west-central part of the county.

The sediments in the deepest part of the basin, which apparently is in McKenzie County, are more than 15,000 feet thick.

The data concerning the pre-Cretaceous systems, as used in this paper, are based on information obtained from petroleum exploration.

Rocks of Pre-Cretaceous Age

Rocks of pre-Cretaceous age generally lie more than 5,000 feet beneath the land surface in Williams County; they are, however, only about 4,600 feet beneath the Missouri River where it crosses the Nesson anticline. The rocks are composed of limestone and dolomite with lesser amounts of sandstone, shale, and evaporites. Some of the limestone is porous, and lost circulation during oil-test drilling indicates that some of the limestones are cavernous. These rocks would yield very large supplies of water. The sandstones are reported to be either fine or very fine grained and would yield a small, dependable supply of water. An analysis of water from the Madison Group of Mississippian age in oil test 157-95-12bc shows that the sample contained 103,000 ppm sodium, 191,000 ppm chloride, and 311,000 ppm dissolved solids. The quality of water elsewhere in the Madison Group and in the other pre-Cretaceous rocks of Williams County probably differs considerably, as it does in Divide County where the analyzed water contained from 205,100 to 328,000 ppm dissolved solids (Armstrong, 1967b, p. 16). Some of the shallower pre-Cretaceous rocks may contain water of much better quality than that in the sample; nevertheless, the water would not be suitable for most purposes.

Cretaceous System

Dakota Group

The Dakota Group consists of the Lakota, Fall River, Skull Creek, Newcastle, and Mowry Formations. A series of sandstone lenses in the basal Dakota Group, commonly referred to as the Dakota Sandstone, is believed to be equivalent to the undifferentiated Fall River and Lakota Formations in Williams County (D. E. Hansen, oral communication). These sandstone lenses form the only important aquifer in the group and are herein referred to as the Dakota aquifer.

The Dakota aquifer generally ranges from 280 to 420 feet in thickness and averages about 375 feet. It is composed of hydraulically connected beds of very fine- to fine-grained sandstone with interbedded gray shale. Locally, drillers' logs indicate considerable amounts of medium sand. Electric logs of oil tests at 154-100-23ac, 159-103-29ac, and 155-95-6cc indicate that sandstone lenses comprise approximately 25 to 45 percent of the total aquifer thickness. The remainder is predominantly shale and silt. The depth to the top of the aquifer ranges from 4,202 feet in well 154-96-2ab near the axis of the Nesson anticline, to 5,590 feet in an oil test at 154-100-23ac near the deepest part of the Williston basin in Williams County (T. F. Freers, written communication). The altitude of the top of the aquifer at these two locations is -2,308 and -3,340 feet (mean sea level), respectively (Hansen, 1958, p. 3).

The Newcastle Formation in Williams County is lithologically similar to the sediments in the Dakota aquifer, but is somewhat finer grained and the formation is much thinner than the Dakota aquifer. The depth and limited thickness of the Newcastle preclude the possibility of its being a major aquifer even though it probably would yield small quantities of water.

Yield

The average coefficient of permeability at most locations in the Dakota aquifer probably is low. In 1966, seven wells (154-96-2ab, 155-95-7cd, 155-96-15aa, 156-95-18adb, 156-96-25cc, 157-95-25bd, and 158-95-35dd) were producing water from the Dakota aquifer. Each of six wells was pumped at the rate of approximately 290 gpm (gallons per minute); the seventh well was pumped at the rate of 156 gpm. Pumping levels were not reported; consequently, the specific capacities of these wells could not be determined. However, by comparing pumping rates with the difference between the static water levels and the pump settings of each well, it is estimated that specific capacities of the wells range between 1 and 3 gpm per foot of drawdown. The specific capacity of well 156-96-25cc is probably less than 0.4 gpm per foot of drawdown.

Quality of Water

Water from the Dakota aquifer in Williams County is of poor quality. The three nearly complete analyses from the basal sands (Armstrong, 1967a, table 4) show that the water is a sodium chloride type with total dissolved solids ranging from 9,650 to 11,000 ppm, sodium ranging from 3,670 to 4,020 ppm, and chloride ranging from 3,900 to 5,330 ppm. Sulfate, which ranges from 848 to 1,300 ppm also is high. These samples were obtained from wells near the eastern part of the county. Analyses of water from Burke and Divide Counties (Armstrong, 1967b, p. 29) and from a well in the NE¼NE¼ sec. 29, T. 36 N., R. 53 E. in Montana indicate that the water in the Dakota aquifer is similar throughout Williams County and the nearby surrounding area.

Fox Hills and Hell Creek Formations

The Fox Hills and Hell Creek Formations have not been tapped by any water wells in Williams County. However, the electric and drillers' logs of oil tests at 154-100-23ac (Hansen, 1958) and 155-95-6cc (Garske, 1958) indicate the presence of clay with some silt, sand, and lignite within the interval occupied by these two formations. Most other electric logs of oil tests in the county that show the Fox Hills and Hell Creek intervals indicate the presence of some sand or lignite between about 1,400 and 2,000 feet. Locally, however, these lithologies are poorly developed.

The Fox Hills and Hell Creek Formations probably would yield small to moderate quantities of water in most areas of Williams County. The larger yields could be obtained only in those areas where the sand is relatively thick and the average grain size is larger than very fine sand, 0.125 mm (millimeters). For example, in well 155-95-6cc the sample description of the sands of the Fox Hills and Hell Creek Formations and the thickness as shown on the electric log indicate that yields in excess of 1 gpm per foot of drawdown could be obtained at this location. However, the log of well 154-100-23ac shows that the formations contain much clay and very fine sand; consequently, yields probably would be smaller at this location.

The quality of the water in these formations has not been determined in Williams County, but it probably would be similar to the water obtained from a well (152-102-11ab) tapping the Fox Hills Formation in McKenzie County. The water was a very soft sodium bicarbonate type with 1,320 ppm dissolved solids. The water also contained 5.7 ppm fluoride, which greatly exceeds the U. S. Public Health Service standards for human consumption.

Tertiary System

Fort Union Group

The Fort Union Group of Tertiary age is the youngest bedrock in the county. It crops out along the Missouri River bluffs and in a few small areas elsewhere in Williams County (fig. 4). The Fort Union generally underlies the glacial drift at depths of less than 100 feet throughout much of the southern half of the county, except where the drift exceeds 100 feet in the large buried valleys. Depths to the Fort Union are commonly more than 100 feet in the northern half of the county, but many exceptions do exist. The group has been subdivided into four formations in some parts of North Dakota: the marine Cannonball Formation; the continental Ludlow Formation, which is a lateral equivalent to the Cannonball; the continental Tongue River Formation; and the continental Sentinel Butte Formation.

Plate 1 (in pocket) shows the topographic surface of the Fort Union Group as it would appear if the glacial drift and alluvial material were removed. Where depth to bedrock is less than 50 feet, the bedrock surface is reflected to a great extent through the drift. Elsewhere, except in the ancestral Yellowstone valley, the bedrock surface generally is masked by the drift. The ancestral Yellowstone River valley, the Ray valley (possibly an ancestral valley of the Little Missouri River), and both the ancestral and modern Missouri River valleys are shown with some of their tributaries on plate 1. Many small tributaries probably exist, but are not shown because of lack of data. The preglacial topography of Williams County was rugged, and probably was similar to that of the present badlands area in Billings and McKenzie Counties.

Cannonball and Ludlow Formations

The Cannonball Formation does not crop out and apparently does not directly underlie the glacial drift or alluvium in Williams County. Forty-four feet of glauconitic fine sand, believed to be part of the Cannonball Formation, was penetrated beneath 341 feet of alluvium and Tongue River sediments in test hole 154-96-12ccb. The top of the sand is at an altitude of 1,544 feet. The total thickness is not known because the sand was not completely penetrated. Information from oil tests is rather scanty, and definite identification of the Cannonball Formation has not been made in these tests. However, the top of the formation was tentatively picked in oil-test hole 154-100-23ac at an altitude of 1,323 feet. The electric log and the lithologic log (Hansen, 1958) of the oil test suggest that the Cannonball Formation is composed of 130 feet of interbedded sand, clay, silt, and some lignite, with the sand and lignite occupying about 45 percent of the total interval.

The areal extent of the formation is not known, but the presence of the Cannonball Formation in northwestern Divide County (Armstrong, 1967b) as well as in southern Williams County (test hole 154-96-12ccb) indicates that the Cannonball underlies all of Williams County.

The Ludlow Formation does not crop out in Williams County. If the formation is present in the subsurface, it has not been identified as a separate unit.

Yield

The sand thicknesses penetrated indicate that the Cannonball Formation will yield at least a few gallons per minute to wells in Williams County. However, data are not sufficient to estimate maximum possible yields.

Quality of Water

No water samples were obtained from known Cannonball aquifers in Williams County. However, a sample from well 155-97-36dca1 (Armstrong, 1967a, table 1) indicated a mixture of water from the Cannonball and Tongue River Formations. The water is a sodium bicarbonate type with 2,070 ppm dissolved solids and 424 ppm chloride. These data, and the description of Cannonball water in Burke County (LaRocque and others, 1963, p. 39) indicate that much of the Cannonball water generally would contain from 2,000 to 4,000 ppm dissolved solids. Also, the chloride content probably is excessive.

Fort Union Group Undifferentiated

The Tongue River and Sentinel Butte Formations are recognizable units only on the surface in Williams County. They are lithologically and hydrologically similar in the subsurface; consequently, they are not differentiated in this report. These formations are composed of a series of nearly horizontal, lenticular beds of lignite, clay, silt, and very fine sand.

Outcrops in the bluffs along the Missouri River and its tributaries indicate that some lignite beds have an areal extent of as much as 10 square miles, but other sediment types generally cannot be traced for more than a few hundred yards. Clay and silt lenses are more common than sand and also appear to have a somewhat greater lateral extent.

Individual sand lenses within the undifferentiated Fort Union Group are usually not more than a few feet thick and are of very limited extent. Locally, however, such as in well 155-99-1abc, sand lenses are more than 10 feet thick (Armstrong, 1967a, table 2). Freers and Hansen (written communication, 1966) have reported a 90-foot section of fine to very fine, silty sand in the Missouri River bluffs a few miles west of the Hofflund aquifer.

Yield

The Fort Union Group is composed predominantly of fine-grained sediments. The quantity of water that can be developed depends to a great extent on the thickness, sorting, and grain size of the sand in the vicinity of the well. Because most of the sand lenses are very fine to fine grained and thin, the coefficient of transmissibility is low. At the present time (1968) there are no known wells capable of producing more than 30 gpm from the Fort Union Group in Williams County. However, E. H. Prather (well driller from Tioga) reports that a few of the wells he drilled south of Tioga for oil-well drilling needs but subsequently abandoned, produced as much as 40 gpm. These wells were reported to be about 350 feet deep. Also, it is possible that properly constructed wells completed in several of the sand lenses in the Fort Union would yield more than 40 gpm. Wells 152-100-3bbb and 155-97-36dcal produce flows from depths of 750 and 780 feet, respectively. Properly constructed wells in the same producing horizons as these wells probably could be pumped at a rate of more than 40 gpm also, but the drawdowns would be large.

Electric logs of several oil-test wells indicate a rather widespread sandy zone with interbedded clay and silt in western and central Williams County. This zone generally is between 600 and 800 feet deep and may be as much as 150 feet thick.

Laboratory data (Johnson, 1963, table 4) indicate that the coefficient of permeability of a very fine-grained sand generally would be between 10 and 100 gpd (gallons per day) per square foot; for silt the coefficient is between 1 and 10 gpd per square foot. The coefficient of permeability in some of the fine to very fine sand lenses possibly would be two or three times as large as Johnson's table shows. Thus, the coefficient of transmissibility of a 5-foot lens of sand generally would range from 50 to 1,500 gpd per foot.

A method of estimating coefficients of transmissibility from specific capacities was derived from a chart that shows a well in an aquifer with a transmissibility of 2,000 gpd per foot will have a specific capacity of 1 gpm per foot of drawdown (Meyer, 1963, p. 339). Thus, the specific capacity of a small-capacity well can be multiplied by 2,000 to obtain an approximate coefficient of transmissibility (the factor may be as much as 40 percent larger for large-capacity wells). This method assumes that the well is 100 percent efficient, fully penetrates the aquifer, and that the specific capacity is calculated at the end of 1 day of pumping. Specific capacities calculated on less than a day's pumping will result in estimated transmissibilities that are too high. The specific capacities listed in table 2 were based on less than 24 hours of pumping; therefore, the transmissibilities shown are high.

Lignite beds in the Fort Union Group also will yield water. The quantity depends upon the amount of fracturing, the size and extent of the fracture in the lignite, and the transmissibility of the overlying or underlying rocks. Yields from lignite beds are variable from place to place, but are commonly more than 1 gpm.

Most farm wells that pump from the Fort Union Group are completed in the uppermost saturated sand lens. The wells are equipped with cylinder pumps generally with capacities of only 2-4 gpm. Some of the lenses are only a foot or two thick and not capable of yielding more than the capacity of the pumps. The wells are usually deep, but even so, the water levels draw down to near the level of the cylinder when pumping. Most wells completed in lignite seams apparently have higher specific capacities than those finished in sand.

Most of the springs in the small tributary valleys of the Missouri River flow from sand or lignite in the Fort Union Group. Some, however, flow from the contact between the glacial drift and the Fort Union Group, and a few originate in the glacial drift. The springs generally flow at rates of from less than 1 gpm to more than 100 gpm. The smaller springs are usually local in extent, commonly with only one outlet. Water from the larger springs generally issues through fine sand and silt and the discharge area may extend over several hundred square feet.

No estimates of the total flow from the springs in Williams County have been made, but the flow probably amounts to several thousand gallons per minute. The flow makes up a part of the base flow and underflow of the tributaries of the Missouri River.

Well number	Specific capacity, gpm per foot of drawdown	Transmissibility, gpd per foot
157-95-26acc1	1	2,000
26acc2	1.9	3,800
26acb1	.3	600
26acb2	.4	800

TABLE 2

Estimated transmissibility of the Fort Union Group at selected locations

Recharge and Water-level Fluctuations

Recharge to the Fort Union Group probably occurs in small quantities in most areas where water stands at the surface for a considerable time. This allows some water to infiltrate to the zone of saturation. The quantity of recharge to the Fort Union Group is not known, but apparently it differs considerably from place to place and time to time. These variations are illustrated in figure 7, which shows the hydrographs of wells 154-98-11dbb, 155-98-28ddd, and 155-99-18aac. Wells 154-98-11dbb and 28ddd are in areas where there is no pumping within half a mile, and the hydrographs show only the effects of natural recharge and discharge with minor variations possibly from barometric effects. The hydrograph of well 155-99-18aac likewise shows the effect of natural recharge and discharge, but it also includes the effects of the spring and summer pumping of a small-capacity well less than 200 feet away. Also, the drift in the area is relatively permeable so the aquifer responds to recharge and discharge faster than wells 155-99-28ddd and 154-98-11dbb.

Quality of Water

Ground water in the deeper parts of the Fort Union Group is generally high in sodium and bicarbonate, and low in calcium and magnesium. Water in the shallower parts, however, contains a larger proportion of calcium and magnesium, and the quantity of calcium may exceed the sodium. Nearly complete chemical analyses (Armstrong, 1967a, table 4) were made of water samples from 28 wells that are believed to tap the Fort Union Group. The sodium concentration exceeded 50 percent of the cations in 15 samples and exceeded 80 percent in 8 samples. Sulfate exceeded the U. S. Public Health Service recommended limit of 250 ppm in 17 samples. Nitrate was excessive in only one sample. Dissolved solids in the Fort Union samples ranged from 538 to 4,160 ppm and exceeded 1,000 ppm in 17 samples.

Water samples were obtained from three wells in the southern part of the county that are more than 300 feet deep and probably are completed in the Tongue River Formation. The water in these samples was a sodium bicarbonate type that contained more than 1,750 ppm solids and 98 percent sodium. The water was soft and contained less than 20 ppm sulfate. Only one sample (155-97-36dcal) contained more chloride than the recommended limit.

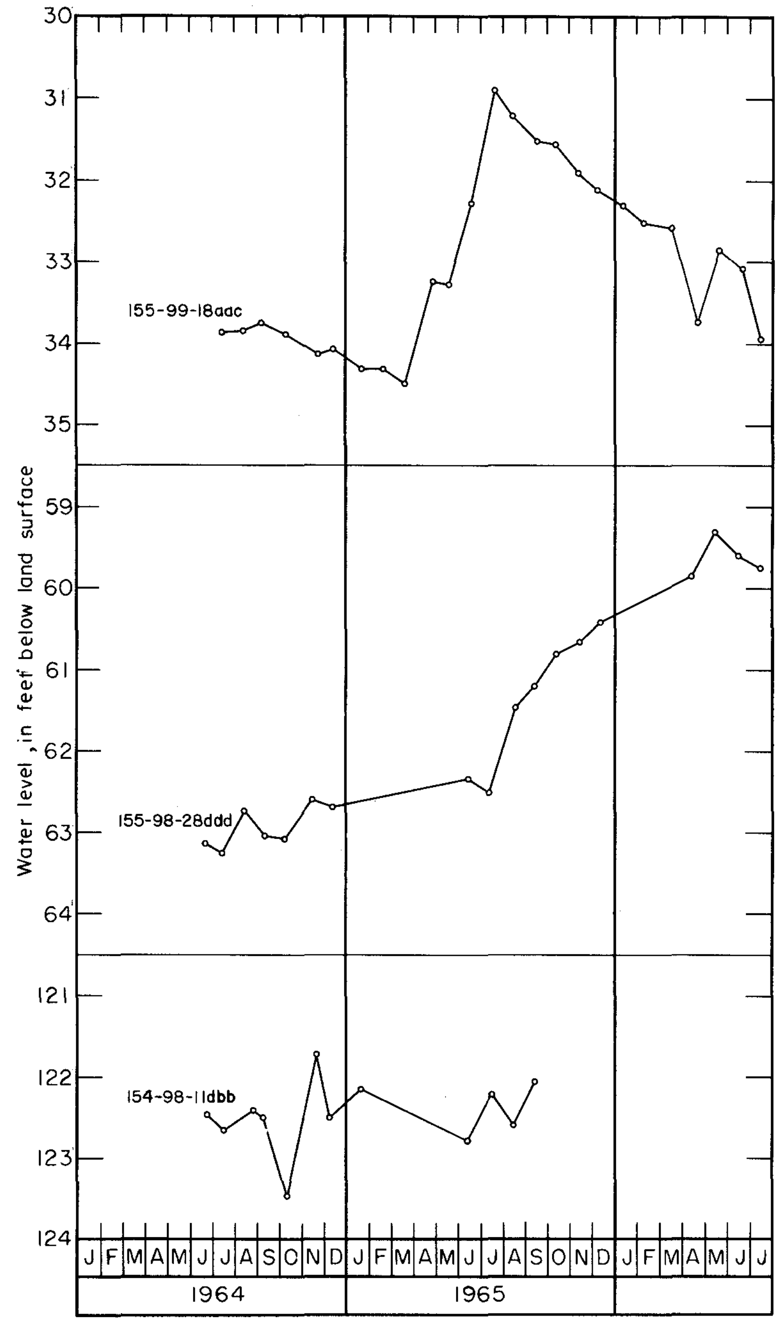


Figure 7. Hydrographs showing water-level fluctuations in wells in the Fort Union Group.

The quality of water differs greatly in shallower wells in the Fort Union Group. Conversely, the water in the deeper horizons is of a more uniform sodium bicarbonate type. Perhaps some unrecognized differences in the chemical composition of the Sentinel Butte and Tongue River Formations also influence the chemical quality of water in the shallow and deeper zones.

Quaternary System

Glacial Drift

For the most part, Williams County is covered by glacial drift that, in places, may be as much as 500 feet thick. The various types of drift deposits, as well as deposits in the Fort Union Group, were mapped and described in detail by T. F. Freers (written communication). The areas shown as stagnation and end moraines contain many prairie potholes and sloughs and are the principal areas of recharge. However, some recharge also occurs in the outwash areas and in some of the other geologic units in the county.

Most of the glacial drift is composed of till, a relatively impermeable mixture of clay, silt, sand, and gravel that yields little or no water. However, some drift consists of stratified glaciofluvial deposits of sand and gravel. The ability of the glaciofluvial deposits to yield large quantities of water depends on their transmissibility, size, and on the amount of recharge. If the sand or gravel deposit is enclosed in till, it receives recharge slowly; consequently, such deposits, particularly small ones, will not yield large quantities of water for sustained periods.

Vorhis (1949, p. 11) reported that there are three permeable zones within the drift in northwestern Williams County; which included one near the base of the drift, one at medium depth, and a shallow zone. The presence of three widespread permeable zones was disputed by Witkind (1959, p. 76) and their existence was not substantiated by this investigation.

Except in areas of buried valleys, a considerable part of the county is covered by relatively thin drift and only very local aquifers, if any, exist above the Fort Union Group. Water levels in these local aquifers compare with the regional water table or piezometric surface, which parallels the land surface in a very general way. Ground-water divides are in the general areas of the surface-water divides. The piezometric surface generally slopes toward the large drainages, such as Little Muddy Creek or the Missouri River, which are the principal areas of ground-water discharge in the county.

The principal aquifers in Williams County are in preglacial valleys and in valleys that were eroded by glacial melt water. These aquifers have been classified by their geographic, geologic, and hydrologic characteristics. Most are hydrologically distinct; however, the Ray aquifer, the aquifer in the Alamo outwash, and the aquifers in the alluvium and outwash in the Little Muddy Creek valley and tributaries are all part of an aquifer system associated with the ancestral Yellowstone valley and are hydrologically connected. The general direction of groundwater movement is indicated by arrows on plate 2 (in pocket).

In places it is difficult to distinguish glaciofluvial material from alluvium because the alluvium is predominantly reworked glaciofluvial material. In the present Missouri valley and some of its tributaries, the aquifers probably are comprised of glaciofluvial materials in the lower part and alluvium in the upper part.

The availability of water from glacial drift and alluvial aquifers in Williams County is shown in plate 2. Information from test holes and private wells, the bedrock topography map (pl. 1), and geologic map (fig. 4) were utilized to determine the extent of the aquifers. The yield of the aquifers was determined by extrapolating the thickness and water-bearing characteristics from each test hole. Test-hole logs were examined in detail, and the materials were divided into lithologic units.

The permeability of each unit was estimated from the grain size, apparent sorting, and drilling characteristics of the materials by using the range of values in the following table:

Material	Permeability (gpd per ft^2)
Gravel	2,500 - 4,000
Sand and gravel	2,000 - 2,500
Coarse sand	1,500
Medium sand	1,000
Fine sand	500
Silty sand	100 - 200
Silt	50

After the permeability was estimated at each test-hole site, the transmissibility was determined by multiplying the permeability coefficients of each hydrologic unit by the unit thickness; the products were then totaled. Probable specific capacities then were determined using Meyer's (1963) chart. Arbitrary drawdowns of 10 to 15 feet were used as a guide in determining the yields shown on plate 2. Combined yields are shown wherever two aquifers underlie the same area. Most of the test holes were drilled by hydraulic rotary methods, which commonly produce samples having less silt and clay and a higher degree of sorting than a true sample. Some allowances were made for this discrepancy when permeabilities were assigned. The aquifer tests that were run in the county also indicate that the method used in determining transmissibilities for the construction of the availability map was conservative, but reasonably accurate.

The Ray, Grenora, Hofflund, and Trenton aquifers and the northern part of the Little Muddy aquifer generally will yield more than 500 gpm. The central part of each of these aquifers probably can provide considerably more than 500 gpm. Near the edges, however, pumping rates in excess of 500 gpm could not be sustained for long periods. The areas shown as capable of yielding 250 to 500 gpm generally are underlain by finer grained sediments or coarse material containing interstitial silt or clay. The areas shown as capable of yielding from 50 to 500 gpm and 50 to 250 gpm are those areas near the edge of valleys where sand or gravel beds generally are thinner, contain more silt, or data are not sufficient for more precise estimates. The 50 to 250 gpm estimates also include areas where glaciofluvial deposits are thin or are in narrow valleys. Locally, yields in excess of those shown probably could be obtained for short periods; perhaps even for a few days. The areas shown as capable of yielding less than 50 gpm cover most of the county where saturated glaciofluvial deposits generally are of very limited extent or nonexistent.

If sufficient water for domestic and livestock uses cannot be obtained from glaciofluvial deposits in the drift, a well penetrating the underlying Fort Union Group probably will provide a sufficient supply.

Little Muddy Aquifer

The Little Muddy aquifer underlies the north-south trending reach of Little Muddy Creek and extends northeastward from near Appam into Divide County. The aquifer is in a buried bedrock valley that was eroded by the ancestral Yellowstone River. The bedrock topographic map (pl. 1) shows the course of the ancient river through Williams County. The valley subsequently was buried beneath fluvial and glacial deposits to a depth of at least 378 feet.

Logs of test holes in the buried valley indicate two aquifer zones, each of which may contain sand and gravel lenses greater than 10 feet thick (pl. 2). The upper zone is in glacial outwash, which generally does not extend more than 150 feet below the land surface.

The upper zone of the Little Muddy aquifer is 0 to 116 feet thick and consists predominantly of mixed sand and gravel, or locally of either sand or gravel. Generally gravel is more common in the lower part of the zone. The material is coarsest near the head of the outwash deposits that form the uppermost part of the aquifer in the northern part of the county. The material becomes finer toward the south and the gravel lenses are generally thinner and less widespread in the southern part than in the northern part of the aquifer. The average thickness of the coarser grained materials in the upper zone is about 43 feet. Locally, however, silt or clay lenses interfinger with the sand or gravel, and reduce the effective thickness of the aquifer.

The lower zone of the Little Muddy aquifer is separated from the upper zone by 11 feet to as much as 225 feet of till or clay. The lower zone is composed of a series of glaciofluvial sand and gravel deposits that average about 28 feet thick but may be as much as 110 feet thick. Generally this lower zone is more than 130 feet below the land surface. The distribution of the deposits in the aquifer indicates that they are lenticular stream-channel deposits that do not occupy the full width of the ancient valley. Hence, the deposits are long and narrow. The lower zone of the Little Muddy aquifer extends northward into Divide County and is the equivalent to aquifer C in the buried Yellowstone channel (Armstrong, 1967b, fig. 9).

Schmid and Hoisveen's cross sections (1961, p. 11-16) indicate that the sand and gravel lenses in the lower zone of the Little Muddy aquifer are not hydraulically connected to the upper zone. However, the aquiclude between the upper and lower zone is thin in the vicinity of the confluence with the Ray aquifer. In this area there is leakage, if not a direct connection, between the lower and upper zones.

Yield.—A 72-hour pumping and 48-hour recovery test was made on the Little Muddy aquifer to determine the aquifer characteristics and to verify the estimates used in determining the yields shown on plate 2. The test was made using Mr. Norman Helgeson's newly drilled irrigation well (158-100-17abc4). The well is 92 feet deep, has a 14-inch diameter steel casing, and is finished with 20 feet of 70-slot galvanized iron screen. The well was equipped with a 120-horsepower turbine pump that was powered by a propane-driven engine. The water was discharged through a 5-inch pipe to a ditch approximately 1,000 feet to the northwest of the pumped well. The rate of discharge, 440 gpm for the first 24 minutes and 800 gpm for the remainder of the 72-hour test, was measured with a modified Hall pilot tube coupled to a recorder. The discharge was regulated by varying the speed of the engine.

Water samples were collected from the discharge pipe. The samples were collected after 1½, 4, 8, 24, 48, and 72 hours of pumping.

Complete analyses were made on the first, fourth, and last samples taken during the test.

Six observation wells (5, 2, 3, 4, 6, and 7) located at 158-100-17abb, 17abcl, 17abc3, 17abd, 17acb, and 17ada, respectively (Armstrong, 1967a), were drilled and cased with 1.25-inch plastic pipe, which was slotted at the bottom 10 or 15 feet. Wells 158-100-8daa2, 17abc5, and the pumped well, 158-100-17abc4, also were used as observation wells. Random measurements also were made in 158-100-6ddd and 8 daa1. No other wells were pumping in the area during the test.

Observation wells 1, 2, and 5 were equipped with continuous recording devices that showed time in 2.5-minute divisions. Thus, time could be interpolated to the nearest minute. Observation wells 6 and 8 were equipped with continuous recorders that showed time in 15-minute divisions. Time on these recorder charts was interpolated to the nearest 5 minutes so the starting time of the tests as shown on the charts may be in sufficient error to introduce a small error in the early test results. Hydrographs of drawdown and recovery in observation wells 1, 2, 4, 5, 6, and 7 are shown in figure 8. Observation wells 3 and 8 are not shown on the hydrograph because of incomplete records due to equipment failure during the early part of the test.

The semilogarithmic and logarithmic plots from observation wells 1 and 2 are shown in figures 9 and 10, respectively. These are representative of the data used for analyzing the test results. All computed values for coefficients of transmissibility and storage fall within a reasonable range. The abrupt change shown on the plots after 24 minutes is due to the increase of the pumping rate from 440 to 800 gpm. The reduced slope on the plots after about 600 minutes is due to recharge, probably from the lower zone of the Little Muddy aquifer. The Ray aquifer and Little Muddy Creek also may have contributed some recharge. The amount of deviation from the type curve at 2,300 minutes is shown in figure 10. The slight increase in the slope of the curve during the latter part of the test (last six plotted points) is probably due to a relatively impermeable boundary to the southeast of the test area.

The observation wells were located at different distances and directions from the pumped well so that the pumping and recovery data would provide a more complete picture of the aquifer characteristics. Figure 11 shows the amount of drawdown that occurred after 3 days of pumping.

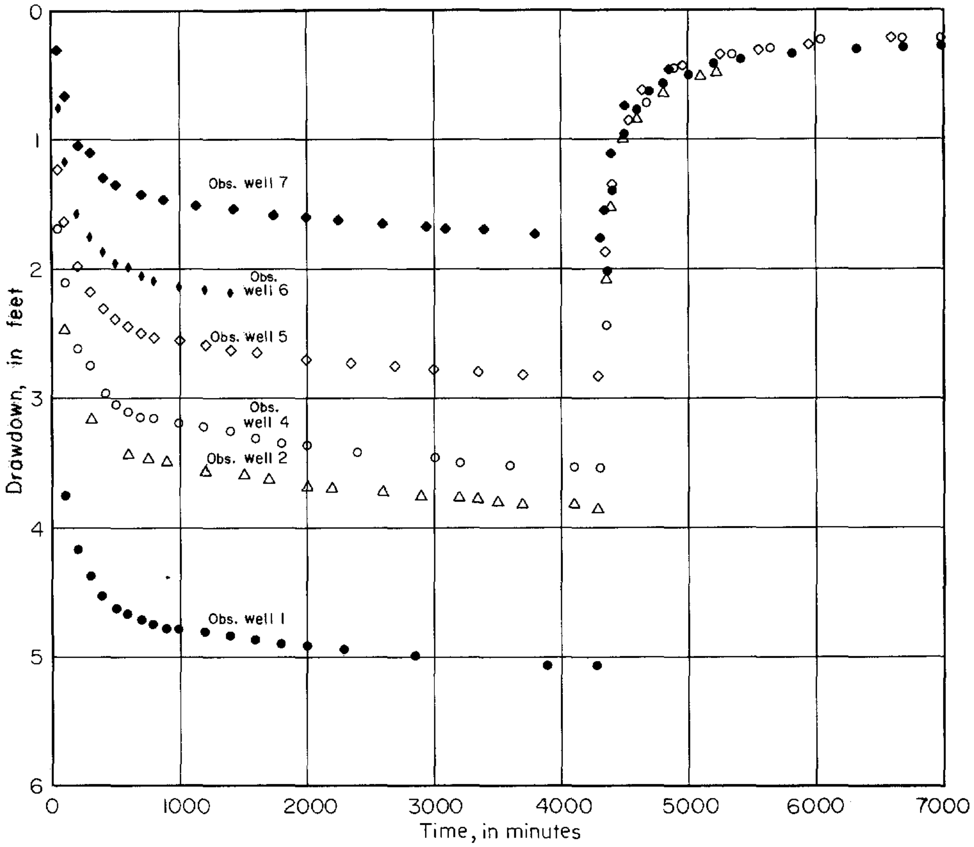


Figure 8. Hydrographs of drawdown and recovery curves for the Little Muddy aquifer test.

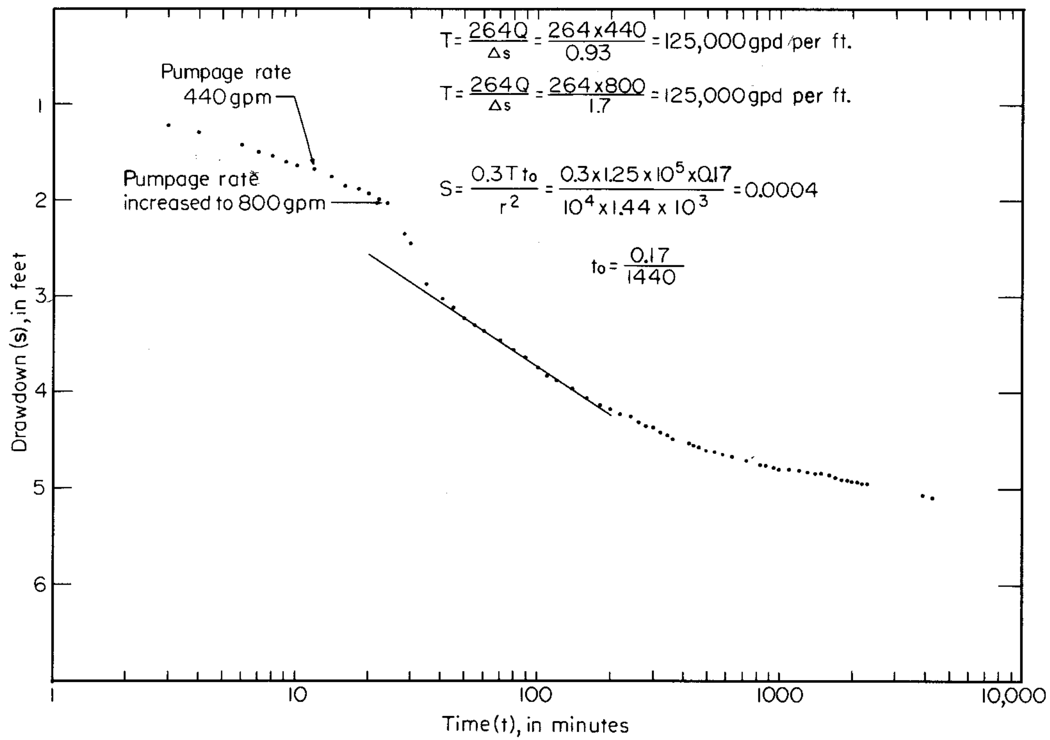


Figure 9. **Graph showing semilogarithmic plot of drawdown (s) versus time (t) at observation well 1 during the Little Muddy aquifer test.**

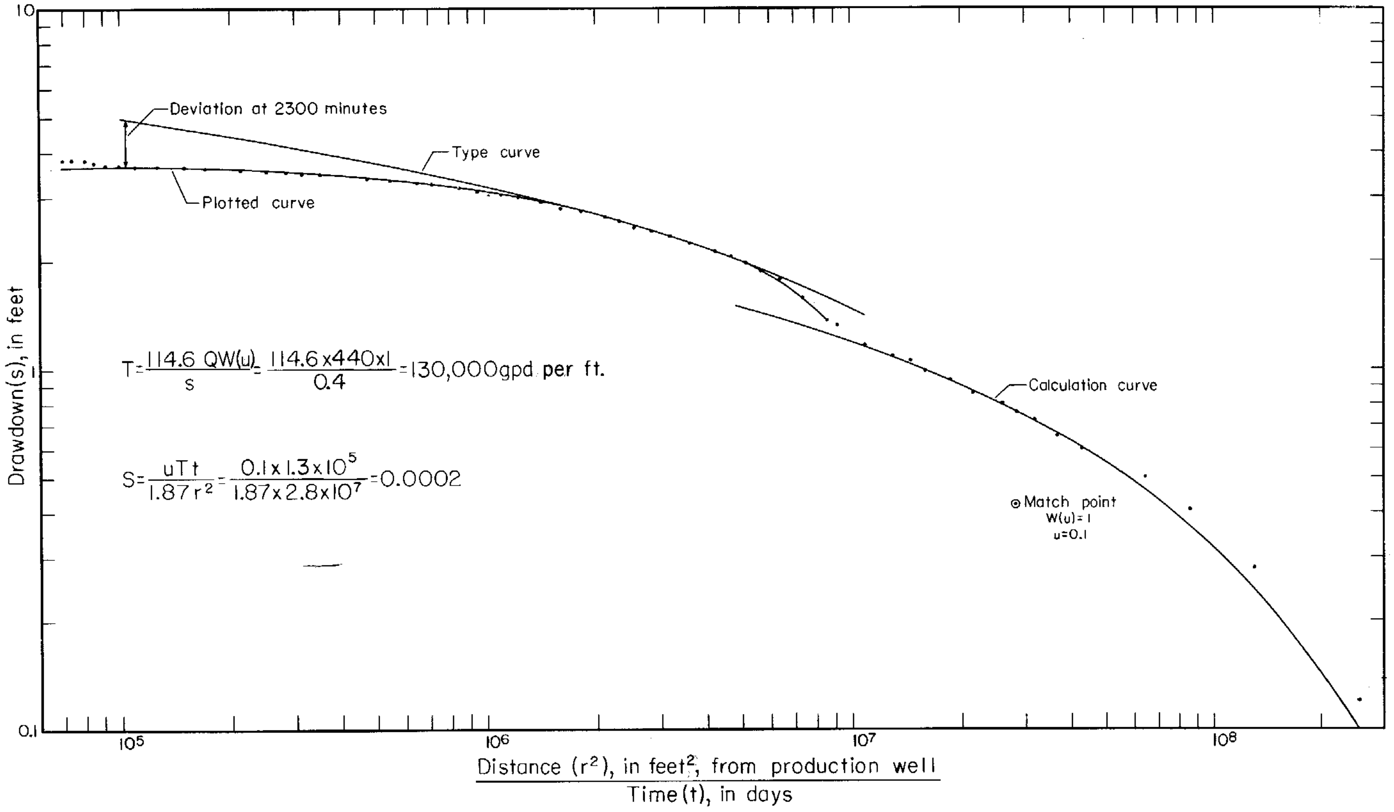


Figure 10. Graph showing logarithmic plot of drawdown (s) versus the radius squared divided by time (r^2/t) in observation well 2 during the Little Muddy aquifer test.

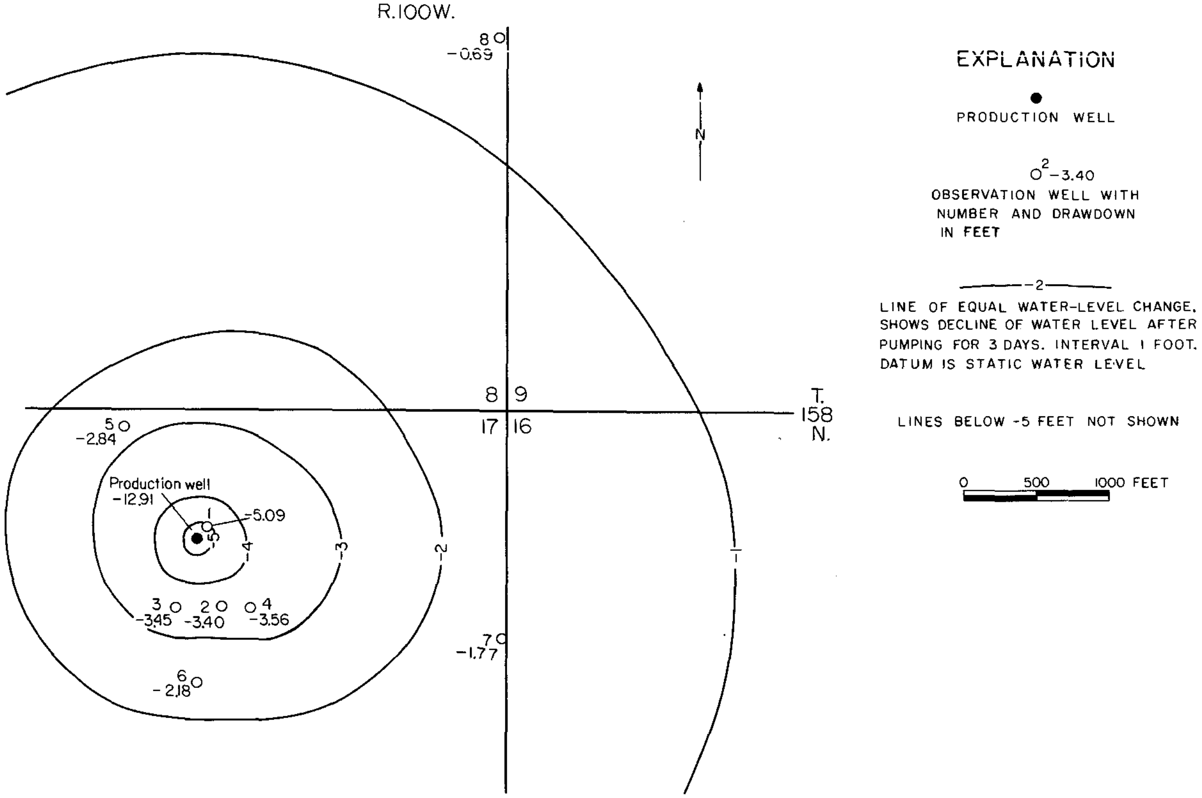


Figure 11. Map showing location of wells and area of influence for Little Muddy aquifer test.

The analysis of the test using the Theis (1935) formula showed that the average coefficient of transmissibility and storage for the Little Muddy aquifer is approximately 130,000 gpd per foot and 0.0004, respectively. The specific capacity of the pumped well after 3 days of pumping was 62 gpm per foot of drawdown. These data indicate that the aquifer probably will yield as much as 1,200 gpm with about 20 feet of drawdown after 3 days. Apparently much of the gravel in this aquifer has a permeability coefficient of about 6,000 gpd per square foot. A theoretical projection of the data indicates that 1,200 gpm could be maintained for a full irrigation season with less than 30 feet of drawdown. However, the effects of the aquifer boundary southeast of the test area may result in larger drawdowns than were calculated.

Storage.—Test drilling indicates that the coarser grained materials in the upper zone average about 43 feet in thickness beneath an area of about 80,000 acres. Because of the irregular distribution and probable narrowness of the lower zone, it is assumed that the average thickness of 28 feet in the lower zone occupied only about 60 percent of the area of the upper zone. The volume of coarse-grained materials would be 4.9 million acre-feet. Assuming a porosity of 32 percent, which is about the average porosity of 40 sand and gravel samples (Wenzel, 1942, p. 13, 143), then the aquifer would contain as much as 1.5 million acre-feet of water in storage. Probably about half, or 750,000 acre-feet, of this would be available to properly designed and constructed wells. About 300,000 acre-feet of the stored water is available in Tps. 158 and 159 N., Rs. 100 and 101 W.

Laboratory experiments (Prill and others, 1965) show that much more than 50 percent of the water in sand and gravel will drain over a long period of time; consequently, the above figures should be considered as a minimum quantity of available water. Pumping tests should be made on each well to determine the rates at which the water could be produced at reasonably sustained pumping levels and pumping rates.

Recharge.—Recharge to the Little Muddy aquifer is derived from the following sources: direct infiltration of precipitation; underflow from the outwash in the Little Muddy Creek drainage; surface flow from Little Muddy Creek and tributaries, and larger springs along the sides of the valley; underflow from the Ray aquifer; and underflow from the Fort Union Group. The quantity of recharge from the various sources is not known, but the high dissolved solids and sulfate in the water south of the junction with the Ray aquifer indicate considerable recharge from the Ray aquifer. The quantity of recharge from all sources during any given year approximately equals the amount of discharge.

The lower zone generally has a higher piezometric surface than the upper zone. The head on the water in well 158-100-8daa2 (lower zone) is approximately 4 feet higher than 9daa2 (upper zone). Elsewhere the difference in head has not been determined. However, wells drilled on the flood plain of Little Muddy Creek commonly flow if finished in the lower zone, and do not flow when finished in the upper zone. The higher head in the lower zone is probably due in part to recharge from the Fort Union Group and in part from recharge northward in the Little Muddy aquifer.

The hydrographs of wells in the Little Muddy aquifer (fig. 12) generally show only small annual fluctuations and indicate that near equilibrium conditions exist. The rise that occured in observation **well** 159-100-28add between May 20 and June 22, 1965, and probably in 155-100-9ccd also, apparently was caused by above normal snowmelt. The base flow of Little Muddy Creek in 1965 also increased, indicating a direct relationship between aquifer water levels and stream base flow. The average base flow of the Little Muddy Creek at Williston is about 7 cfs or about 5,100 acre-feet per year. This quantity plus the unmeasured amount of underflow in the channel make up a large part of the discharge from the aquifer and thus is nearly equal to the amount of recharge. In addition to the water in storage, the 5,100+ acre-feet per year also would be available to wells.

Quality of water.—The water in the Little Muddy aquifer differs in quality from place to place. The shallow water in the aquifer north and west of Little Muddy Creek in T. 158 N., R. 100 W. is generally a very hard sodium or magnesium bicarbonate type and contains fewer dissolved solids than elsewhere, commonly less than 900 ppm. South of T. 158 N., and in the lower part of the upper zone to the north, the water is very hard, but sodium is more abundant than the other cations; sulfate exceeds bicarbonate in 6 of 9 samples. The total dissolved solids range from 1,030 to 2,050 ppm. Chloride and nitrate commonly are present in only very small quantities.

Very little is known of the quality of water in the lower zone of the aquifer, but it apparently is similar to the upper-zone water in the

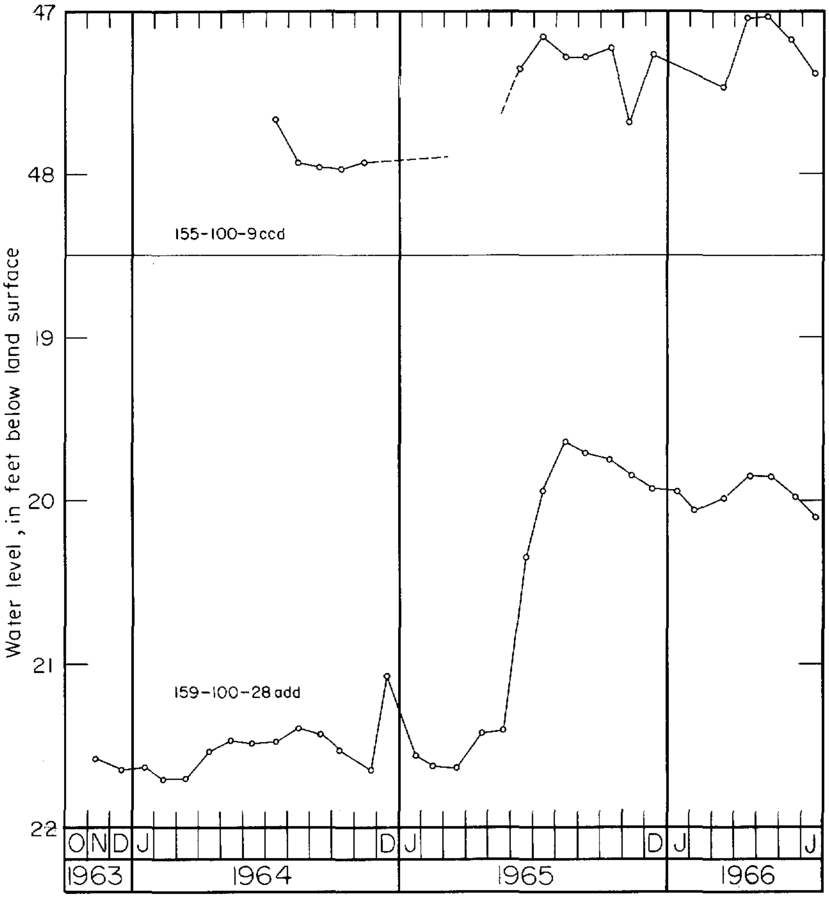


Figure 12. Hydrographs showing water-level fluctuations in the Little Muddy aquifer.

southern part of the aquifer. A sample of water from the lower zone in test hole 158-100-8daa1 contained a very hard, sodium bicarbonate type water with 1,520 ppm dissolved solids. Sulfate constituted about 44 percent of the anions present.

Ray Aquifer

The Ray aquifer underlies approximately 100 square miles in north-central Williams County. The sand and gravel comprising the aquifer was deposited in a preglacial valley (possibly an ancestral course of the Little Missouri River when it was a tributary to the preglacial Yellowstone River). The gradient of this buried valley is 10 to 11 feet per mile (fig. 13). The aquifer was penetrated completely by 27 test holes. The top of the aquifer ranges from 66 to 187 feet below the land surface. The altitude of the top of the aquifer ranges from 2,158 above sea level at Ray, North Dakota, to less than 2,000 feet near Appam, North Dakota. Figure 14 shows the shape and width of the aquifer and indicates that the aquifer occupies the entire lower part of the ancient river valley.

The aquifer is composed principally of sand with some gravel lenses. Much of the sand is medium to coarse grained and coarse grains predominate. Generally the grain size is coarsest near the bottom of the aquifer. Individual sand or gravel lenses are finer grained near the edges of the aquifer and contain considerable interstitial silt and clay.

Yield.—Estimates of the coefficients of transmissibility in the Ray aquifer range from 40,000 to 200,000 gpd per foot. However, ground-water barriers are known to exist so yield estimates in the border areas are somewhat questionable. Using Meyer's chart (1963, p. 339), it is estimated that specific capacities of properly constructed, fully penetrating wells generally should be between 20 and 80 gpd per foot of drawdown. Therefore, short-term pumping rates from about 300 to 2,000 gpm should be possible. Continuous or long-term pumping, however, generally would be in the 50 to 500 gpm range with ideally located wells yielding as much as 1,000 gpm.

Storage.—Test-drilling records indicate that the sand and gravel in the Ray aquifer averages about 60 feet in thickness beneath an area of about 64,000 acres. If the porosity of the materials in the aquifer is

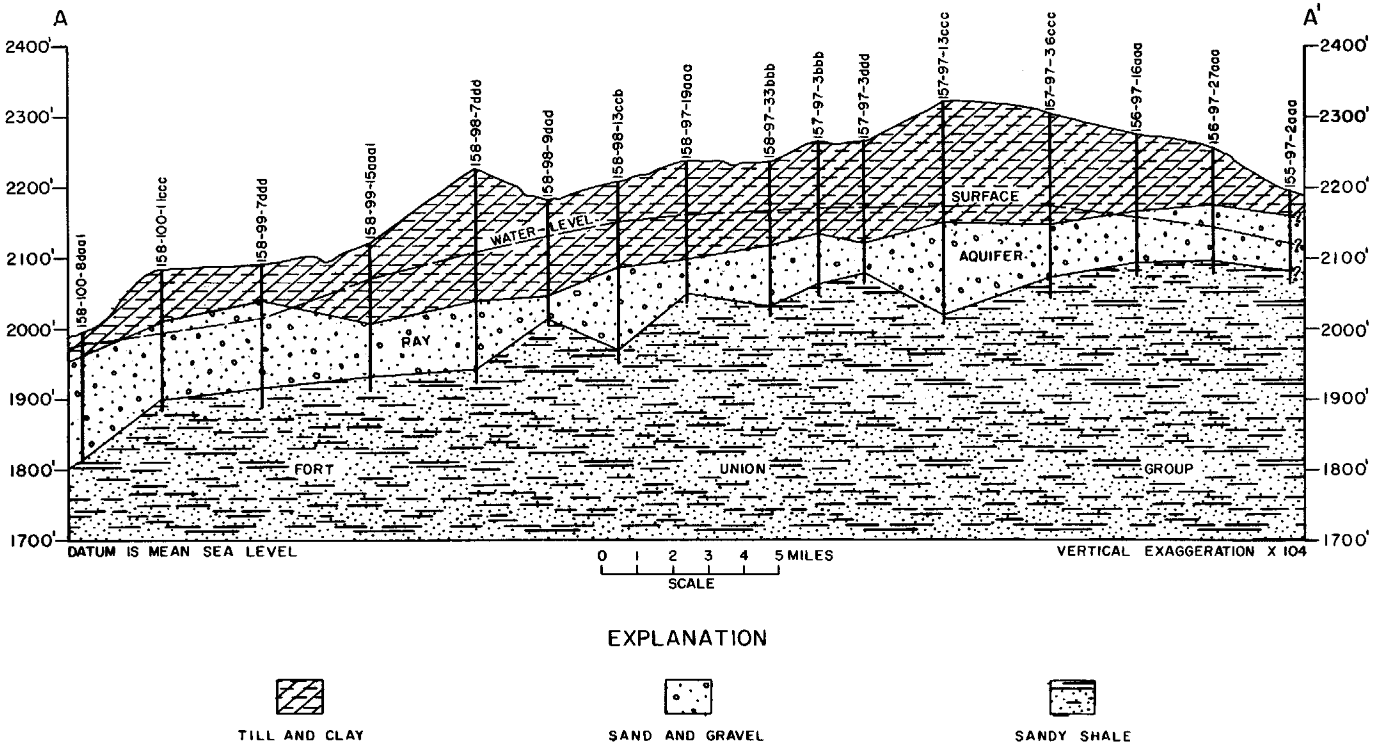


Figure 13. Logitudinal profile of the Ray aquifer.

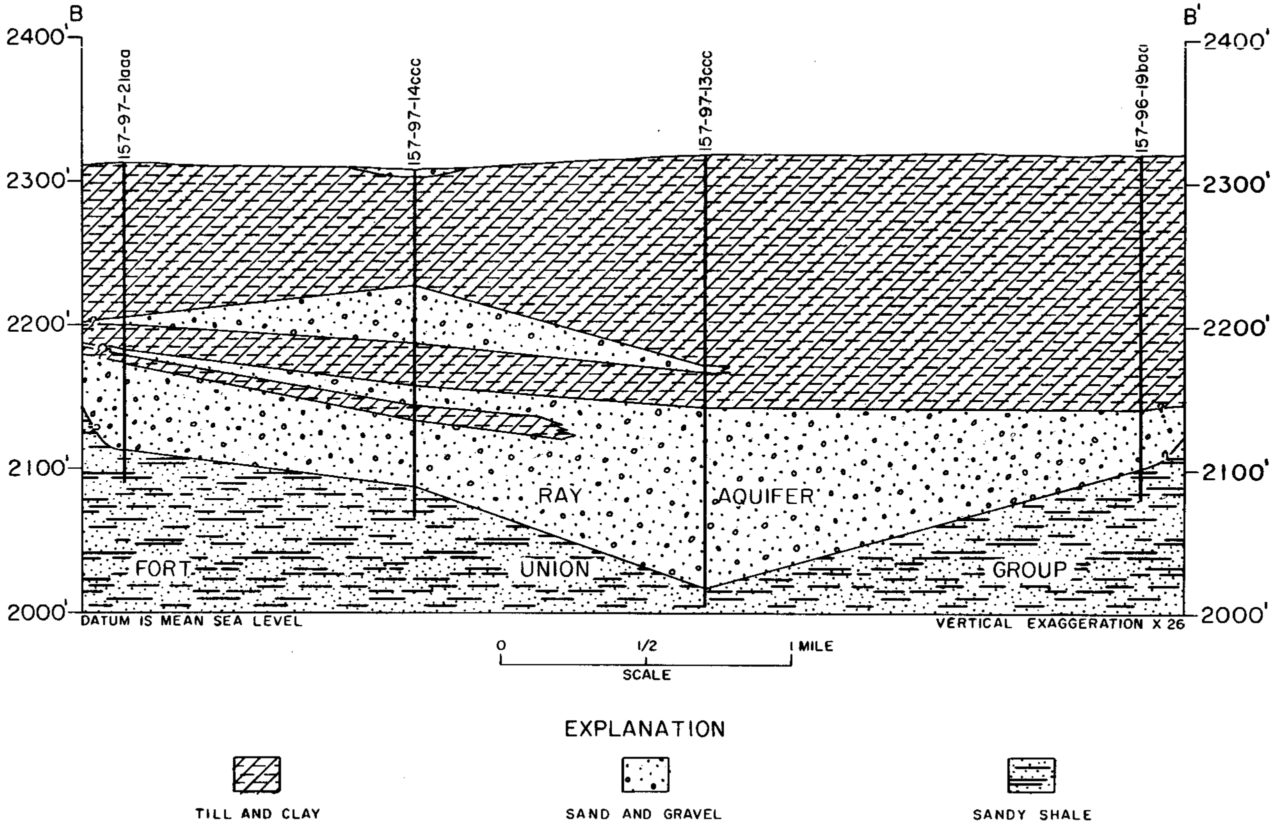


Figure 14. Geologic section showing distribution of materials in the Ray aquifer.

as much as 32 percent, as previously assumed, then the aquifer will contain as much as 1,200,000 acre-feet of water in storage. At least 50 percent of this quantity, 600,000 acre-feet, should be available to properly constructed wells.

Recharge and water-level fluctuations.—Recharge to the Ray aquifer is from the higher adjacent Fort Union sediments as well as from the overlying glacial drift. The quality of water, as well as the water levels in the vicinity of Ray, indicates that there is at least as much recharge from the western side of the aquifer as is being presently discharged. The water-level surface shown on figure 13 indicates a ground-water divide in the vicinity of the drainage divide that separates Little Muddy Creek and Beaver Creek. The location of the divide is shown in plate 2.

The water-level surface slopes southeastward from the divide toward Beaver Creek at about 8 feet per mile. Southward from Ray, the water surface is below the top of the sand and gravel so water-table conditions exist. The slope of the water surface northwestward is only about a foot per mile near the divide, but gradually increases to about 18 feet per mile near test hole 158-99-7ddd. Near this test hole the water surface is below the overlying confining beds. The slope of the water-level surface increases sharply where the Ray aquifer drains into the Little Muddy aquifer.

Hydrographs (fig. 15) of wells in the Ray aquifer generally show annual fluctuations of about a foot and indicate that recharge and discharge are in equilibrium. There has not been sufficient pumpage from the aquifer to upset the equilibrium conditions. Pumpage by the city of Ray apparently has had no significant effect on the water table as indicated by the record of intermittent water-level measurements in well 156-97-16aaa. Water-level measurements in this well were started June 11, 1965. At that time the water level was 115.73 feet below land surface; a measurement made on December 13, 1966 showed the water level to be at 115.37 feet. The difference in these two water levels is within the range of daily fluctuations, thus, the difference should not be interpreted as indicating a general rising water table. An automatic water-level recorder was installed and operated on this well for a short period to determine the magnitude of the daily water-level fluctuations.

Quality of water.—Analyses of water from 17 wells in the Ray aquifer show that the water is very hard. It ranges from 400 ppm hard-

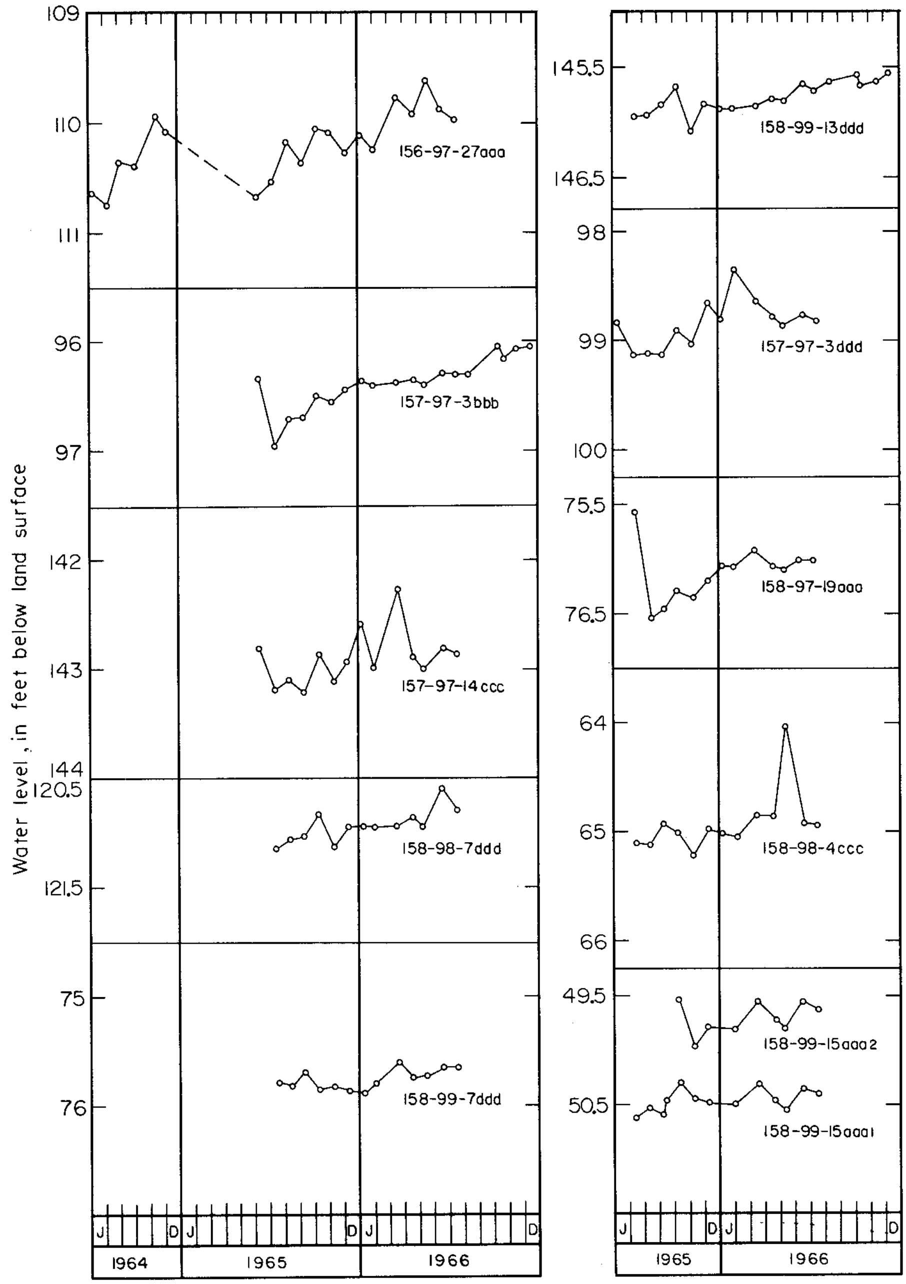


Figure 15. Hydrographs showing water-level fluctuations in observation wells in the Ray aquifer.

ness in well 156-97-9caa to 1,570 ppm in well 157-97-14ccc. Dissolved solids range from 602 ppm in well 156-97-9caa to 2,290 ppm in test hole 158-97-19aaa, and generally exceed 1,350 ppm. The water generally is a calcium magnesium sulfate type. Test hole 158-99-15aal and 15 aaa2 were drilled approximately 30 feet apart in order to obtain water samples from both the upper and lower parts of the aquifer. The analyses of the water from these test holes (Armstrong, 1967a, table 4) show that the water in the upper part is somewhat softer and contains less dissolved solids than water in the lower part.

Sulfate, iron, and dissolved solids generally are present in quantities that exceed the limits set in the U. S. Public Health Service standards (1962) for drinking water. The specific conductance indicates that most of the water in the aquifer has a high to very high salinity hazard and should be considered as marginal for irrigation purposes. However, the sodium-adsorption ratio is low, generally less than 4, so the water probably could be used for irrigation in areas with adequate subsoil and surface drainage. Even in areas of good drainage, care must be exercised, and salt tolerant crops only should be grown. Residual sodium carbonate was not present in most of the water sampled, and where there was some, the quantity was too small to be a problem. Boron generally is present in quantities too small to be significant. Locally, however, boron would be a hazard if used on sensitive crops.

Grenora Aquifer

The Grenora aquifer, which is named after the city of Grenora, underlies about 14,000 acres in the northwest corner of Williams County. The aquifer is composed of a basal gravel and an upper, predominantly fine to coarse sand and gravel. These deposits were laid down in a valley that is believed to have been an ancestral valley of the Missouri River (Alden, 1932, p. 45). Alden's plate 1 (1932) shows that the buried valley extends from near Poplar, Montana northeastward through much of T. 159 N., R. 103 W., Williams County, thence northward into Divide County. Armstrong (1967b, p. 62) described the Grenora aquifer in Divide County and stated that the sand and gravel deposits are thicker and more numerous southward through T. 160 N., R. 103 W., and have a total thickness that ranges from 32 to 87 feet. The average thickness in Divide and Williams Counties is about 80 feet. Apparently the thickening trend continues southward into T. 159 N., R. 103 W.;

test hole 159-103-6ddd contained 109 feet of saturated sand and gravel and test hole 159-103-10bbb contained 116 feet of saturated sand and gravel. The Grenora aquifer extends southwestward into Montana.

Yield.—Wells in the Grenora aquifer generally yield only a few gallons per minute. The discharge rates, however, are limited either by the size of the wells and pumps or by partially penetrating wells. The lithology described in the logs of test holes 159-103-6ddd and 10bbb indicates that, in places, the coefficients of transmissibility of the sand and gravel deposits are more than 100,000 gpd per foot. Specific capacities would be as high as 50 gpm per foot of drawdown for properly constructed wells screened in all of the more permeable zones.

Plate 2 shows the area of the Grenora aquifer in Williams County that is capable of yielding 50 to 500 gpm and more than 500 gpm. The estimate of yield in the northwestern part of the area was based on the lithology in the test holes and on the surface geology. The southeastern part, south of Highway No. 50 and 1¼ to 1½ miles northwest of the southeastern edge of the aquifer and in Cottonwood Creek, was extrapolated using incomplete and partially confirmed information from an oil test and water-well drilling. Therefore, estimates are less reliable in this area than elsewhere on the map.

Data are not available to determine the quantity of water in storage in the Grenora aquifer. However, the thickness and the known areal extent of the aquifer in Divide County (Armstrong, 1967b, fig. 9) in Williams County, and its probable extent in Montana indicate that this aquifer might contain as much water in storage as the Little Muddy aquifer, but only about 180,000 acre-feet of this water is present beneath Williams County.

Recharge and water-level fluctuations.—Recharge to the Grenora aquifer in Williams County apparently is derived from four sources; (1) infiltration of precipitation either directly or from several small lakes in the area, (2) ground-water underflow from Divide County, (3) underflow from the adjacent Fort Union Group, and (4) underflow from outwash and alluvial deposits. The quantity of recharge from the various sources is not known. In 1964, the piezometric surface of the water in the upper part of the aquifer sloped southward from well 160-103-16 bbb (Divide County) to well 159-103-6ddd (Williams County) at a rate of about 6 feet per mile. This slope indicates that some of the recharge is from Divide County. The slope of the piezometric surface in the lower part of the aquifer is not known, but it probably is similar to that of the upper part. The major source of recharge probably would be from nearby Divide County or Montana if large-scale pumping should occur in Williams County.

Hydrographs (fig. 16) of the two observation wells in the Grenora aquifer show a small rising trend, probably due to the increase of precipitation during the period of record. The hydrographs indicate that the shallower part of the aquifer (well 159-103-6ddd, 160 feet deep) responds more rapidly to changes in precipitation than the lower part (well 159-103-10bbb, 250 feet deep).

Quality of water.—The water in the Grenora aquifer in Williams County, as determined from two samples, is a very hard, sodium bicarbonate type. Sulfate, iron, and dissolved solids are present in quantities that exceed the limits set in the U. S. Public Health Service standards for drinking water.

Water in the upper part of the aquifer (well 159-103-6ddd) had 1,090 ppm dissolved solids, an SAR of 5.1, and a specific conductance of 1,630 micromhos. This water has a high salinity hazard and a medium sodium hazard, and it should be considered of marginal quality for irrigation. The water also contained 2.6 meq (milliequivalents) per liter residual sodium carbonate, which is higher than the 2.5 meq per liter that is accepted by the U. S. Salinity Laboratory Staff (1954) as the maximum quantity that should be in irrigation water. The water possibly could be used successfully for irrigating on adequately drained soils. However, water from similar stratigraphic positions in the aquifer in southwestern Divide County had much less residual sodium carbonate, consequently the high residual sodium carbonate may be a local phenomenon in the upper part of the aquifer in Williams County.

Water in the basal gravel of the aquifer (well 159-103-10bbb) had 1,300 ppm dissolved solids, an SAR of 9.9, a specific conductance of 1,980 micromhos, and 8.39 meq per liter of residual sodium carbonate. The water is classified as C3-S3 and should not be used for irrigation.

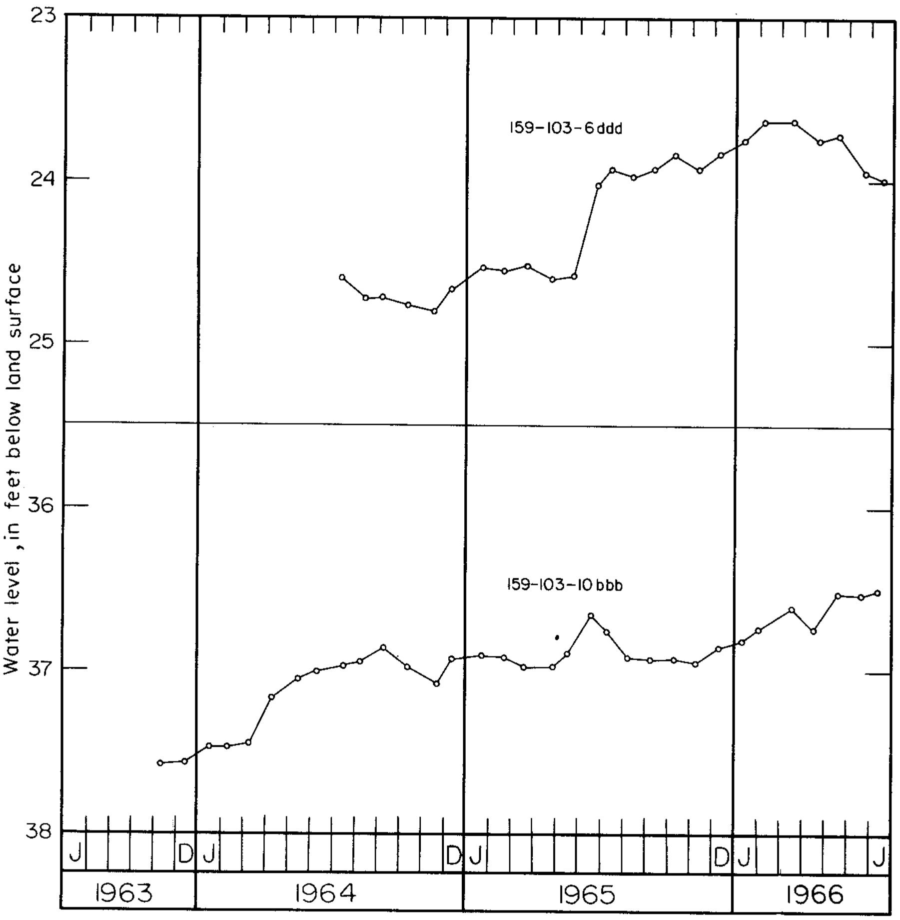


Figure 16. Hydrographs showing water-level fluctuations in observation wells in the Grenora quifer.

Wildrose Aquifer

The Wildrose aquifer is named for the city of Wildrose (159-97-2b), Williams County, which is near the southern edge of the aquifer. The boundaries of the aquifer, which is largely in Divide County, are inferred from geologic evidence and topography. The surficial materials consist of lake deposits (predominantly silts) and deposits of outwash sand and gravel. In the subsurface, the aquifer generally consists of poorly sorted, fine sand to medium gravel in beds that range in thickness from 1 to 29 feet. These deposits seem to occur in interconnected channels. Silt beds also are common in Divide County test holes 160-96-26 bbb, 160-97-13bbb, 160-97-36bcb, and 161-96-35ddd (Armstrong, 1965, table 2).

Yield.–No large-capacity wells have been constructed in the Wildrose aquifer; consequently, little is known concerning the aquifer's ability to yield water. The texture and thickness of the water-bearing materials indicate that production wells capable of 5 to 10 gpm per foot of drawdown should be possible. Generally, in Williams County there is not much more than 60 feet of hydrostatic head above the bottom of the aquifer; consequently, yields probably would be less than 250 gpm. Where the aquifer is unusually thick, yields in excess of 250 gpm might be obtainable.

The city of Wildrose has a municipal well constructed in this aquifer that is reported to yield about 85 gpm. The specific capacity of the well when drilled (1952), based on a 24-hour pumping test at the rate of about 200 gpm, was between 6 and 7 gpm per foot of drawdown.

Approximately 190,000 acre-feet of water is available in the Wildrose aquifer for future withdrawal in Divide and Williams Counties (Armstrong, 1967b, p. 41). However, the quantity of water that could be pumped from wells in Williams County is not known; it probably is considerably less than 25 percent of the total available water in the aquifer.

Recharge.–Recharge to the Wildrose aquifer is derived mainly by direct infiltration of precipitation through the sandy soils of the outwash and lake sediments. Some recharge also may be derived from buried glaciofluvial sand and gravel deposits in the adjacent glacial drift.

The quantity of recharge is not known, but it apparently is sufficient to replace the water presently being discharged by wells in the aquifer. Armstrong (1967b, fig. 14, p. 41) shows that water levels in Divide County fluctuate as much as 2 feet in response to seasonal change in storage. Water levels in Williams County probably fluctuate a similar amount.

Quality of water.—Ground water in the Wildrose aquifer differs considerably in quality from place to place (Armstrong, 1967b, p. 42). The samples from the Wildrose municipal well, 159-97-2baa, and from test hole 160-97-36bcb in Divide County indicate that the water in the Williams County part of the aquifer is a very hard, sodium calcium sulfate type. The water has a low sodium hazard and a high to very high salinity hazard and probably could be used successfully for supplemental irrigation on well drained soils. Residual sodium carbonate and boron are generally absent in this aquifer.

West Wildrose Aquifer

The West Wildrose aquifer is located about 1½ miles west of Wildrose. Part of the aquifer was described in Divide County (Armstrong, 1967b, p. 42). The aquifer in Williams County underlies a topographic sag that is about a quarter of a mile wide and extends from the Divide County boundary through the NW¼ sec. 4, T. 159 N., R. 97 W., to immediately west of Corinth (pl. 2). The aquifer may continue westward beneath the outwash and has not been identified, but it is also possible that the aquifer trends southwest toward the Ray aquifer.

The West Wildrose aquifer is composed of glaciofluvial sand and gravel, probably buried outwash, that is confined in an interglacial channel. In Divide County, Armstrong (1967b, p. 42) reports that the aquifer ranges from 15 to 46 feet in thickness, with the top of the aquifer from 88 to 125 feet below the land surface. Test hole 159-98-10aad in Williams County encountered 23 feet of sand and gravel from 116 to 139 feet below the land surface, and indicates that the thickness and depth of the aquifer in Williams County is similar to that in Divide County.

Yield.—The grain size and thickness of the aquifer materials in Divide County suggest that the transmissibility coefficient should be about 60,000 gpd per foot. Properly constructed wells, therefore, should have a specific capacity of about 20 gpm per foot of drawdown. By comparing the Williams County data with information obtained during a 49-hour pumping test in Divide County (Armstrong, 1967b, p. 71), it was estimated that the specific capacity of a well in the vicinity of 159-98-10aad would be about 10 gpd per foot of drawdown. The aquifer apparently is narrower in Williams County so the actual specific capacity probably would be less than the above calculated quantity. Well 159-98-10acd was the only known well in Williams County that produced water from the West Wildrose aquifer in 1966. The yield of this well is limited by the 10 gpm capacity of the pump.

Assuming the aquifer averages 23 feet in thickness, as it is in test hole 159-98-10aad, and is a quarter of a mile wide, then there would be about 1,200 acre-feet of water in each linear mile of the aquifer. About half of this (600 acre-feet per mile) should be available to wells.

Quality of water.–The quality of the water from well 159-98-10acd is similar to the water from the central part of the aquifer in Divide County, so it is assumed that the water is similar throughout most of the aquifer. The sample contained a very hard, sodium calcium bicarbonate type water containing 588 ppm dissolved solids. Iron is the only element present in quantities that exceed the recommended limits for drinking water. The sodium hazard is low, but the salinity hazard is high; the irrigation classification is C3-S1.

Outwash Aquifers

The outwash deposits in Williams County are generally too thin to form major aquifers. One possible exception is the outwash that occupies part of the Little Muddy valley (fig. 4). The outwash materials have not been differentiated from the other materials in the Little Muddy aquifer except at the surface.

In Williams County outwash materials generally were deposited in small valleys and are composed principally of sand and gravel with minor amounts of silt and clay. Generally, the deposits are thicker and the materials coarser near the center of the valleys. The known thicknesses of the deposits in Williams County range from 0 at the edge to 81 feet in test hole 159-99-22ccb. However, the saturated thickness generally is less than 22 feet.

Yield.—Wells penetrating the outwash deposits commonly yield only a few gallons per minute. The yields in the larger outwash area, however, generally are limited by the size of the wells and pumps. Near the edges of these deposits, especially at topographically high positions, water may occur only near the bottom of the sand or gravel, and well yields may be less than shown on plate 2. In these places, sufficient water for domestic or stock supplies may not be available from small-diameter (commonly 2 to 4 inches) wells, but the water can be obtained by drilling a large collecting reservoir in the underlying material. Much of the outwash in Williams County will not yield as much as 50 gpm, but some may yield more than 250 gpm. The higher yields might be obtained at locations where the material is coarse, the saturated thickness is greater than about 15 feet, and the outwash is more than a few hundred yards wide. Some of the outwash areas that probably will yield more than 50 gpm are located in the valleys near Alamo, McGregor, Grenora, and the lower reach of Beaver Creek (pl. 2).

The outwash, referred to as the Alamo outwash, that extends in a small valley from about 1½ miles west of Corinth to the vicinity of Appam, apparently will yield as much as 50 gpm throughout much of the central part of the outwash area. The outwash also contains some areas where more than 250 gpm could be obtained for periods of a few days. Test hole 159-98-20cbb contained 21 feet of saturated sandy gravel that should have a permeability of about 3,000 gpd per square foot and a transmissibility of about 60,000 gpd per foot.

Assuming that the average coefficient of transmissibility in the outwash is 60,000 gpd per foot, that the average saturated width of the outwash is 0.1 mile, and that the average slope of the water table is 17 feet per mile, it was calculated that 100,000 gpd or 70 gpm moves through the outwash in the vicinity of the test hole. This is near the maximum quantity of water that could be obtained from the aquifer. Pumping would cause an increase in the slope of the water table and increase the amount of recharge at the test hole; thus, a pumping rate somewhat in excess of 70 gpm possibly could be maintained.

The saturated outwash in the vicinity of Appam apparently is considerably wider and probably thicker than at test hole 159-98-20cbb; therefore, yields probably would be greater than at the test hole. Locally, near Appam, wells might yield more than 250 gpm, but the period of time the high yield could be maintained cannot be determined with the available data. A lowering of the water table near Appam might induce recharge from the Little Muddy aquifer and make high yields possible for long periods.

The outwash that extends from Hamlet to the county line east of McGregor is generally too thin and narrow to yield as much as 50 gpm for extended periods of time. There are two small areas in T. 159 N., R. 95 W., however, where the saturated thickness and width of the outwash appear to be great enough to sustain yields somewhat in excess of 50 gpm. One of these areas is in the southern part of sec. 5 and the northern part of sec. 8. The other area is in the southern part of sec. 14. Data are not sufficient to calculate the maximum yield in either area.

The outwash west of Grenora is generally too thin and topographically too high to yield more than a few gallons per minute to wells. The outwash materials, however, do extend eastward beneath the alluvium in a topographically low area on the south side of Grenora. There is at least 6 feet, and possibly as much as 10 feet, of saturated sand and gravel in this low. The city of Grenora obtains its municipal supply from wells tapping these deposits. Wells 1 and 2 are pumped at rates of 130 and 90 gpm, respectively. These rates, however, have not been maintained for as long as 24 hours and probably could not be maintained for much more than 12 hours if both wells were being pumped simultaneously. The city reportedly is able to maintain an average rate of about 150 gpm for at least 5 days by alternately pumping their wells.

The only other area of outwash in Williams County that probably will yield more than 50 gpm for sustained periods of time is in the lower reaches of Beaver Creek (pl. 2). The thickness of the saturated outwash is not known; consequently, actual yields cannot be estimated. However, the 37 feet of sand and gravel encountered in test hole 154-96-4bba suggests that there is more than 10 feet of saturated materials nearer the center of the valley. This, in turn, suggests that at least 50 gpm could be obtained from wells near the center of the valley.

Quality of water.—Water in the outwash in Williams County generally is of better quality than is present elsewhere in the glacial drift. Locally, however, where shallow wells are near septic tanks or barns, the water may be contaminated. The water from wells near Appam and Grenora (Armstrong, 1967a, table 4) probably is typical of much of the water in the outwash deposits. The water is a very hard, sodium calcium bicarbonate type with 540 ppm dissolved solids. The water does not contain any ions in excess of the recommended limits set by the U. S. Public Health Service for drinking water. The samples show a low sodium and a high salinity hazard for irrigation purposes.

The water in the outwash at McGregor is very hard. Magnesium exceeds calcium, and near the edge of the aquifer sodium may be the predominant anion. Sulfate exceeds the recommended limit in the drinking water standards. Except near the edge of the aquifer where there is a high sodium concentration, the water has a low to medium sodium hazard and a high salinity hazard for irrigation.

The exceptionally high dissolved solids content of the water from wells 154-100-20bba and 20bbb (Armstrong, 1967a, table 4) indicates contamination from either salt wastes or leakage from a deep brine well. Well 154-100-20bbb contains the most dissolved solids and is nearest to a salt company's waste piles. Thus, the wastes probably are the source of much of the contamination.

Undifferentiated Drift Aquifers

Numerous small deposits of glaciofluvial sand and gravel are interspersed with the till throughout much of Williams County. The deposits were formed in glacial melt-water channels. Where they are within the zone of saturation, they form aquifers of varying importance depending on their volume, permeability, and accessibility to recharge.

The irregular distribution and limited extent of these aquifers are shown by the differences in the deposits encountered by wells and test holes in sec. 27, T. 157 N., R. 95 W. (Armstrong, 1967a, table 2). For example, the sand penetrated from 61 to 64 feet and from 76.5 to 80 feet in 157-95-27ddb was not penetrated in well 157-95-27ddc which is less than a quarter of a mile south. Some farmers have reported drilling several test holes within a small area of a farm before enough sand was penetrated to yield a sufficient supply of water for domestic purposes. Others failed to discover any drift aquifers of significance and, consequently, must haul water or drill deep wells into the bedrock aquifers.

Yield.—The small size of most of the undifferentiated drift aquifers severely restricts their capacity to yield water to wells. Most yields from these aquifers generally are between 1 and 200 gpm, but yields of more than 10 gpm are unusual. The larger yields obtained in the Tioga area suggest that large yields might be obtainable elsewhere in the county from some of the undifferentiated drift aquifers.

The following table was compiled from pumping-test data supplied by C. A. Simpson and Son. Neither the coefficients of transmissibility nor specific capacity of the wells, when compared with each other, seem to be unusual, but when the drillers' logs are used for comparison, the coefficients seem to be high. The apparent inconsistency possibly is due to unusually well-sorted gravel deposits in the area.

Recharge and water-level fluctuations.—Recharge to the undifferentiated drift aquifers is principally from sloughs (prairie potholes), areas of surficial sand or gravel, and adjacent deposits of glacial till. Most of the sloughs contain water during the spring and early summer months. Even though many of these areas are underlain by materials having very low permeabilities, the water is available for a period long enough for some recharge to occur. The quantity of recharge from any one slough probably is small, but the total amount of recharge is significant and it probably is sufficient to replace most of the water presently being discharged from the aquifers. An exception is in the Tioga area where pumping rates in the city wells have declined in recent years. The reduced rates may be caused by lower hydrostatic head and a loss of storage or by any of several other factors, such as: sand in the wells, partially plugged screens, corrosion, loss of pump efficiency, or even a change of pump capacity. Water-level records and pumping data are not available to determine actual causes of the decline in pumping rates.

Figure 17 shows the monthly water-level fluctuations in two shallow observation wells; each taps a small, shallow undifferentiated drift aquifer near a small slough. The hydrographs of wells 156-95-36bbb and 157-96-11cdc show comparatively large water-level fluctuations. Water-level trends during periods of no measurements probably approximated the trends that occurred in well 156-95-36bbb after May 1965. Since there was no pumping near either well, the water levels appear to reflect the seasonal variations of precipitation and depth of water in nearby sloughs (Armstrong, 1967a, tables 1 and 3). Water levels in the

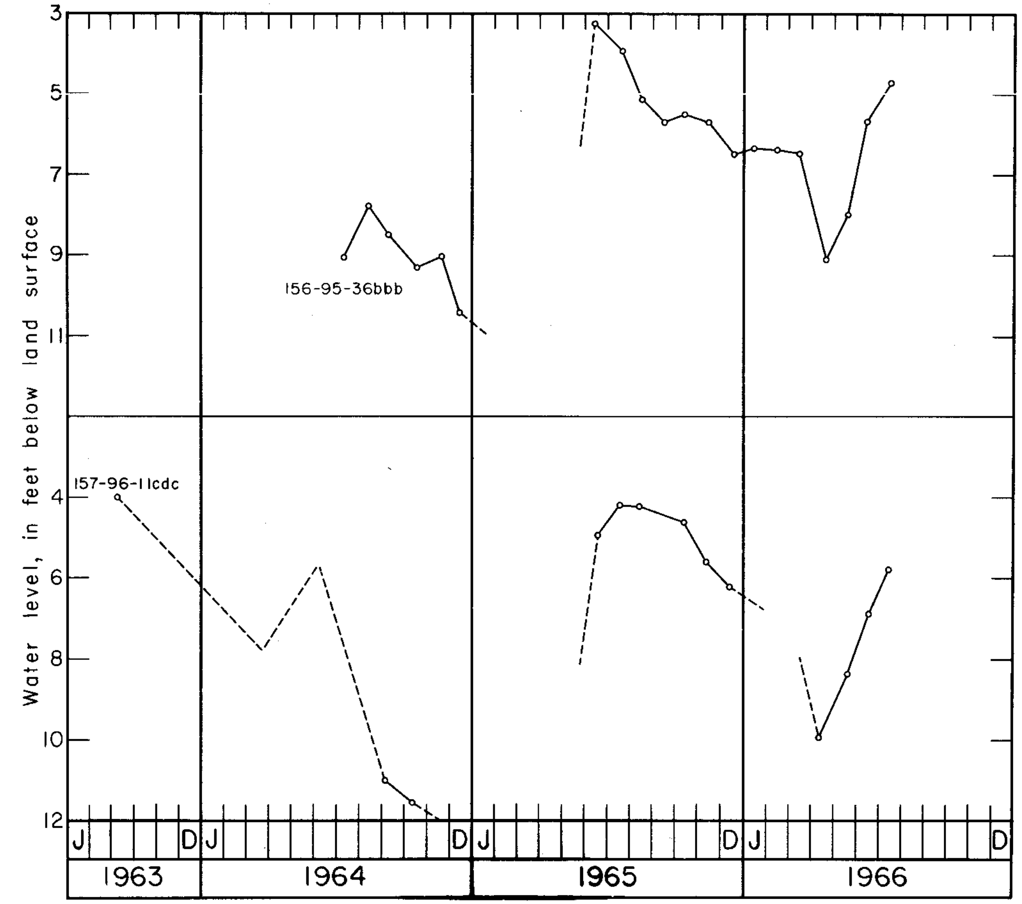


Figure 17. Hydrographs showing water-level fluctuations in observation wells in undifferentiated drift aquifer.

deeper drift aquifers apparently do not fluctuate as much as the shallow water levels unless they are affected by pumping.

Quality of water.—Ground water in the undifferentiated drift aquifers differs considerably in quality. The total dissolved solids in the samples obtained ranged from 410 ppm in well 157-95-27ddc (100 feet deep) to 2,770 ppm in test hole 159-98-10aad (216 feet deep). Hardness ranged from 302 ppm in well 157-95-27ddc (100 feet deep) to 1,800 ppm in well 158-96-25dcb2 (63 feet deep). Sulfate ranged from 26 ppm in well 157-95-27ddc to 1,430 ppm in well 158-96-25dcb2. The percent sodium was usually less than 50. The water generally had a lower sodium hazard and a medium to very high salinity hazard (fig. 6) for irrigation. The one known exception is the water from test hole 159-98-10aad, which had a very high sodium hazard.

Alluvium and Glacial Drift Undifferentiated

Trenton Aquifer

The Trenton aquifer underlies about 26,000 acres of flood plain and terrace along the north side of the Missouri River in southwestern Williams County (pl. 2). The nearly level flood plain, which stands a few feet above the low water channel, is irrigated with water from the river. The valley terrace is about 30 to 40 feet higher than the flood plain and has a gentle southeastward slope.

The aquifer consists of interbedded silty clay, sand and gravel. The sand and gravel generally is poorly sorted. The materials were deposited in part of the ancestral Yellowstone valley by the proglacial Yellowstone and Missouri Rivers after the ancestral Yellowstone River was blocked north of Williston. Some of the material that is referred to as alluvium in logs (Armstrong, 1967a, table 2) probably is outwash. However, when any part of the glacial drift could be definitely identified, it was delineated.

The aquifer was penetrated by 10 test holes during the investigation. The top of the aquifer in these test holes was from 17 to 90 feet below the land surface. The thickness of the aquifer ranged from 1 foot in test hole 153-102-17cca2 to 125 feet in test hole 152-103-7ddd. The aquifer is thinnest on the north side near the Fort Union bluffs (fig. 4) and is thickest near the center of the valley. Drillers of seismograph shot holes report that the sand and gravel thins between test holes 152-103-7ddd and the south side of the valley.

Test-hole data indicate that the average thickness of the aquifer is about 30 feet. However, most of the test holes were drilled near the northern edge of the aquifer where water levels are deep and the aquifer is thinner than further south; consequently, the apparent average is not realistic. Using the test-hole data as a guide, and correlating these data with area and apparent water levels, it can be assumed safely that the average thickness of the aquifer is at least 50 feet and probably 60 to 70 feet.

Yield.–There are no large-capacity wells in the Trenton aquifer at the present time, even though a considerable amount of water is apparently available. Estimated coefficients of transmissibility vary widely from place to place within the aquifer. Near the edge, such as at 153-102-17cca2, the aquifer is thin and the coefficient of transmissibility probably is less than 2,000 gpd per foot; however, in the thicker parts of the aquifer, such as at test hole 152-103-8bbb, the coefficient probably exceeds 200,000 gpd per foot. South of Buford, and within about half a mile south of the county road from Trenton to Buford, the aquifer generally is thin. Elsewhere, the coefficient of transmissibility apparently exceeds 60,000 gpd and the specific capacity of properly constructed wells probably would exceed 24 gpm per foot of drawdown and may be as much as 80 gpm per foot of drawdown. Thus, more than 500 gpm can be obtained wherever the water level can be lowered at least 20 feet. At some locations, yields of more than 1,500 gpm could be obtained.

Storage.– The quantity of water in the Trenton aquifer cannot be determined with a high degree of accuracy because of the uncertainty concerning the thickness of the sand and gravel. Assuming that an average of 50 feet of saturated sand and gravel underlies the 26,000 acres of the aquifer, it was calculated that about 420,000 acre-feet of water is in storage. At least 210,000 acre-feet of this water should be available to properly constructed wells. If the average thickness is as great as 60 feet, then there would be about 250,000 acre-feet of obtainable water.

Recharge and water-level fluctuations.—Recharge to the Trenton aquifer is primarily from the following sources: (1) underflow from the Fort Union Group, (2) infiltration of irrigation water, (3) precipitation and runoff, and (4) infiltration of Missouri River water across the lower parts and spurs of land between the river meanders. Few data are available to determine the quantity of recharge from each source. Recharge from direct precipitation and the accompanying runoff is greatest during and immediately following intense storms and during the few weeks between the time frost leaves the ground and plants start to grow. At these times, there are significant rises in water levels in the aquifer. The northern part of the aquifer contains a poor quality sodium sulfate type water; whereas, the southern part, which underlies the Missouri River meander spurs, has a fair quality calcium bicarbonate type water. These contrasting types of water suggest that the northern part of the aquifer receives much of its recharge from the nearby Fort Union Group, and the southern part receives most of its recharge from the Missouri River and infiltration from irrigation water.

The hydrograph of well 153-102-16ddd (fig. 18) shows the probable influence of recharge from irrigation. The higher peaks apparently are due to the influence of leakage from an overflow ditch about 2 feet from the well. The water level in the well drops rapidly when the ditch is empty. The early spring rise probably is due to precipitation, snowmelt, and runoff. Generally, an additional rise in May is caused by the application of irrigation water. The fluctuations that occur during the summer probably are due to the frequent irrigation of land near the observation well. The overall trend of the hydrographs is upward. The upward trend probably is due primarily to higher water levels in the discharge area (the Missouri River and Lake Sakakawea) as well as recharge from irrigation water. When the water table is near the land surface, the upward trending water level may cause some water logging in areas of poor surface drainage. The hydrograph of well 152-103-7ddd (fig. 18) shows that the water level rises to within 4.1 feet of the land surface. This well is near a drainage ditch that can drain some of the water, but in some of the low-lying areas south of sec. 7, T. 152 N., R. 103 W., a high water table could become a problem in the near future.

Quality of water.—All of the water in the Trenton aquifer is very hard, but otherwise rather variable in quality from place to place. However, there appears to be a pattern in the variability of the water. The

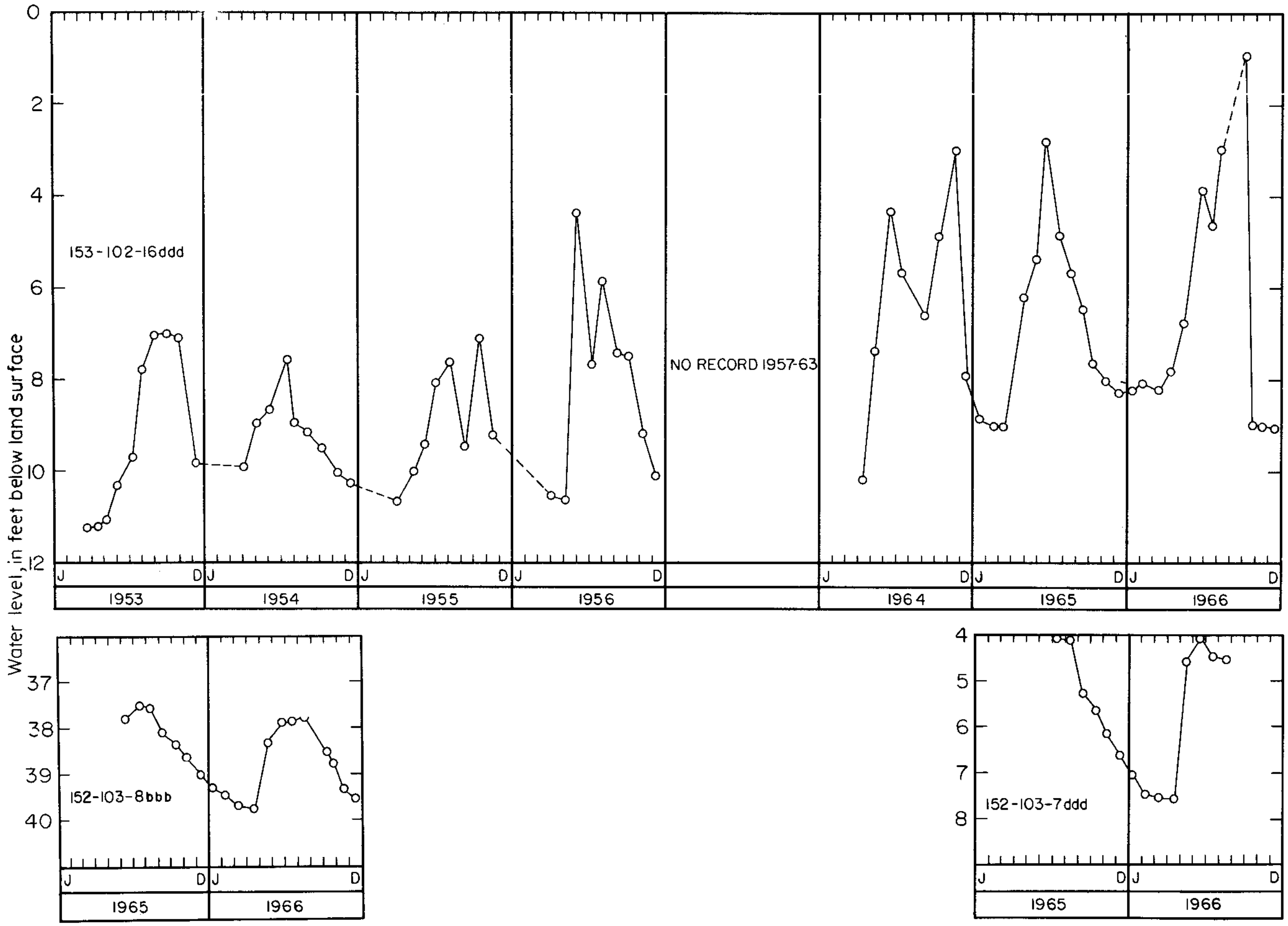


Figure 18. Hydrographs showing water-level fluctuations in observation wells in the Trenton aquifer.

water near the northern side of the aquifer is a sodium sulfate type; high in dissolved solids with generally more than 3,000 ppm, except southeast of Trenton where it is less than 2,000 ppm. Sulfate generally exceeds 850 ppm and the percent sodium is commonly more than 60. The water from test hole 152-103-8bbb, which is more than a mile south of the north edge of the aquifer, is a sodium calcium sulfate type containing 1,650 ppm dissolved solids, 770 ppm sulfate, and 49 percent sodium. At test hole 152-103-7ddd, which is approximately a mile south of well 152-103-8bbb, the water is a calcium sodium bicarbonate type containing only 979 ppm dissolved solids, 256 ppm sulfate, and 37 percent sodium. Records (U. S. Geological Survey, 1964, p. 38) show that from October 1963 through September 1964 the dissolved solids in the Missouri River averaged 439 ppm. The difference in the quality of water southward from the north side of the aquifer probably is due to recharge by the river in the southern part of the aquifer.

Based on U. S. Public Health Service drinking water standards, the water near the northern side of the aquifer generally contains excessive quantities of dissolved solids, sulfate, and iron. The water also has a very high sodium and salinity hazard for irrigation. Locally the residual carbonate also is very high. The water in the aquifer that is under the village of Trenton also contains excessive quantities of nitrate and may indicate some pollution.

The sample of water from test hole 152-103-8bbb, which is approximately a mile south of the north edge of the aquifer, is similar to the water along the northern edge, but it is somewhat better quality. However, the water is not recommended for domestic use, but it possibly could be used for irrigation with proper management and adequate drainage. It has a medium sodium hazard and high salinity hazard. The sample did not contain any residual carbonate.

The sample of water from test hole 152-103-7ddd indicates that in the southern part of the aquifer the water probably could be used for domestic purposes. The water does contain more dissolved solids, iron, and sulfate than is recommended, but the excesses are not great enough to cause physical distress. Most of the iron can be removed at reasonable costs so it is not a serious problem.

The sample of water from well 152-103-7ddd indicates that in the southern part of the aquifer the water has a low sodium and a high salinity hazard. The water contains 1.4 meq per liter of residual sodium carbonate; consequently, it is considered marginal for irrigation. Even with the hazards present in the water, it probably could be used successfully with good management practices and the proper use of amendments.

Southward from well 152-103-7ddd, toward the river, the water probably improves in quality and is more suitable for both domestic and irrigation uses. It is not likely, however, that the water in this area will be used for irrigation as long as the better quality surface water is available from the Missouri River.

Hofflund Aquifer

The Hofflund aquifer underlies approximately 9,600 acres of an abandoned valley of the Missouri River in the southeastern part of the county (pl. 2). This does not include any part of the aquifer that has been covered by Lake Sakakawea. Surface elevations indicate that the valley may be equivalent to the higher terrace overlying the Trenton aquifer, but definite correlation was not made. This aquifer, like the Trenton aquifer, is composed of outwash sand and gravel overlain by alluvial sand, gravel, silt, and clay. A till wedge separates the aquifer in the westernmost part of the area, and is used as a basis for separating the alluvium from the glacial drift; elsewhere the alluvium and glacial drift have not been differentiated.

The only water-level data available are from the lower part of the aquifer, but it appears that only the lower few feet of the upper alluvial sand and gravel are saturated.

The depth to the top of the aquifer from land surface ranges from about 10 feet at test hole 154-96-8aad (Paulson and Powell, 1962, p. 42) to 114 feet at 154-97-1aaa. The thickness of the sand and gravel ranges from 15 feet at test hole 154-96-18bbb to more than 78 feet at test hole 154-96-8bab. The average thickness is approximately 45 feet. These depths and thicknesses do not include the upper part of the aquifer where it is separated from the lower part by till.

Yield.—Two large-capacity wells were drilled in the western part of the Hofflund aquifer in 1966. Aquifer tests were made at the sites of each of these wells within a few days of their completion. Aquifer test 1 was made July 14-19, 1966 on Mr. Howard Lund's irrigation well (154-97-14acc1). The well is 136 feet deep with 30 feet of galvanized iron screen from 106 to 136 feet and gravel packed. The well was equipped with a turbine pump powered by a 120-horsepower propane engine. The water was discharged through a 6-inch pipe to a gully about 900 feet to the west of the pump. The rate of discharge was measured with a modified Hall pilot tube coupled to a recorder. Water samples for chemical analyses were collected from a hose about 80 feet from the pump after approximately 24, 48, and 72 hours of pumping. Five observation wells were drilled and equipped with automatic recorders. The equipment at each of the observation wells malfunctioned for varying periods during the test. However, sufficient data were obtained to determine the transmissibility and storage coefficients of the aquifer.

Figure 19 shows semilogarithmic plots of the data from observation wells 3 and 4. They show the influence of at least one and possibly two relatively impermeable boundaries. The influence of the nearest boundary, which is known to be about a quarter of a mile east, appeared at about 8 minutes at well 3 and 12 minutes at well 4. The continued downward trend in the slope of the plots may be due either to curves in the boundary or the influence of another boundary at the opposite side of the aquifer, which is believed to be more than a mile to the west. The decrease in the trend of the slope, which begins at about 500 minutes, probably is due to the influence of recharge from Lake Sakakawea. Irregularities shown in the latter part of the plot in observation well 3 apparently are due to the effects of changing barometric pressure.

The specific capacity of the pumped well after 3 days of pumping was 77 gpm per foot of drawdown. The average coefficients of transmissibility and storage calculated from the distance-drawdown graphs (fig. 20) at 5 minutes using the Theis nonequilibrium formula were 440,000 gpd per foot and 0.001, respectively. The 10- and 20-minute graphs also are plotted on figure 20 to show the apparent reduction of the transmissibility coefficient. The observed drawdown at observation well 3 was somewhat greater than the theoretical drawdown due to the position of the observation well near the boundary.

The second aquifer test made on the Hofflund aquifer was conducted August 18-23, 1966 using Mr. Roy Viall's irrigation well, 154-97-12bab. The well is 117 feet deep with 97 feet of 16-inch diameter

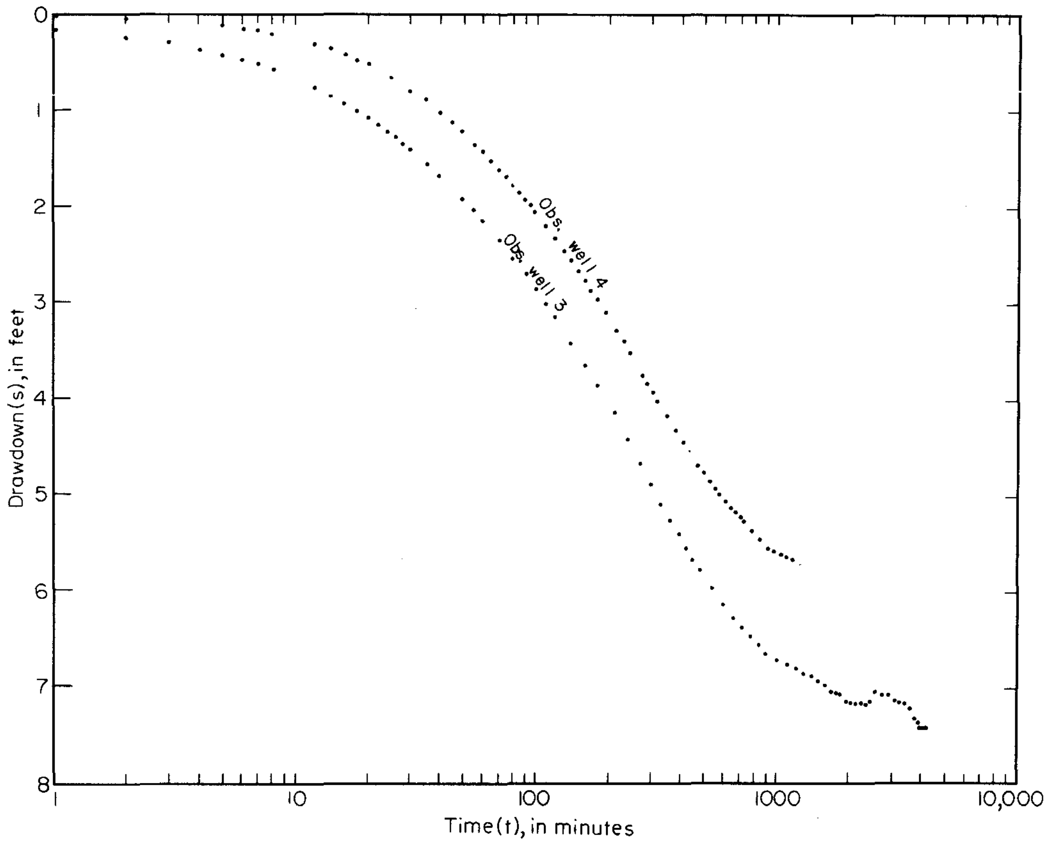


Figure 19. Graphs showing semilogarithmic plots of drawdown (s) versus time (t) during aquifer test 1, Hofflund aquifer.

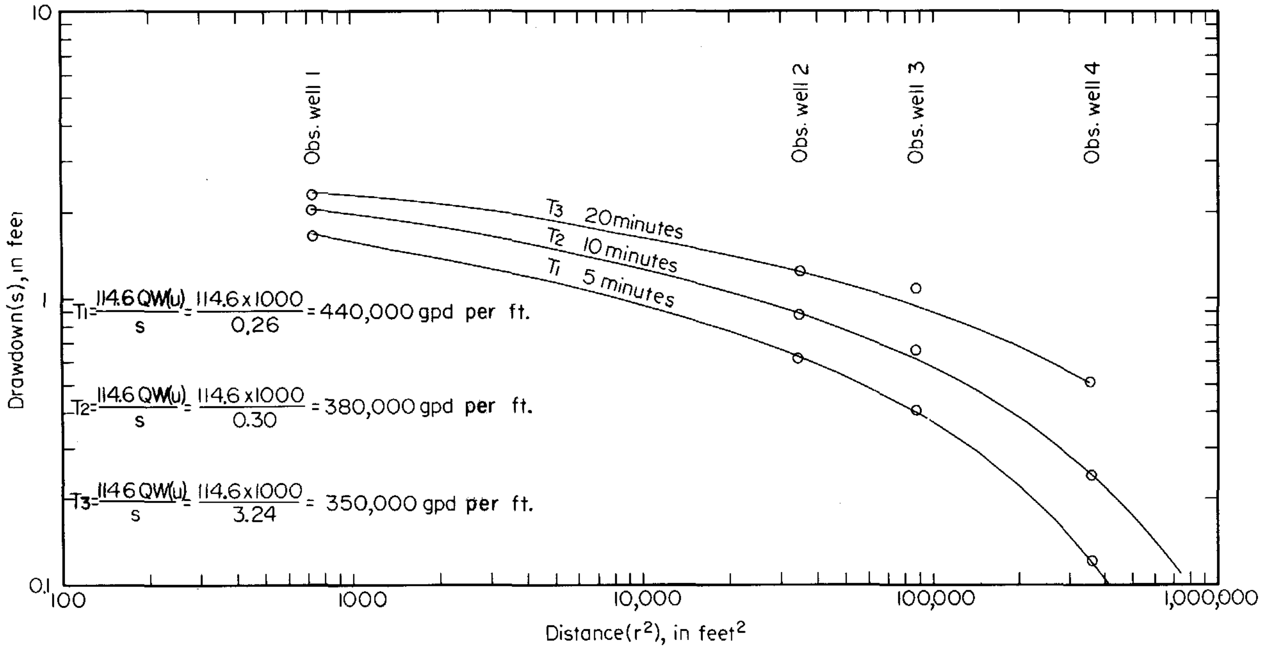


Figure 20. Graph showing logarithmic plot of distance squared (r^2) versus drawdown (s) at 5, 10, and 20 minutes during aquifer test 1, Hofflund aquifer.

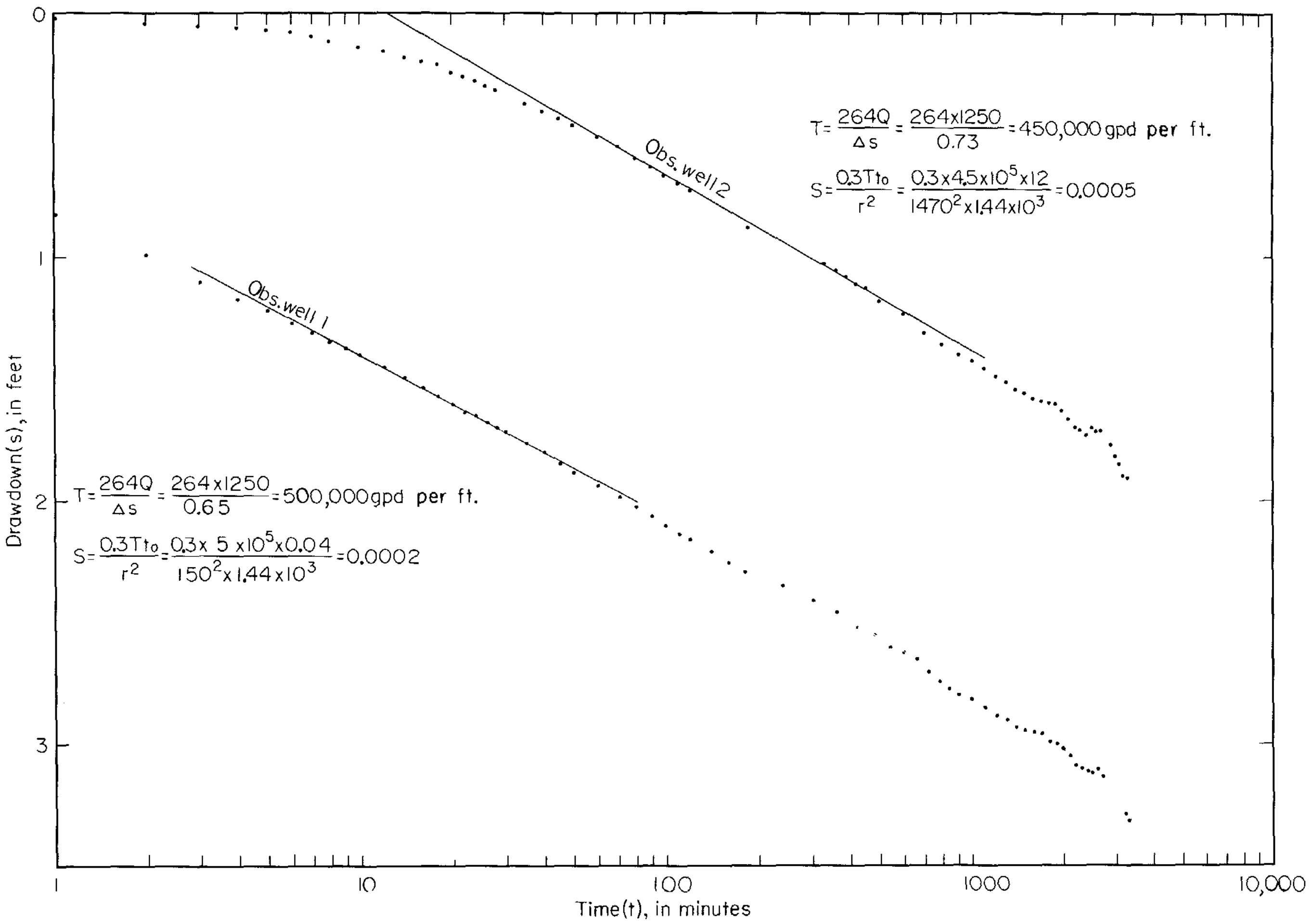
steel casing and 20 feet of 16-inch screen. The well was equipped with the same test pump that was used in the Lund well. The rate of discharge was measured with an orifice tube and manometer as the water was discharged into a pit near the well. Two observation wells were equipped with automatic water-level recorders. Observation well 1, 154-97-12bba, was 150 feet west of the pumped well; observation well 2, 154-97-12bbb, was 1,470 feet to the west of the pumped well.

The specific capacity of the test well after 55 hours of pumping was 92 gpm per foot of drawdown. Figure 21 shows the semilogarithmic plots of the drawdown in observation wells 1 and 2. The results of the data analysis are shown in the following table.

Well	Coefficient of transmissibility "T" Semilog solution	 Theis type curve	Coefficient of storage
Pumped well	a/ 560,000	....	......
Observation well 1	500,000	500,000	0.0002
Observation well 2	450,000	440,000	.0005

a/ Corrected for partial penetration (Johnson, 1966, p. 134).

The test analysis indicates that a relatively impermeable boundary is located approximately a mile from the pumped well. This corroborates the geologic evidence, which indicates that the aquifer pinches out about half a mile to three quarters of a mile west of observation well 2. The high coefficients of transmissibility obtained from the two aquifer tests indicate that yields as high as 2,000 gpm can be obtained



$$T=\frac{264Q}{\Delta s}=\frac{264\times 1250}{0.73}=450{,}000 \text{ gpd per ft.}$$

$$S=\frac{0.3Tt_0}{r^2}=\frac{0.3\times 4.5\times 10^5\times 12}{1470^2\times 1.44\times 10^3}=0.0005$$

$$T=\frac{264Q}{\Delta s}=\frac{264\times 1250}{0.65}=500{,}000 \text{ gpd per ft.}$$

$$S=\frac{0.3Tt_0}{r^2}=\frac{0.3\times 5\times 10^5\times 0.04}{150^2\times 1.44\times 10^3}=0.0002$$

Figure 21. Graph showing semilogarithmic plot of drawdown (s) versus time (t) during aquifer test 2, Hofflund aquifer.

from the aquifer. The high coefficients of transmissibility also indicate that the coefficient of permeability of some of the gravel in the aquifer may be as high as 20,000 gpd per square foot.

Storage.—Based on an average thickness of 45 feet, an assumed porosity of 32 percent, and a recoverability of 50 percent, there should be about 70,000 acre-feet of water available in storage in the Hofflund aquifer. However, the estimated 50 percent recoverability probably is very conservative for aquifers with transmissibility coefficients higher than 200,000 gpd per foot; consequently, the 70,000 acre-feet of available water is also a very conservative estimate of available water in storage. Considering the quantity of water in storage, the high transmissibility, and the quantity of water available from Lake Sakakawea for recharge, there should be adequate water for several large-capacity wells in the Hofflund aquifer. Adequate well spacing should be maintained, especially near the edges, to keep interference between wells to a minimum.

Recharge and water-level fluctuations.—Recharge to the Hofflund aquifer is principally from underflow from the Fort Union Group, the intermittent streams that drain across the flats, and Lake Sakakawea. Prior to the damming of the Missouri River, the water levels in the aquifer probably were 20 to 50 feet lower than the present level. As Lake Sakakawea filled, the water levels in the aquifer rose correspondingly. The hydrographs (fig. 22) of the water level in observation wells 154-96-8bab and 154-97-12bbb generally show a steadily rising water level. Lake Sakakawea had receded about 2 feet from its maximum summer level at the time of the August 16, 1966 measurement in well 154-97-12bbb, and the water levels apparently leveled off in the western part of the aquifer. The rising water level in well 154-96-8bab indicates that water levels in the central and eastern parts of the aquifer are still rising to adjust to the new base level being established by the lake. Future water levels in the aquifer, although dependent on the quantity of recharge from all sources, probably will be dominantly influenced by pumping and changes in the level of the lake.

Quality of water.—The water in the west and central parts of the Hofflund aquifer generally is a very hard, sodium calcium bicarbonate type with 691 to 1,120 ppm dissolved solids. The slight increase in percent sodium and total dissolved solids in the water from well 154-97-24 bbb to 154-96-8bab (Armstrong, 1967a, table 4), and the report of "poor quality" water in an abandoned well in the southeastern part of

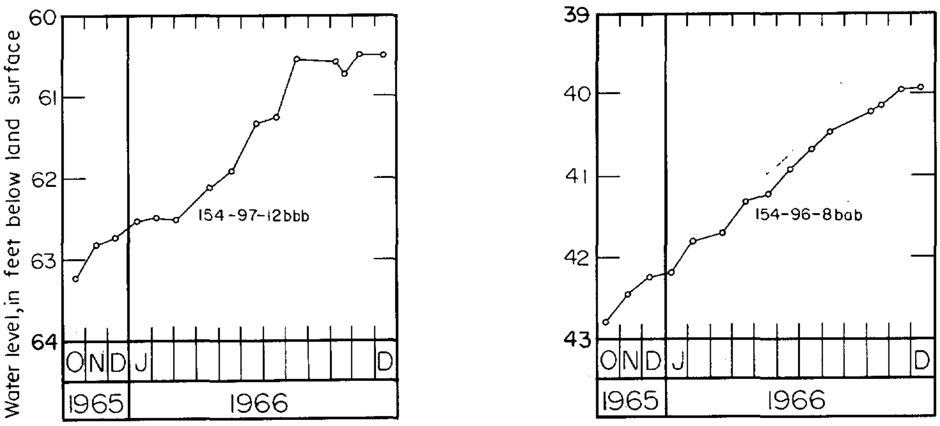


Figure 22. Hydrographs showing water-level fluctuations in observation wells in the Hofflund aquifer.

the aquifer, probably indicate that both sodium and dissolved solids increase in an easterly direction.

The water contains more dissolved solids, sulfate, and iron than the recommended limits set by the U. S. Public Health Service drinking water standards. However, none of the constituents are present in quantities that would be likely to cause any physical distress.

The chemical analyses that have been taken indicate that the water has a low sodium and a high salinity hazard for irrigation. Residual sodium carbonate is generally less than 1.25 epm and generally is not a problem. Water from test hole 154-96-8bab in the central part of the aquifer, however, contained 1.48 meq per liter and should be considered as marginal in respect to the residual sodium carbonate hazard. Boron ranges from 0.20 to 0.55 ppm and does not constitute a hazard to any crops generally grown in the Williams County area. The water in the aquifer should not be used on poorly drained soils because of the high salinity hazard, but it probably can be used elsewhere if good management practices are followed.

Alluvium and Outwash

The areas mapped as alluvium (fig. 4) are underlain by sand, gravel, and silt lenses that generally are only a few inches thick in some of the smaller drainageways, but may be many feet thick in some of the larger tributaries of the Little Muddy Creek and Missouri River. Some of the larger tributaries not only contain alluvium near the surface, but probably also contain outwash near the base of the channels. The deposits usually have not been differentiated because the materials are lithologically similar and the genesis is hydrologically not important.

The yield that can be obtained from the undifferentiated sand and gravel will vary with the width and thickness of the deposits. Where the deposits are thick, large yields can be obtained, but the valleys are generally narrow so large yields probably could not be maintained for more than a short time, possibly only a few hours. Where the deposits are thin, only small quantities of water can be obtained. Many of these small alluvial deposits, however, will yield sufficient water for domestic and stock purposes. The alluviated valleys are, therefore, the most likely places to prospect for shallow water in the higher and drier areas of Williams County.

The quality of the water in the alluvium is unknown in most places in Williams County.

PUBLIC WATER SUPPLIES

Williston

The city of Williston, which has an estimated 12,000 water users, obtains its water supply from the Missouri River. Their treatment plant capacity is rated at 6mgd (million gallons per day), but their average use is only 1.1 mgd. The average daily use is approximately 92 gallons per person.

The quality of the water from the Missouri River at Williston differs considerably throughout the year. According to the U. S. Geological Survey (1964, p. 37-38), records from 1950 to 1964 show the maximum dissolved solids and hardness were 771 and 398 ppm, respectively (December 25-31, 1961), and the minimums were 199 and 115 ppm, respectively (June 21-26, 1959). The time-weighted average was 477 ppm dissolved solids and 243 ppm hardness. The raw water is treated to reduce the hardness, filtered to eliminate undissolved solids, and chlorinated to eliminate bacteria.

Tioga

The average use for the city of Tioga in 1963 was 210,000 gpd, with an average of 100 gpd per person. In 1965, the city had 9 wells that were capable of yielding a total of 640,000 gpd (U. S. Public Health Service, 1963, p. 125). The average use of water in 1965 was approximately 131,000 gpd of metered water and an estimated 15,000 to 30,000 gpd of unmetered water used during the summer months. Relatively cool, wet weather apparently was the principal cause of the reduced use of water during 1965.

The quality of water used by Tioga varies with the well or wells in production. The water contains dissolved solids ranging from 410 to 1,588 ppm, sulfate ranges from 26 to 567 ppm, and hardness ranges from 302 to 664 ppm (Armstrong, 1967a, table 4). Well 4, 157-95-27 dbd, probably has the most influence on the total supply because it is the well most frequently used. According to Armstrong (1967a, p. 131), the water from this well is a magnesium sodium bicarbonate type with 106 ppm calcium, 97 ppm magnesium, 176 ppm sodium, 827 ppm bicarbonate, 356 ppm sulfate, 0.2 ppm fluoride, 1,170 ppm dissolved solids, and 664 ppm hardness. The sodium-adsorption ratio is 3.

Ray

The city of Ray obtains its water supply from 4 wells, which are capable of yielding 666,000 gpd (U. S. Public Health Service, 1963, p. 124). In 1963, the average use of water was approximately 75,000 gpd, which is approximately 75 gpd per person.

The quality of the municipal water supply depends on the well in production. In general, the water is a very hard, magnesium calcium bicarbonate type with high iron. Analyses of water by the North Dakota State Department of Health (1964, p. 19) show that the total dissolved solids range from 579 ppm to 1,138 ppm. The calcium and magnesium may have precipitated while the samples were in storage so the dissolved solids probably are somewhat low.

Grenora

The city of Grenora obtains its water supply from two wells, which are rated as being capable of yielding 220,000 gpd. In 1963, the average use of water was approximately 50,000 gpd (U. S. Public Health Service, 1963, p. 122), which is approximately 110 gpd per person. In 1965, the estimated average use was between 28,000 and 34,000 gpd, or between 70 and 84 gpd per person.

The quality of the municipal water supply depends to some extent on the well in production. However, both wells yield water that is a very hard, calcium bicarbonate type. Well 2 has better quality water than well 1. Except for the slightly high iron in well 1, there are no ions in excess of the recommended limits set by the U. S. Public Health Service standards.

Wildrose

The city of Wildrose obtains its water supply from well 159-97-2baa, which will pump about 122,000 gpd. The average use, however, is about 20,000 gpd, or about 50 gpd per person.

The water sampled June 8, 1965 was a very hard, sodium calcium sulfate bicarbonate type (Armstrong, 1967a, table 4).

Wheelock

The village of Wheelock maintains a well, 156-98-35bda, for the convenience of the local population. They have no distribution system. The water is a very hard, sodium carbonate type having a dissolved solids content of 1,240 ppm. The sulfate ion and iron exceed the recommended limits set by the U. S. Public Health Service.

INDUSTRIAL WATER SUPPLIES

Practically all of the water used for industrial purposes in Williams County is used in connection with the production of petroleum products, salt, milk, and gravel.

The largest industrial use of ground water in Williams County is for the pressure maintenance in some of the oil fields. In 1966, there was approximately 934 acre-feet of brines produced with oil that was returned to the oil-producing formations. In addition, a total of approximately 4,000 acre-feet of water was pumped from the Dakota aquifer. The water is pumped into the oil-bearing beds to maintain the formation pressure as oil is being produced.

The Signal Oil and Gas Company's Tioga plant generally uses an average of about 46 gpm, principally for cooling purposes; this is about 74 acre-feet per year.

The Dakota Salt Co. reports that their Williston plant uses 170 gpm (224 acre-feet per year) in the solution and recovery of salt.

The quantity of ground water used in the processing of milk in the county can be roughly extrapolated from estimates of pumpage reported from two of the larger dairies in Williston. These estimates indicate that approximately 92 acre-feet per year is used for cooling and sanitation at the processing plants.

The gravel industry is estimated to use approximately 30 acre-feet of ground water per year for washing gravel.

SUMMARY

The alluvium and glacial drift aquifers with the greatest potential for ground-water development are: the Little Muddy, Ray, Trenton, Hofflund, and Grenora aquifers. The Little Muddy aquifer averages about 60 feet in thickness under an area of approximately 80,000 acres. The aquifer apparently contains at least 750,000 acre-feet of water that can be pumped at rates of from 50 to about 1,200 gpm. The higher rates are obtainable in the northern part of the aquifer. The water in the northern part generally is a very hard, sodium or magnesium bicarbonate type that generally contains less than 900 ppm dissolved solids. The water in the southern part is commonly a very hard sodium sulfate type containing from 1,030 to 2,050 ppm dissolved solids.

The Ray aquifer averages about 60 feet in thickness under an area of approximately 64,000 acres. The aquifer contains at least 600,000 acre-feet of water that can be pumped at rates of from 50 to more than 500 gpm. The higher rates are obtainable near the central part of the aquifer. The water generally is a very hard, calcium magnesium sulfate type with 602 to 2,290 ppm dissolved solids.

The Grenora aquifer apparently averages about 80 feet in thickness and underlies approximately 14,000 acres in Williams County; the aquifer extends northward into Divide County and westward into Montana. The thickness and extent suggest that the aquifer probably contains as much available water as the Little Muddy aquifer, but only about 180,000 acre-feet of water directly underlies Williams County. Well yields generally should range between 50 to 500 gpm. The two samples of water from the aquifer show a very hard, sodium bicarbonate type water that contains from 1,090 to 1,300 ppm dissolved solids.

The Trenton aquifer probably averages more than 50 feet in thickness under an area of about 26,000 acres. The aquifer contains at least 210,000 acre-feet of water that probably can be pumped at rates as high as 1,500 gpm. The water along the northern side is a very hard, sodium sulfate type generally containing more than 3,000 ppm dissolved solids. The water grades southward into a sodium calcium bicarbonate type with as little as 979 ppm dissolved solids.

The Hofflund aquifer averages about 45 feet in thickness under an area of about 9,600 acres. The aquifer contains at least 70,000 acre-feet of water in storage that can be pumped at rates as high as 2,000 gpm. The water in the west and central parts of the aquifer is a very hard, sodium calcium bicarbonate type that contains from 691 to 1,120 ppm dissolved solids.

The Wildrose and West Wildrose aquifers, and the larger outwash deposits near Alamo and Grenora, are the most important minor aquifers in Williams County. These aquifers are capable of yielding water at rates of from 50 gpm to as high as 250 gpm. The water in these aquifers generally contains less than 1,000 ppm dissolved solids.

The water in the glacial drift aquifers is generally very hard and has a wide range of dissolved solids. Water containing low total dissolved solids usually is a calcium bicarbonate type. Water containing high total dissolved solids usually is a sodium sulfate type.

Except for a few square miles of the Little Muddy aquifer, most of the water in Williams County may be marginal to unsuitable for irrigation purposes. However, the Hofflund aquifer and the southern part of the Trenton aquifer contain water that probably could be used for irrigation of salt-tolerant crops on all but heavy types of soil. Water from the Grenora, Ray, and Little Muddy aquifers possibly could be used for irrigation if adequate drainage is available and proper management practices are followed.

Water in the Dakota Group is too saline for most uses. The chemical quality of the water in the Fort Union Group, and probably in the Fox Hills and Hell Creek Formations also, generally is too poor to be recommended for human consumption or agriculture uses; but, in most places it is suitable for livestock. Locally, however, some of the Fort Union water can be used for human consumption without any noticeable ill effects.

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