NORTH DAKOTA GEOLOGICAL SURVEY
WILSON M. LAIRD, *State Geologist*

BULLETIN 44

NORTH DAKOTA STATE
WATER CONSERVATION COMMISSION
MILO W. HOISVEEN, *State Engineer*

## COUNTY GROUND WATER STUDIES 5

# GEOLOGY AND GROUND WATER RESOURCES

## of Eddy and Foster Counties, North Dakota

## PART III – GROUND WATER RESOURCES

by

HENRY TRAPP, JR.

GEOLOGICAL SURVEY
United States Department of the Interior

Prepared by the United States Geological Survey in cooperation with the North Dakota State Water Commission, North Dakota Geological Survey, and the Boards of Commissioners of Eddy and Foster Counties.

GRAND FORKS, NORTH DAKOTA

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This is one of a series of county reports published cooperatively by the North Dakota Geological Survey and the North Dakota State Water Conservation Commission. The reports are in three parts; Part I describes the geology, Part II presents ground water basic data, and Part III describes the ground water resources.

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# GEOLOGY AND GROUND WATER RESOURCES of Eddy and Foster Counties, North Dakota

## Part III - Ground Water Resources

by Henry Trapp, Jr.

## ABSTRACT

Eddy and Foster Counties have substantial water resources in glacial-drift aquifers. Only a small part of the potential yield has been developed. At least 20 percent of the area is underlain by aquifers capable of yielding 50 gallons per minute to individual wells; in most of the remaining area, adequate supplies are available for rural domestic use and stock watering.

The glacial aquifers are composed of sand and gravel, and include surficial and buried outwash-plain deposits, channel deposits, terrace deposits, and ice-contact deposits.

The New Rockford and Carrington buried outwash aquifers probably have the greatest potential as sources of water. Wells in the Carrington aquifer are capable of yielding over 1,000 gallons per minute. Similar yields are possible from the New Rockford aquifer.

Surficial outwash aquifers, such as the Northwest Eddy and Central Eddy aquifers, underlie substantial areas, but they generally are thin. However, one irrigation well in the Northwest Eddy aquifer yields more than 750 gallons per minute, and similar yields may be obtained in a few other surficial aquifers.

Glacial till supplies water to many domestic and stock wells. The yields of these wells are generally less than 10 gallons per minute.

Water from the glacial drift ranges in dissolved solids content from 250 to 6,000 parts per million, with the more productive aquifers generally in the range of 250 to 2,000 parts per million. Dissolved solids and iron commonly exceed the limits recommended by the U.S. Public Health Service for drinking water. Less frequently, sulfate, chloride, and nitrate exceed the limits. The water is very hard.

For the more productive glacial aquifers, the irrigation classification generally ranges from medium to high salinity and low to high sodium hazards.

Of the rocks underlying the glacial drift, only the Cretaceous Pierre Shale and Dakota Sandstone have been used as aquifers. Waters from these rocks are generally saline.

New Rockford, Sheyenne, and Carrington presently have municipal water systems that derive their water from wells. Suitable sources of ground water are available to most of the other communities in the area.

# INTRODUCTION

## Purpose and scope

A study of the geology and ground-water resources of Eddy and Foster Counties, in east-central North Dakota (fig. 1), was begun in 1962 by the U.S. Geological Survey, in cooperation with the North Dakota State Water Commission and the North Dakota Geological Survey. The purpose was to study the availability, quantity, and quality of the ground-water resources of the two-county area. The availability of water for irrigation and for municipal use was of primary interest.

Records of about 2,000 wells and springs were collected during the study and 89 test holes were drilled. Periodic measurement of water levels was begun in 1963, and, during most of 1964 and 1965, from 50 to 60 wells were measured each month. One hundred eleven water samples were analyzed chemically. These data have been published in "Geology and Ground Water Resources of Eddy and Foster Counties, North Dakota, Part II, Ground Water Basic Data" (Trapp, 1966). A report on the geology of the area was published as Part I of this series (Bluemle, 1965). This volume, Part III, contains interpretation of the hydrology based on the geologic and hydrologic data of Parts I and II.

## Previous investigations

Simpson (1929) prepared the first comprehensive report on the geology and ground water resources of the State. His report includes a brief discussion of the geology, ground-water resources, public water systems, and quality of ground water of each county.

As a result of the drought of the 1930's, the U.S. Army Corps of Engineers made a study of water supply and sewage disposal problems in the basins of the James and Sheyenne Rivers (Sayre, 1935). In this report (p. 118, 127), A. N. Sayre of the U.S. Geological Survey made recommendations following a local study of water levels in the village of Sheyenne, Eddy County. He also described the municipal supply at New Rockford (p. 112), and mentioned that the wells there produce from a buried gravel aquifer reported to be 60 miles long east and west and 2 miles wide.

Abbott and Voedisch (1938) listed representative well schedules and chemical analyses of ground water, by counties, throughout the State.

In 1938 and 1939, the North Dakota Geological Survey and the Works Projects Administration made the first detailed well inventory of Eddy and Foster Counties (North Dakota Geol. Survey and Works Projects Administration, 1938,

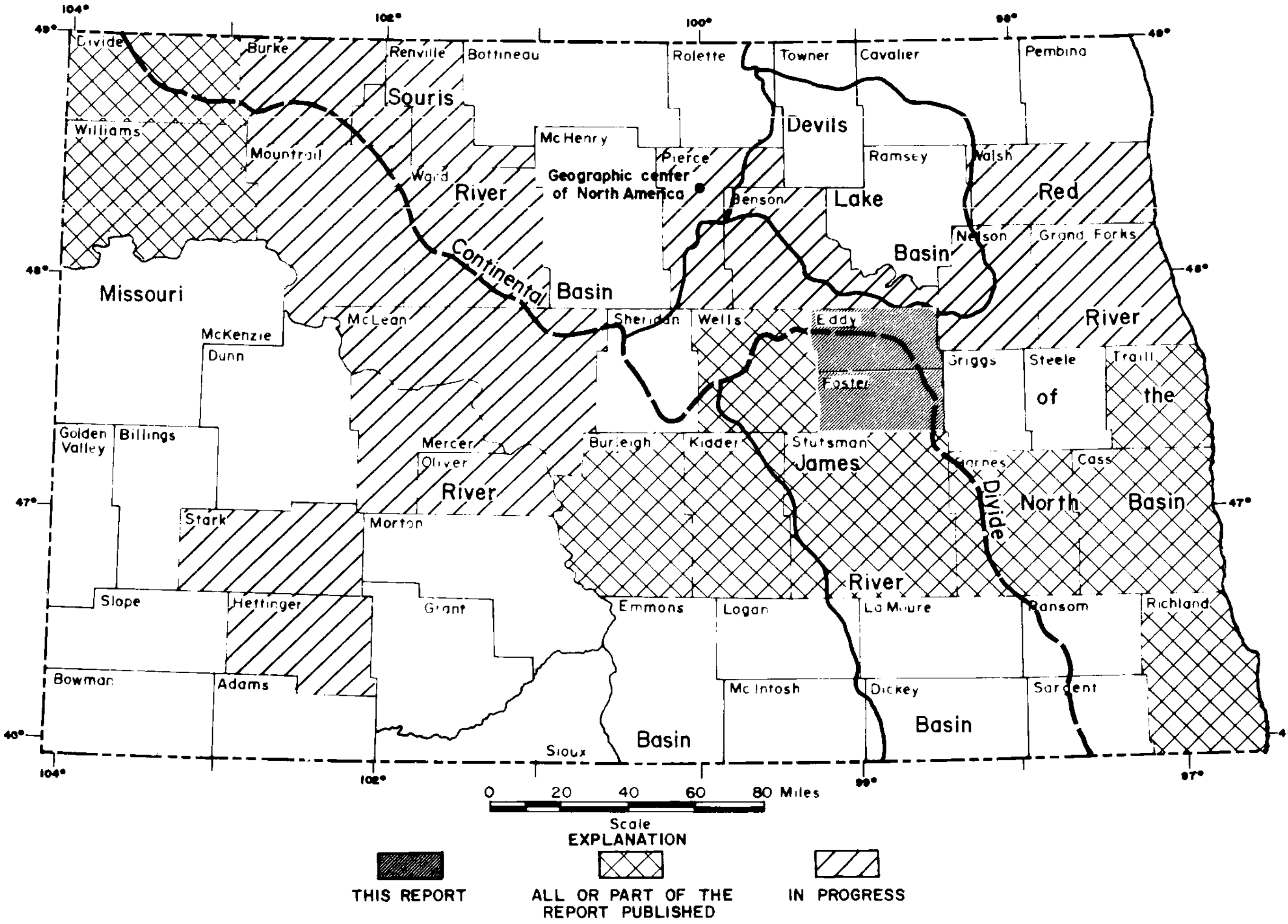


FIGURE 1. Map of North Dakota showing location of Eddy and Foster Counties in relation to drainage basins and the Continental Divide.

1939) as part of its general Statewide coverage.

Rasmussen (1945), in making a Statewide reconnaissance of possible well irrigation areas, mentioned the Rosefield Township artesian aquifer (buried outwash) in southwestern Eddy County, and also springs draining from surficial outwash above the Sheyenne River. He gave flow measurements for two springs.

During the 1940's and 1950's, the U.S. Geological Survey, in cooperation with the North Dakota State Water Commission, did test drilling around Carrington and Glenfield (Foster County) and New Rockford and Brantford (Eddy County). The results were not published at that time, but the logs of most of the test holes are published in Part II of this report.

During the 1950's and early 1960's, the U.S. Bureau of Reclamation was investigating parts of Eddy and Foster Counties as proposed irrigation and canal sites for the Garrison Diversion Project. Selected logs of test holes and water-level measurements supplied by the Bureau are given in Part II of this report.

Paulson and Akin's report on the Devils Lake area (1964) included part of northeastern Eddy County, although most of the area studied lies in Benson and Ramsey Counties.

Froelich (1964) studied the ground-water potential of the area within and immediately surrounding the village of Sheyenne, in northwestern Eddy County. This involved detailed test drilling and water sampling.

## Acknowledgments

The early stages of this investigation were under the direction of C. J. Huxel, Jr., of the U.S. Geological Survey. Roger Schmid, Larry L. Froelich, and Alain Kahil of the North Dakota State Water Commission logged the test holes drilled for the project. Milton Lindvig of the North Dakota State Water Commission was in charge of aquifer testing and prepared preliminary interpretations of aquifer-test data.

This work was made possible by the cooperation of the residents and officials of Eddy and Foster Counties, who furnished essential information on wells and springs and permitted measurements to be made and samples to be taken. Special thanks are due to the officials and townspeople of New Rockford, to H. M. Olson of the Carrington Irrigation Branch Station, and to Arvid and Erlund Berglund of Sheyenne, because these people permitted the use of their wells and pumps for aquifer tests.

Well and test-hole logs were furnished by the following drilling contractors: Leroy Butts of Carrington, Kamoni Brothers of Pettibone, Douglas Ramey of McHenry, Carl Ringdahl of McVille, and Schnell, Inc., of Bismarck. The U.S.

Bureau of Reclamation permitted reproduction and publication of many logs, water-level measurements, and other data in the Bismarck office files. The Great Northern Railway furnished logs and construction details of its wells and the California Company provided a number of seismic shot-hole logs.

## Well-numbering system

The wells, springs, and test holes referred to in the report are numbered according to a system based on the location in the public land classification of the United States Bureau of Land Management. It is illustrated in figure 2. The first numeral of the well number denotes the township north of the base line, the second numeral denotes the range west of the principal meridian, and the third numeral denotes the section in which the well is located. The three letters locate the well within the section; the first denotes the quarter section, the second the quarter-quarter section, and the third the quarter-quarter-quarter section (10-acre tract). In each case, the letters a, b, c, and d refer to the northeast, northwest, southwest, and southeast elements of the division. Consecutive terminal numerals are added if more than one well is recorded with a 10-acre tract. Thus, well number 147-62-15aad is in the SE1/4NE1/4NE1/4 sec. 15, T. 147 N., R. 62 W. (fig. 2).

# GEOGRAPHIC AND GEOLOGIC SETTING

## Physical geography

Eddy and Foster Counties are located about 100 miles southeast of the geographic center of North America (fig. 1).

The Continental Divide runs through the counties. To the southwest, the drainage is to the Gulf of Mexico by way of the James, Missouri, and Mississippi Rivers; to the northeast the drainage is to Hudson Bay by way of the Sheyenne River and the Red River of the North. The principal tributaries of the James River in Eddy and Foster Counties are Pipestem Creek, Rocky Run, and Kelly Creek. The northern tip of Arrowwood Reservoir on the James River extends into southern Foster County. The narrow Sheyenne River valley in Eddy County has no sizable tributaries, but Bald Hill Creek, which heads in northeastern Foster County, flows into the Sheyenne in northern Barnes County. Both the James and Sheyenne Rivers have frequent periods of no flow.

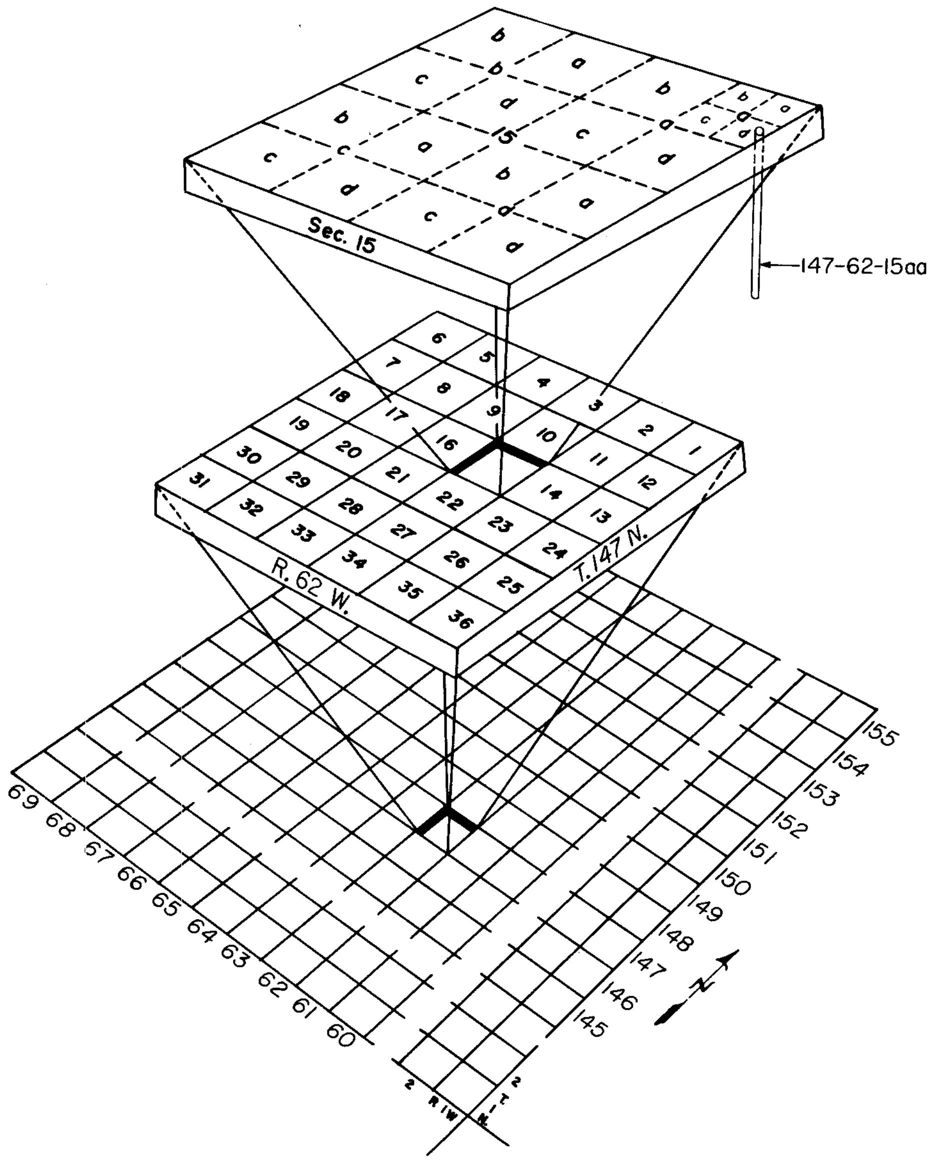


FIGURE 2. Diagram showing system of numbering wells, springs, and test holes.

Much of the area, although located within the drainage basins of the James and Sheyenne Rivers, is internally drained. There are numerous lakes, sloughs, and small ponds, most of them intermittent; Juanita Lake, North and South Washington Lakes, Johnson Lake, and Horseshoe Lake are natural lakes that are generally considered permanent, although at least one of these (North Washington Lake) is reported to have been dry or nearly dry during the drought of the 1930's. The quality of water varies considerably from one lake to another, and in each lake with wet and dry seasons, but most of the lakes contain moderately saline water. Juanita Lake and Lake George, in Foster County, contain fresh water.

The total relief in the two-county area is about 600 feet, with the highest point nearly 2,000 feet above sea level at the southwest corner of Foster County, and the lowest point below 1,370 feet on the Sheyenne River at the east boundary of Eddy County. Most of the land surface lies between 1,450 and 1,600 feet and is gently rolling. The southwest corner of Foster County is on the east slope of the Missouri Coteau. Most of the central Eddy County, on the other hand, is nearly flat.

The topography of Eddy and Foster Counties is the result of glacial erosion and deposition. Although most of the present landforms were produced during the retreat and minor readvances of the last ice sheet, it is probable that more than one ice sheet advanced over the area (Bluemle, 1965, p. 19, 20, 56). The preglacial topography was eroded by glacial ice and melt water and subsequently almost completely covered by glacial drift. The area's glacial history explains the present poorly integrated drainage and abundant lakes.

## Climate

As of November 1965, there were precipitation and temperature stations in Carrington, at Sheyenne, and 5 miles north of McHenry. There was a precipitation recording station at Melville. In addition, a precipitation and temperature station at Maddock Agricultural School in Benson County is only 12 miles northwest of the project area. It has a longer continuous record than Sheyenne; therefore, its precipitation record has been used on one of the hydrographs in this report.

The climate at Carrington may be taken as typical for the area, this is described as follows (Skrede, no date):

"The climate is typical of the Great Plains with cold winters, warm summers, and moderate annual rainfall. Because there are no obstacles to the winds from the arctic north or the subtropical south, the area is subject to wide variations in temperature from day to day, and month to month. Summers are warm and pleasant with sunny days and cool nights. Hot, humid days are rare. Temperatures of 90 degrees or more occur on an average of 19 days per year, ranging from 2 days in the coolest summers to 38 days in 1936.

"Cold waves and blizzards in the winter season are a rather frequent occurrence, but on rare occasions this area may enjoy a 'chinook' wind, that is, a mild, dry, westerly wind. Temperatures during the winter months of December, January, and February average about 10 degrees, but maximum temperatures exceed 32 degrees on 21 days during these months. Minimum temperatures drop to below zero 57 times each year.

"The annual precipitation at Carrington is 17.30 inches, of which 75% occurs in the growing season and 50% in the months May, June, and July. There has been a range in precipitation from less than 7 inches in the drought year of 1936, to nearly 24 inches in 1954. Summertime precipitation is generally in the form of thunderstorms with about 30 storms per year, mostly in June and July. June is usually the wettest month of the year and June, 1954, when 6.85 inches of precipitation was measured, is the wettest month on record. Precipitation of 0.10 inches or more can be expected on an average of 40 days per year. Rainfall of 1.00 inch or more per day can be expected 2 or 3 times per year. The likelihood of one inch or more of rain in any 7-day period during the summer is greatest during the fourth week in June when the chance is once in three years. The likelihood of a dry 7-day period, trace or less, is greatest the first week in November when the chance is two years in three. Precipitation intensities of about 1.10 inches in 1 hour, 1.60 inches in 6 hours, and 2.10 inches in 24 hours can be expected once in 2 years. Thirty-four inches of snow can be expected in Carrington each year, but snowfall has varied from about 13 inches in 1930-31 to over 80 inches in 1949-50. Over 35 inches of snow fell in January, 1950, for the greatest monthly total, while 12 inches on April 5, 1933, is the record one-day amount. Measureable snow can be expected one year in two in October, two years in three in April, and one year in four in May.

"Wind, sunshine, and relative humidity records are not available, but the following data from Devils Lake should approximate conditions at Carrington. Prevailing winds are from the northwest in all months except June and August when southeasterly winds predominate. The average wind movement during the year is about 10 miles per hour. March, April, and May are slightly windier than the other months. Sunshine averages about 60% of the possible amount ranging from 45% in winter to about 70% in summer. About 220 days during the year are classified as either clear or partly cloudy. Relative humidity in the summer ranges from 85% in the early morning to 50% in the late afternoon and during the winter averages about 75% day and night."

For the period in which hydrologic data were being collected for this project, Carrington in 1962 had a total precipitation of 23.77 inches, or 6.47 inches above the annual mean of 17.30 inches; in 1963 had 13.93 inches, or 3.37 inches below the mean; in 1964 had 26.31 inches (a new record), or 9.01 inches above the mean; and in 1965 had 22.17 inches; or 4.87 inches above the mean.

# Economic geography

The total area of the two counties is about 1,300 square miles, and, according to the 1960 census, the population is 10,297. The county seat of Eddy County is New Rockford, population 2,177, and the county seat of Foster County is Carrington, population 2,438. In Eddy County, the village of Sheyenne has a population of 423, and unincorporated communities include Brantford and Hamar. In Foster County, the villages of Glenfield, population 129, and McHenry, population 155, are incorporated; unincorporated communities include Barlow, Bordulac, Grace City, Juanita, and Melville (U.S. Bureau of the Census, 1960).

The economy of the two-county area is based on diversified dry-land farming and stock raising, with wheat, flax, and barley as the main cash crops. Turkeys are raised commercially around New Rockford, where there is a processing plant. Irrigation farming, using wells, is practiced on two farms within the area and at the State-owned Carrington Irrigation Branch Station. Parts of the area are within irrigation districts of the recently authorized Garrison Diversion Project, whose Conservancy District headquarters is Carrington.

# Geology

## PREGLACIAL ROCKS

The Precambrian basement surface in Eddy and Foster Counties lies roughly between 2,800 feet below the surface in the eastern part of the area to 4,300 feet in northwestern Eddy County. The Precambrian rocks are crystalline metamorphic and igneous rocks generally called "granite," although other rock types are also present.

Little is known of the Precambrian in North Dakota since it does not crop out within the State and there has been no economic incentive to explore it in the subsurface.

The sedimentary rocks overlying the Precambrian basement were deposited in the Williston Basin, a structural and sedimentary basin that covered most of North Dakota, and adjoining parts of South Dakota, Montana, Saskatchewan, and Manitoba. Eddy and Foster Counties lie on the eastern flank of the basin. The center of subsidence and deposition shifted through geologic time, but was always west of this area (Ballard, 1963, p. 31, fig. 8). Thus, the sedimentary formations dip and thicken in a generally westward direction. Through Paleozoic time, a structural high centered in western Foster County was intermittently elevated. This high, named the Foster high by Ballard (p. 32-33), resulted in local thinning and nondeposition of some of the Paleozoic rocks.

The Paleozoic rocks in Eddy and Foster Counties range in age from Cambrian to Mississippian. Their lithology is predominantly carbonate except for sandstones in the Winnipeg and Deadwood Formations, shales in the Winnipeg, and the Carrington Shale facies in the lower part of the Mississippian section.

Although the Williston Basin was still sinking and receiving sediment in Mesozoic time, westward thickening is not as pronounced in the Mesozoic formations as in the Palezoic formations in Eddy and Foster Counties. Likewise, the westward dip is gentler in the Mesozoic formations. The oldest Mesozoic beds are considered to be Jurassic; these are overlapped by Cretaceous rocks in the eastern part of the area (Bluemle, 1965, p. 12-15). At approximately the location of the Paleozoic Foster high, northwestern Foster and southwestern Eddy Counties, the Greenhorn to Jurassic interval is anomalously thick (Hansen, 1955, fig. 8).

The Mesozoic rocks are predominantly shale, with sandstone beds in the lower part of the Cretaceous section. These Cretaceous sandstones, together with the interlayered shale, are generally referred to as the Dakota Sandstone by the U.S. Geological Survey. The North Dakota Geological Survey uses the term "Dakota Group" to apply to the stratigraphic interval in which the sandstones are found plus the overlying bentonitic Mowry Shale. This stratigraphic interval, and its subdivision into formations, is based largely on electric log correlation (Bluemle, 1965, p. 13).

According to the North Dakota Geological Survey usage, the uppermost sandstone in the Dakota Group, and its silty or shaly equivalents, is called the Newcastle Formation ("Muddy"). Hansen (1955, fig. 9) showed the total sand thickness in the Newcastle Formation to range from 0 in northwestern Eddy County to 70 feet in southeastern Foster County. However, in southeastern Foster County, the Newcastle is very fine grained and difficult to distinguish in rotary samples (North Dakota Geol. Survey, 1954-63, Circ. 22).

The Cretaceous sandstones below the Newcastle lie within the Lakota-Fall River interval according to Bluemle (1965, p. 13). These sandstones are lenticular and they interfinger with shale and siltstone. The sandstones consist of clean quartz sand with abundant pellets of iron carbonate. A well driller is likely to call the first sandstone encountered below the Upper Cretaceous shales the "first Dakota sand" or, if waterbearing, the "first flow." Therefore, these driller's terms may refer to different sand bodies in different areas.

The Pierre Shale is the youngest Cretaceous formation in Eddy and Foster Counties. It forms the bedrock surface below the glacial drift and crops out locally, particularly along the bluffs of the Sheyenne and James Rivers. Its thickness within the project area ranges from about 250 to 1,000 feet with the variation due more to variations in elevation of the bedrock surface than to basinward thickening. In test holes penetrating a few feet of bedrock in this area, the Pierre is commonly described as shale, olive gray to olive black, fissile, noncalcareous to slightly calcareous, locally fossiliferous, and with occasional bentonite layers and gypsiferous streaks. In some holes, the Pierre is described as clay, light gray to dark greenish gray, soft, smooth, plastic, and easily confused with Pleistocene lake clays. It is not certain whether these clays encountered in the test holes represent buried preglacial weathered zones or claystone and marlstone zones within the Pierre similar to the lower part of the formation in Barnes County, as reported by T. E. Kelly (1966, p. 23, 25). Kelly also stated that the fissile shale parts of the Pierre are more highly jointed and fractured than the marly or clayey zones.

## GLACIAL AND POSTGLACIAL DEPOSITS

Glacial drift covers almost all of Eddy and Foster Counties (Bluemle, 1965, pl. 1). The maximum thickness is more than 420 feet, but the average is about 125 feet. The average drift thickness is greater in Foster than in Eddy County, although the greatest thickness penetrated by a test hole (423 feet) is in northern Eddy County.

The drift is unconsolidated, and consists of fragments of older rock eroded and transported by the ice sheets. Glacial drift may be subdivided into four principal types on the basis of lithology and inferred origin. These types include till, outwash, ice-contact deposits, and lake deposits.

### Till

Till is predominantly unsorted and unstratified drift, but pockets of sand or gravel may be incorporated in the unsorted mass (Flint, 1947, p. 103-113). Till is deposited from glacial ice by dumping, pushing, lodgment (or plastering-on), and ablation (let down by sublimation and melting). End moraine, ground moraine, and dead-ice moraine are landforms that are composed chiefly of till.

Bluemle (1965, pl. 1) mapped Eddy and Foster Counties in terms of the landforms associated with each of the exposed drift sheets. His map shows end moraines or ground moraine covering approximately 60 percent of the area. Thus, it may be inferred that the predominant surficial rock material is till. In addition to the areas mapped as moraine, till also underlies much of the outwash and lake deposits.

Till is made up of rock fragments ranging in size from clay to large boulders. Ninety-four near-surface samples of till from Eddy and Foster Counties, with gravel and coarser sizes removed, were analyzed for size. They averaged about 40 percent sand, and, if classified as soils, most would be considered loams (Bluemle, 1965, p. 16, fig. 7, table 2). They are not necessarily representative of the till at depth since the uppermost till may have been partially washed by melt waters during deposition (Flint, 1947, p. 111, 113). In many of the test holes drilled for this project, changes in the drilling rate and the behavior of the rig indicated a change to a more compact till at depth. This may suggest the change to a lodgment till or an older drift sheet. In either case, the percentage of sand probably would be different from that of the surficial till.

The till in Eddy and Foster Counties is composed of particles and fragments of the local Pierre Shale bedrock, of Paleozoic carbonates and Precambrian igneous and metamorphic rocks from Canada, and lignite and sandstone from northern North Dakota. Particles of Pierre Shale probably make up the bulk of the finer material; pebbles and boulders are composed largely of more resistant rock (Bluemle, 1965, tables 3-4). Finely divided limestone is well distributed throughout the till; practically all samples effervesce vigorously when acid is applied. Gypsum crystals were frequently noted in test-hole cuttings, and these probably originate in part from anhydrite zones in the Paleozoic carbonate source rock.

The till generally is olive gray in the subsurface, but is oxidized to dusky and yellowish shades of brown. The color change generally comes at about 15 to 30 feet below the surface; this represents the approximate position of the water table.

### Outwash

Outwash is sorted and stratified drift deposited by melt-water streams beyond the edge of a glacier. The coarser material is deposited first, and the finer material is transported farther before deposition. The very finest materials, silt and clay, are likely to be deposited only in standing water; in this report, these are treated separately as lake deposits. Outwash, as used here, will be applied only to sand and gravel. Outwash may be confined to a channel or it may be spread over a broad expanse, where it is called an outwash plain.

In Part I of this report, plate 1 shows the exposed areas of outwash (Bluemle, 1965). In addition to surficial outwash, outwash may be buried beneath later glacial drift. Both buried outwash channel and buried outwash plain deposits have been found in Eddy and Foster Counties.

### Ice-contact deposits

Ice-contact deposits are bodies of stratified drift that were deposited in contact with melting glacial ice. It is less sorted and stratified than outwash, and the bedding is frequently slumped or contorted.

Ice-contact landforms include kames, eskers, and disintegration ridges (Bluemle, 1965, p. 27). These are frequently conspicuous topographic features, but occupy only a small fraction of the area of Eddy and Foster Counties. There may be buried ice-contact features in the area, but these would be almost impossible to distinguish from buried outwash.

### Lake deposits

Very fine-grained stratified drift, namely silt and clay, was deposited by glacial melt waters in lakes. Most of the exposed glacial lake deposits in Eddy and Foster Counties are only a few feet thick. In the subsurface, considerable thicknesses of silt and clay have been penetrated in a few test holes. In some places the silt and clay appear to be associated with melt-water channels. Melt-water streams in these channels probably were temporarily dammed and the silt and clay were deposited by the melt-water lakes thus formed.

Recent lake plains are floored with thin layers of dark, organic clay.

### Alluvium

Alluvium in Eddy and Foster Counties comprises the postglacial flood-plain deposits, largely restricted to the principal streams. The alluvium is generally less than 10 feet thick, and distinguished from glacial outwash in the valleys by being finer grained and usually darker colored.

# GROUND-WATER RESOURCES

## Principles of occurrence

The circulation of water, involving its transfer from the atmosphere to the land surface by means of precipitation, its infiltration into the soil and ground-water reservoirs, runoff and spring discharge into streams, eventual transport to the ocean, and its return to the atmosphere is termed the hydrologic cycle (fig. 3). There are many possible short circuits, recyclings, and delays in the path that an individual water particle takes in its journey from the atmosphere to the ocean and back. For example, it might be evaporated shortly after falling as rain, or it might be trapped for thousands of years as part of a polar ice cap or in a ground-water reservoir.

This report is concerned mainly with the part of the hydrologic cycle in which water enters ground-water reservoirs, is stored in them, and leaves. Particular emphasis has been placed on the nature and extent of ground-water reservoirs and the quantity and quality of water in storage in Eddy and Foster Counties.

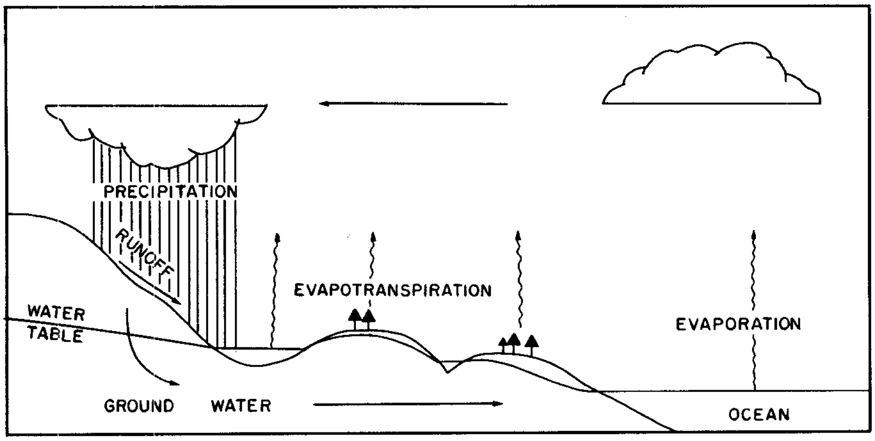


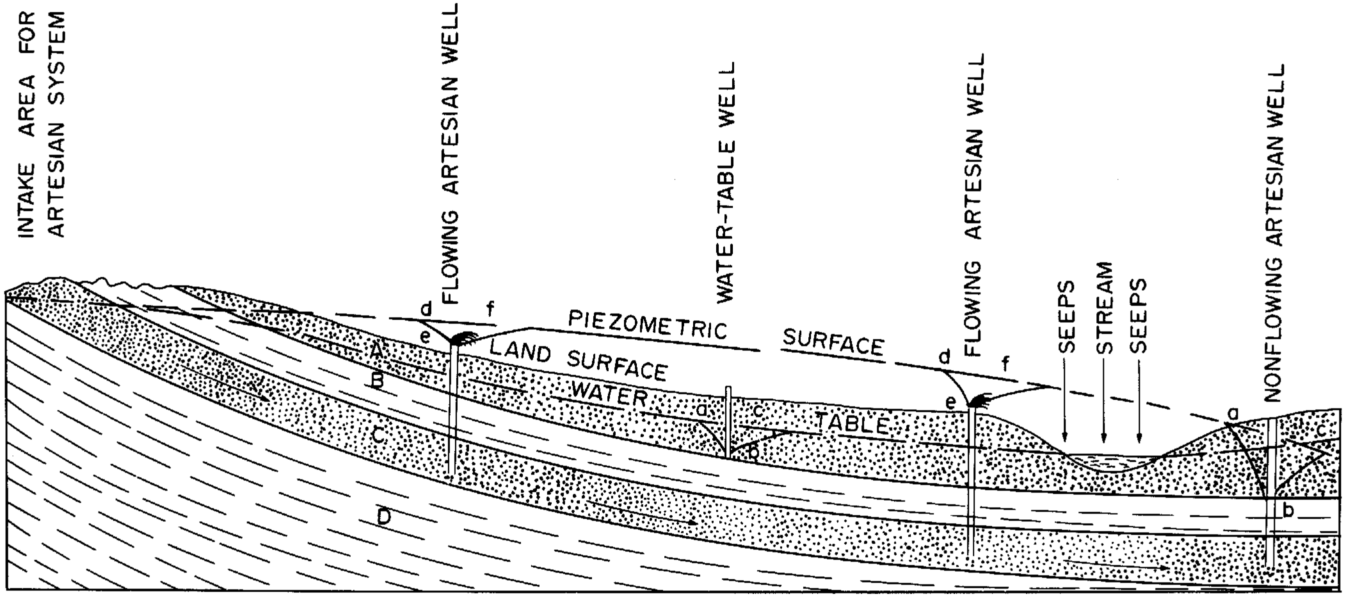
FIGURE 3– The hydrologic cycle.

However, it should be kept in mind that ground water may seep out onto the surface and become surface water, and vice versa, and that both ground water and surface water are ultimately dependent on precipitation.

The rock (including unconsolidated sediments) forming the upper part of the earth's crust generally contains numerous small pores. In clay and silt, these are abundant, but extremely small. Sand and gravel have fewer but larger openings. Rock also frequently is jointed or cracked. The many pores and joints in the rock serve as the storage space for ground water, and also the paths by which it moves. If a relatively large percentage of the volume of a rock is made up of pore space, the rock is said to be porous. Porosity is expressed as the percentage of the total volume of the rock occupied by pore space. If, as a result of relatively large and interconnected joints and pore spaces, the rock transmits water readily, it is said to be permeable. Permeability is expressed as the rate of flow of water, in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot (vertical) per foot (horizontal) at a temperature of 60° F. Field permeability is permeability at aquifer temperature.

That part of the upper earth's crust in which pores and joints are filled with water is known as the zone of saturation. Where the water is not confined beneath an impermeable layer, the upper surface of the zone of saturation is called the water table. It is free to rise and fall with changes in the amount of water entering and leaving the saturated zone (recharge and discharge). The water table is not a flat surface but generally reflects, in a subdued way, the irregularities of topography. Generally, the water table intersects the land surface at springs, streams, and lakes.

A body of rock that will yield water in sufficient quantity to serve as a source of supply is called an aquifer. In artesian aquifers, water is confined under suf-



A. Permeable surficial material B. Upper confining bed C. Artesian aquifer D. Lower confining bed

abc Cone of depression caused by pumping a water-table or a nonflowing artesian well

def Cone of depression caused by natural discharge from a flowing artesian well

——→ Direction of ground-water movement

**FIGURE 4. Idealized section illustrating artesian and water-table conditions.**

ficient hydraulic pressure to cause it to rise above the level at which the aquifer is penetrated in a well (fig. 4).

Artesian conditions exist where the aquifer underlies a confining layer or mass of relatively impermeable materials, so that pressure may be maintained in the aquifer. Water may enter the aquifer at its outcrop and percolate down to the water table and then laterally with the hydraulic gradient beneath the confining bed. The weight of the water in the hydraulic system produces pressure, which is transmitted throughout the aquifer and against the confining bed (fig. 4). Artesian aquifers also may receive recharge from other aquifers or from surface bodies of water.

The imaginary surface that coincides with the level to which water will rise in each well drilled into an aquifer is the piezometric surface. This surface may lie above, below, or at either the water table or land surface. If the piezometric surface is above land surface, wells penetrating the aquifer will flow, but not all artesian wells flow.

When water is withdrawn from an artesian aquifer by a well, the aquifer remains saturated, but its pressure is reduced. The aquifer contracts and the water remaining expands very slightly to compensate for the volume withdrawn. An analogy can be made with an inflated rubber balloon, from which some air is released. The balloon remains full of air, but somewhat smaller and under less pressure. However, unlike water in an aquifer, the air in a balloon is able to expand much more in response to decreased pressure.

In an artesian aquifer where the confining layer is sufficiently permeable to transmit substantial amounts of water into or out of the aquifer, the aquifer is called leaky artesian or semiconfined. The division between leaky artesian and artesian aquifers is arbitrary since in nature, few if any confining layers are completely impermeable. Leaky artesian conditions are the most common among the buried outwash aquifers of Eddy and Foster Counties. In many of these aquifers, the piezometric surface closely approximates the water table in the overlying till aquifers.

Specific yield, specific retention, storage coefficient, and coefficient of transmissibility are all terms used in defining the characteristics of aquifers. Specific yield is the quantity of water that an aquifer will yield under the force of gravity if it is first saturated and then allowed to drain. It is expressed in percentage as the ratio of the volume of the water drained to the volume of the aquifer. Specific retention represents the water remaining in the aquifer after it is drained; it is equal to the porosity less the specific yield. Aquifers composed of fine-grained materials have relatively high specific retentions. Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. For water-table aquifers, the changes in head refer to changes in the water table, and the storage coefficient is essentially equal to the specific yield. For artesian aquifers, the head changes refer to changes in piezometric surface, and the coefficient is numerically small, indicating that large pressure changes over extensive areas are required to produce substantial water yields. The coefficient of transmissibility of an aquifer is the rate of flow of water, at the prevailing water temperature, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent. Transmissibility is equal to aquifer thickness multiplied by the field coefficient of permeability.

The coefficients of storage and transmissibility are usually determined by aquifer tests (or "pumping tests"), which involve frequent or continuous water-level measurements in observation wells while a production well is pumped at a carefully controlled rate of discharge. Detailed discussions of aquifer test analysis methods are given by Theis (1935), Jacob (1940), Ferris and others (1962), Walton (1962), and Bentall and others (1963a, 1963b). Transmissibility can also be derived from laboratory measurements of permeability when the aquifer thickness is known. The coefficients of storage and transmissibility define the ability of an aquifer to store and transmit water; they are useful in predicting the performance of wells and changes of water level in the aquifer.

# Chemical quality of water

## GENERAL PRINCIPLES

Precipitation (rain, snow, sleet, and hail) is the ultimate source of almost all surface and ground water. Water derived from precipitation is known as meteoric water. Rain and snow are usually thought of as pure water, but they contain measurable quantities of dissolved and suspended mineral matter, manmade impurities, and gases. Nevertheless, they are much purer than most surface and ground waters. When precipitation reaches the ground, it dissolves part of the soluble mineral constituents of the soil and rock. The amount dissolved depends on the solubility of the rock, its surface area (how finely divided it is), the length of time the water is in contact with it, temperature, and the concentration of dissolved material already in the water. Carbon dioxide forms a weak acid when dissolved in water, and is an important factor in the solution of limestone and other carbonate rocks.

As stated previously, the glacial drift covering Eddy and Foster Counties comprises a variety of rock materials brought from other areas by the ice sheets. Thus, there is a variety of material available for solution by the ground water. The more abundant soluble minerals in the drift include calcite (calcium carbonate), dolomite (calcium magnesium carbonate) and gypsum (hydrated calcium sulfate).

These are widely distributed through the drift and also are largely finely divided, facilitating their solution. Thus, calcium and magnesium are the most abundant positive ions (cations) in the glacial drift, and sulfate and bicarbonate are the most abundant negative ions (anions).

The Pierre Shale and most of the underlying sedimentary formations are marine in origin. They were deposited in saline ocean water. After withdrawal of the seas, saline water was trapped in some of the sediments. This residual saline water, which may have been modified by reaction with, and solution of, the sediments, bacterial activity, and mixture with other waters, is known as connate water. Connate water may be the source of the high chloride concentrations in waters from the Pierre Shale and Dakota Sandstone, although most of the water in these aquifers probably is of relatively recent meteoric origin. Water with a perceptibly salty taste is sometimes reported from drift aquifers, particularly the deeper ones. This water probably has been in contact with the Pierre Shale.

The chemical process of ion exchange (cation or base exchange in particular) commonly affects the quality of ground water (Hem, 1959, p. 219-223). Certain clay minerals exchange adsorbed ions held within their crystal structure for ions in the water. The most important process of this type is the exchange of sodium in the clays for calcium and magnesium in the water, by the reaction:

$$2\,\mathrm{Na\,X} + \mathrm{Ca}^{++} \rightleftharpoons \mathrm{Ca\,X}_2 + 2\mathrm{Na}^{+}$$

where X represents a unit of exchange capacity in the solid-phase material. Divalent cations are usually held more tightly than monovalent ones, so the reaction tends to go to the right, but the exchange process is a reversible reaction. If the water contains a high concentration of sodium ions, the equilibrium could be shifted to the left. This produces undesirable effects when the water is used for irrigation, as will be explained further in this report.

The base exchange process commonly acts as a natural softening process for ground water. An example is water in the Pierre Shale in Eddy and Foster Counties, which, although highly mineralized, is in many places softer than the less mineralized glacial drift waters. Most of the recharge entering the Pierre aquifers first seeps through the overlying glacial drift, and has a composition similar to water produced by glacial drift aquifers. However, after a period of contact with clay minerals in the shale, the hardness-producing calcium and magnesium ions apparently are exchanged for sodium, and the water becomes softer than the drift waters.

## RELATIONSHIP OF QUALITY OF WATER TO USE

The practical significance of the chemical composition of a water depends on its intended use. The suitability of a water for public supply and domestic use can be judged by standards that have been established by the U.S. Public Health

Service (1962a, p. 7-8) for drinking water furnished by interstate carriers. Some of these standards are as follows:

Iron should not exceed 0.3 ppm (parts per million).
Sulfate should not exceed 250 ppm.
Chloride should not exceed 250 ppm.
Fluoride should not exceed 1.7 ppm.
Nitrate should not exceed 45 ppm.
Dissolved solids should not exceed 500 ppm.

These standards were established initially to protect the health of interstate travelers, and now they are generally used in evaluating the suitability of public water supplies in the United States. Although many people continually drink water containing concentrations substantially higher than the suggested limits, persons unaccustomed to such water may suffer ill effects until they become accustomed to the change.

Iron gives a bitter taste to water. In concentrations of over 0.3 ppm, it tends to stain laundered clothes and porcelain fixtures.

Sulfate has a laxative effect, particularly when associated with magnesium or sodium ions. Persons using water containing sulfate generally become acclimated to it, however. Excessive sulfate also gives a "flat" taste to water.

Chloride gives a salty taste to water. The limit of 250 ppm recommended by the U.S. Public Health Service is based primarily on considerations of taste. Supplies with concentrations in excess of the recommended limits are used without obvious ill effects.

A small amount of fluoride (less than 1.7 ppm) in drinking water consumed by children reduces the occurrence of dental caries (tooth decay). If water containing fluoride in excess of the recommended limit is used for drinking, it will tend to produce objectionable mottling of tooth enamel, with the effects increasing with increased fluoride concentration. Other more serious effects on health may follow from continued intake of water containing a fluoride concentration over 8 ppm.

Nitrate in excess of 45 ppm in drinking water may be hazardous to infants, and a high nitrate intake may be harmful to livestock. Moreover, the presence of nitrate may indicate pollution of the water supply.

The recommended limit of 500 ppm for dissolved solids is based on considerations of taste. Water containing dissolved solids in excess of this limit is likely to have a "mineral" taste, at least to a person not accustomed to it. As with chloride and sulfate, a considerable number of supplies with dissolved solids in excess of the recommended limits are used without any obvious ill effects. Waters are classified as fresh or saline on the basis of dissolved solids content, as follows (Robinove and others, 1958, p. 3):

| Class | Dissolved solids (ppm) |
|---|---|
| Fresh | Less than 1,000 |
| Slightly saline | 1,000 to 3,000 |
| Moderately saline | 3,000 to 10,000 |
| Very saline | 10,000 to 35,000 |
| Briny | More than 35,000 |

Hardness of water is an important consideration in domestic, municipal and industrial supplies. It is expressed in parts per million as calcium carbonate. Hardness causes increased soap consumption in water for washing and forms deposits in laundered clothes and incrustations in pipes and hot-water tanks. For ordinary domestic purposes, hardness begins to be objectionable at about the level of 100 ppm (5-6 grains per gallon). The U.S. Geological Survey classifies hardness according to the following table:

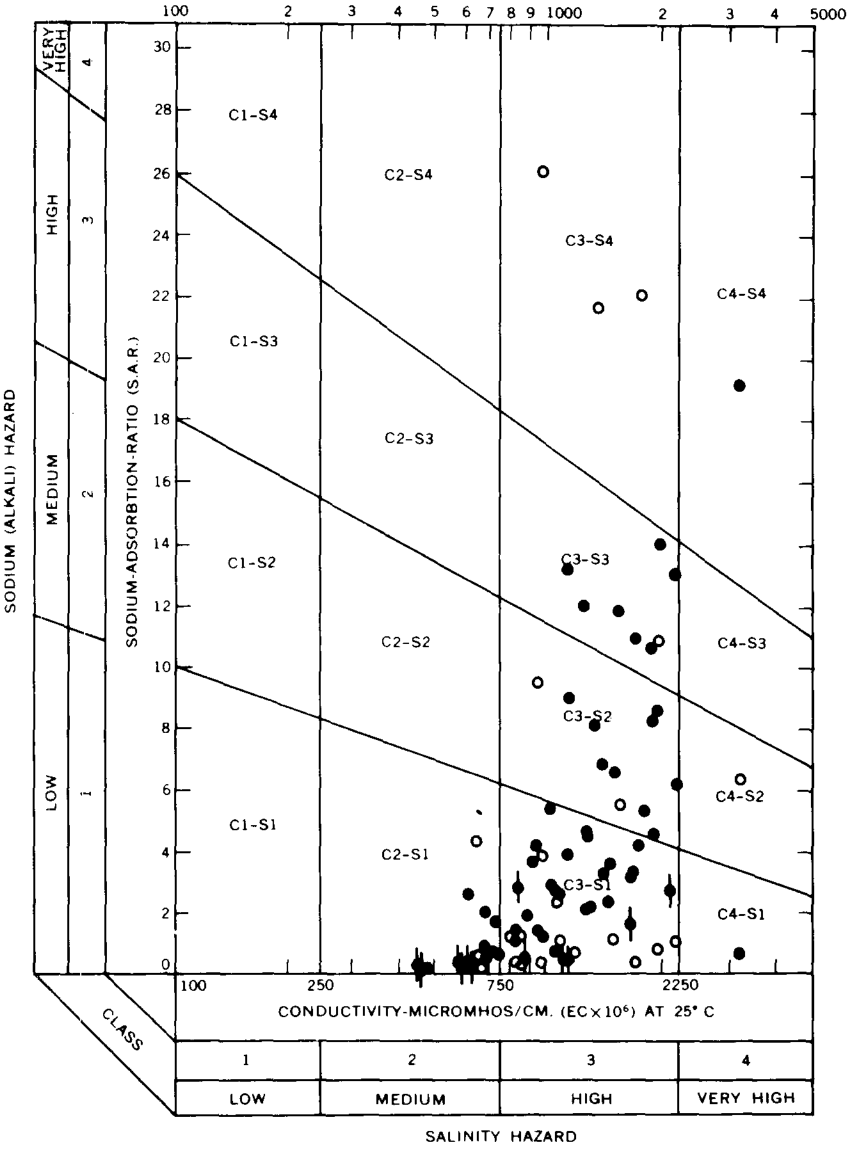
| Hardness range (calcium carbonate in ppm) | Hardness description |
|---|---|
| 0- 60 | Soft |
| 61-120 | Moderately hard |
| 121-180 | Hard |
| More than 180 | Very hard |

The chemical characteristics of water that are most important in determining its quality for irrigation are: (1) Total concentration of soluble salts; (2) relative proportion of sodium to other cations; (3) concentration of boron or other elements that may be toxic; (4) under some conditions, the bicarbonate concentration (U.S. Salinity Laboratory Staff, 1954, p. 69-82).

Waters containing a high concentration of dissolved solids, when used for irrigation, tend to cause the soil to increase in salinity, and this is undesirable for growing crops. Soil type, drainage, and the amount of water used are also factors determining whether use of a given water for irrigation will cause a buildup in soil salinity, and the salt tolerance of the crops to be grown must be considered.

A high concentration of sodium in irrigation water has an unfavorable effect on the soil through the process of base exchange. Sodium in the water is exchanged for calcium and magnesium in the soil. This produces "alkali soil" (U.S. Salinity Laboratory Staff, 1954, p. 5-6), which is difficult to till and unfavorable for the entry and movement of water. The tendency of irrigation water to produce this condition depends not only on the sodium content, but also on the sodium content in relation to the calcium and magnesium content. This may be expressed either as sodium percentage or sodium-adsorption-ratio. Low values are desirable.

Figure 5 shows the diagram used for the classification of irrigation waters.



## EXPLANATION

- ○ **Water from glacial drift, undifferentiated**
- ɸ **Water from outwash or other glaciofluvial deposits (surficial)**
- ● **Water from outwash or other glaciofluvial deposits (buried)**

**Two samples with specific conductance and sodium-adsorption ratio determinations (145-63-15dcc2 and 150-67-21cab1) fell off scale and were not plotted**

FIGURE 5. Diagram showing classification of water samples for irrigation use from the glacial drift.

The classification is based on sodium-adsorption-ratio (SAR) and conductivity. According to the U.S. Salinity Laboratory Staff (1954, p. 79, 81, fig. 25), "Low-salinity water (C1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop***. Medium-salinity water (C2) can be used if a moderate amount of leaching occurs***. High-salinity water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected. Very high-salinity water (C4) is not suitable for irrigation under ordinary conditions.

"Low-sodium water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium***. Medium-sodium water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange capacity, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability. High-sodium (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management***. Very high sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity***."

The concentration of bicarbonate may affect the exchangeable sodium percentage in the soil. This is most likely to happen with waters containing a considerable amount of dissolved solids, large excess of sodium over calcium, and an excess of bicarbonate over calcium. The calcium and magnesium in the water may precipitate as carbonates, with the result that the exchangeable sodium percentage in the soil water would increase.

A measure of the hazard involved in irrigating with waters containing high concentrations of carbonate and bicarbonate is residual sodium carbonate (RSC). This is defined:

$$\mathrm{RSC} = (\mathrm{CO_3}^{+} + \mathrm{HCO_3}^{-}) - (\mathrm{Ca}^{++} + \mathrm{Mg}^{++})$$

in which the concentrations are expressed in milliequivalents per liter. Waters with more than 2.5 meq per liter RSC are not suitable for irrigation purposes. Waters containing 1.25 to 2.5 meq per liter are marginal, and those containing less than 1.25 meq per liter are probably safe.

## QUALITY OF WATER IN EDDY AND FOSTER COUNTIES

In Part II of this report, 120 chemical analyses of water from wells, springs, and lakes are listed (Trapp, 1966, table 4). The dissolved solids content (residue on evaporation at 180°C) of the water samples ranges from 245 ppm (spring, 150-64-31bba) to 7,590 ppm (well 150-66-17adc2, Pierre Shale aquifer).

In addition, Part II also lists specific conductances of water samples from about

350 wells and springs not otherwise analyzed (Trapp, 1966, table 1). Specific conductance, or electrical conductivity at 25°C, is a measure of the ease with which the water conducts electric current. It varies with the amount of solids dissolved in the water; the greater the amount of solids, the higher the specific conductance. However, the relationship between specific conductance and dissolved solids is not a simple one. It depends not only on the concentration of dissolved solids but also on the kind of dissolved solids present. According to Hem (1959, p. 40), in the relationship:

A x specific conductance = dissolved solids (ppm)

the value of the factor A ranges from 0.5 to 1.0, but usually has a value between 0.55 and 0.75, unless the water has an unusual composition.

In figure 6, the values of dissolved solids (residue) in parts per million have been plotted against specific conductances for the same samples. Straight lines representing the relationships:

Dissolved solids = specific conductance
Dissolved solids = 0.65 x specific conductance
Dissolved solids = 0.5 x specific conductance

have also been drawn on the graph. All but three of the points plotted fall within the limits of the upper and lower lines, and there is a definite alignment of points along the line:

Dissolved solids = 0.65 x specific conductance

especially within the limits of conductance values from 500 to 3,000. Therefore, for most waters in this area, specific conductance values can be multiplied by 0.65 to obtain an approximate value for dissolved solids.

The average of the specific conductances given in Part II of this report (Trapp, 1966, table 1) is 2,000. Multiplying by 0.65 gives an average dissolved solids content for all the waters of 1,300 ppm. The average conductance of ground water from the glacial drift is slightly over 1,400, so that the average dissolved solids content of glacial drift waters is about 925 ppm.

Waters from the glacial drift in Eddy and Foster Counties are commonly hard and predominantly of calcium bicarbonate and calcium sulfate type. Waters from surficial outwash tend to be the least mineralized, and water from till the most mineralized, of the drift waters. The Pierre Shale waters are generally more mineralized but softer than drift waters. They are typically sodium chloride bicarbonate type.

The distribution of glacial drift waters from Eddy and Foster Counties, when plotted on a diagram for the classification of irrigation waters, is shown on figure 5. Most of the waters sampled fall into the high salinity class (C3), with some in

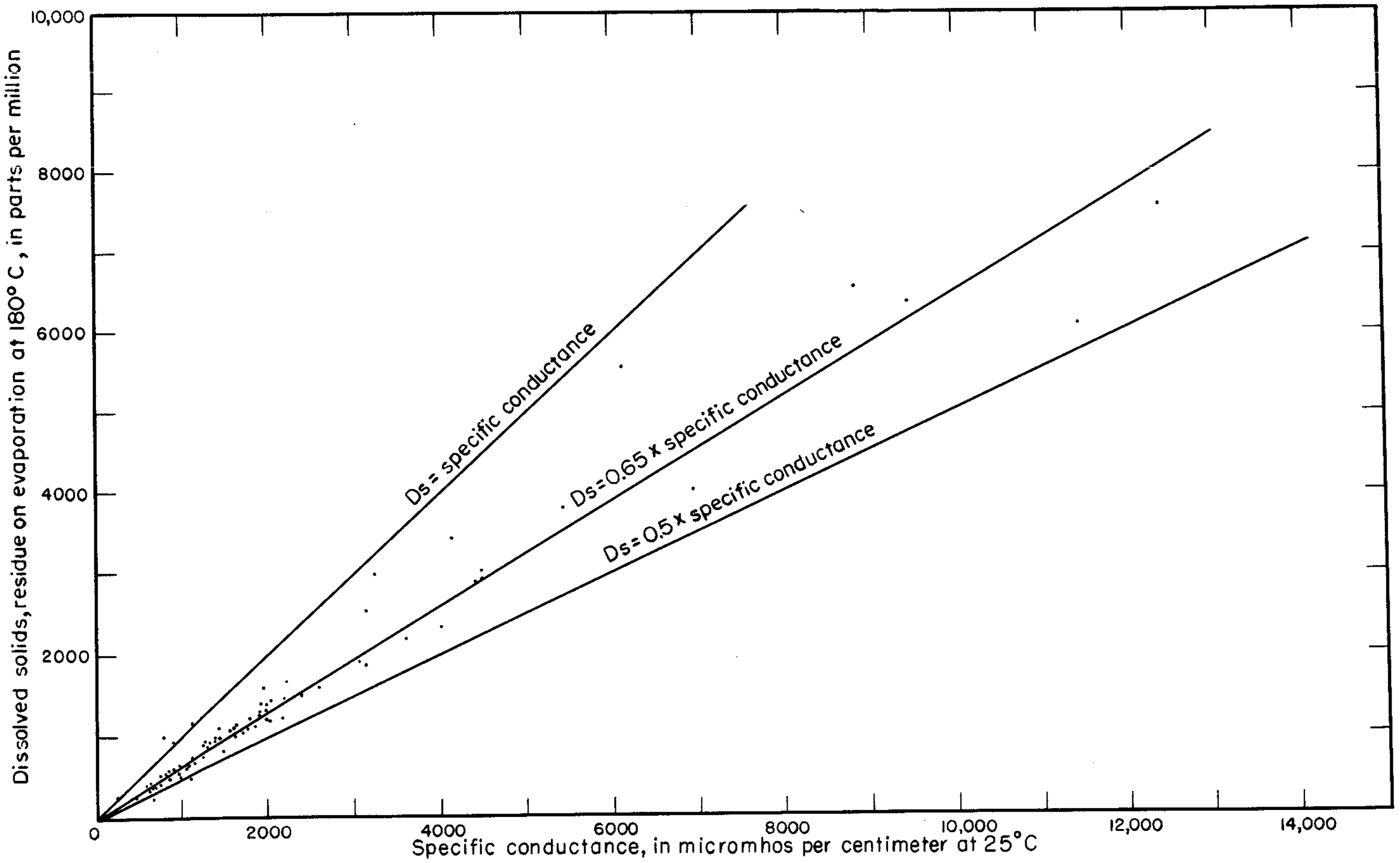


FIGURE 6. Graph showing relation of specific conductance to dissolved solids in water samples.

the medium salinity (C2) and very high salinity (C4) classes. Most of the waters sampled in Eddy and Foster Counties fall in the low sodium (alkali) hazard class (S1), but others range from the medium to the very high sodium hazard classes (S2 to S4).

The chemical quality of waters from individual aquifers will be discussed in the following sections.

# Ground water in the consolidated rocks

## ROCKS BELOW THE DAKOTA SANDSTONE

Little is known about the water-bearing potential of the rocks below the Dakota Sandstone. The Jurassic strata consist of limestone and sandstone. The limestone may contain solution cavities and fractures. The Paleozoic section consists largely of limestones and dolomite, and some sandstone.

Some of the Paleozoic limestone and dolomite strata produce oil in the western part of the State, and the waters associated with the oil are brines. Also, the waters in the Paleozoic rocks in the eastern-most part of the State (around Grand Forks) are very saline. It is usually assumed that water in the Paleozoic in central North Dakota is also very saline. However, there is evidence that at least some of the water in the Palezoic rocks in Eddy and Foster Counties is not highly saline. An exploratory oil dry hole, the Calvert Drilling, Inc., Woodrow Topp No. 1 (147-64-2ac, Foster County), reported a recovery of 1,868 feet of very slightly muddy "fresh" water on a drill-stem test of the Mississippian Lodgepole Limestone from 1,895 to 1,958 feet (North Dakota Geol. Survey, 1954-63, Circ. 266). In the Calvert Drilling, Inc., George S. Garland No. 1 (147-67-28aa, Foster County) the reported recovery from a drill-stem test of the Mississippian from 2,173 to 2,215 feet was 120 feet of slightly muddy "fresh" water, and 1,860 feet of "fresh" water (North Dakota Geol. Survey, 1954-63, Circ 265). The Ray Holbert, Sarah Dunbar No. 1 (146-63-13bb, Foster County) reported a drill-stem test recovery of 2,160 feet of "fresh" water from the Ordovician Red River Formation from 2,372 feet to 2,446 feet (North Dakota Geol. Survey, 1954-63, Circ. 89). Unfortunately, no chemical analyses are available for this water, and its designation as fresh may be only relative to the brines commonly found in oil-bearing formations. Paleozoic aquifers may be hydrologically interconnected with the Dakota Sandstone in parts of the area, and may contain similar waters.

The depth to the top of the Paleozoic rocks ranges from 1,700 feet in the eastern parts of Eddy and Foster Counties to 2,300 feet in the western part. Because of their great depth and the questionable quality and quantity of water obtainable from them, it is unlikely that they will be important aquifers in the near future. However, if a well is drilled to the Dakota, and an inadequate supply found there, deepening the well to the Paleozoic might be considered. In the western part of the area, this would mean about 150 feet of additional drilling; farther east, the Paleozoic immediately underlies the Dakota Sandstone.

## DAKOTA SANDSTONE

The Dakota Sandstone comprises the most extensive and best known artesian aquifer system in the United States. The sandstone underlies most of the Dakotas, and its facies equivalents extend north into Canada, south into Texas, and westward into the Rocky Mountain area. Its outcrops at the base of the Black Hills and Front Range are at a high elevation relative to the central and eastern Dakotas, and the outcrop areas serve locally as areas of recharge. The Dakota probably receives recharge also from the Mississippian Madison Limestone (Swenson, 1968), which crops out around the Black Hills and Front Range at even higher elevations. A possible source of recharge closer to Eddy and Foster Counties is downward leakage through overlying rock in the Missouri Coteau. The greater thickness of saturated material above the Dakota due to the higher surface elevation may produce sufficient head for recharge. In a broad band from the edge of the Missouri Coteau to the eastern limits of the Dakota Sandstone, water was originally under sufficient pressure in the Dakota aquifer to rise a considerable height above the surface. Most of Eddy and Foster Counties is in the artesian area.

Artesian water in the Dakota Sandstone was discovered in 1886 in South Dakota. Exploitation was slow at first, but as drilling methods improved to lower the cost of deep wells, a great many flowing wells were drilled in the early part of the century. Many of these flowed under very high pressures, and people were inclined to think that the supply was inexhaustible. Wells were allowed to flow uncontrolled. The casings of many wells were inadequately sealed against the high pressures, or later corroded, producing underground leakage of unknown magnitude. As water was removed from storage more rapidly than the permeability of the aquifer and the distance from recharge areas permitted replenishment, the artesian head declined rapidly, as did well-head pressures and rates of flow, and many wells ceased to flow. In the 1920's and 1930's, the State of North Dakota took steps to preserve the artesian head by preventing waste (Hard, 1929; Wenzel and Sand, 1942). Kelly (1966, p. 21) reports that the decline in head since 1938 in Barnes County seems to be small.

There has been little exploitation of Dakota Sandstone water in Eddy and Foster Counties. The city of Carrington had a 1,947 foot well (146-66-19ac), which flowed 10 gpm (gallons per minute) of hard, salty water. The well tended to clog with sand; because of this, and the poor quality of the water, it was abandoned around 1910 (Simpson, 1929, p. 131-32). In recent years, three Dakota wells have been drilled in southwestern Foster County, the water being used for stock watering and limited domestic purposes. Two of these wells flow, but at low well-head pressures, and the water level is 17 feet below land surface in the third.

The Dakota Sandstone aquifers consist of lenses of very fine to fine sandstone with shale interbeds. At least until more water wells are drilled into the Dakota, the best source of information on sand thicknesses and porosity are the logs of exploratory oil tests. Hansen (1955, figs. 6-10), using oil-test logs, showed the sandstone thickness increasing to the southeast in Eddy and Foster Counties. The average total sandstone thickness is about 150 feet. Wenzel and Sand (1942, p. 41) gave laboratory determinations of porosity and permeability from the Glenfield Oil Co. well (146-62-18d, Foster County). The weighted average porosity for the 90 feet analyzed is 42.6 percent, and the average coefficient of permeability is 225. Multiplying this coefficient by the average thickness of 150 feet gives a transmissibility of approximately 34,000 gpd per foot (gallons per day per foot). This may be too high since the total thickness from Hansen's maps includes the upper "Newcastle" sand, which may have a lower permeability. Using only the 90 feet analyzed in the Glenfield oil well, the transmissibility would be about 20,000.

In adjoining parts of the Dakota artesian basin, two or more "flows" of water were encountered, with a difference in head and water quality for different sand lenses. As many as seven flows have been reported. Wenzel and Sand (1942, p. 15), reported that the water from the "first flow" is generally soft but somewhat salty; water from the "second flow" is much harder but lower in chloride. The water from deeper zones was reportedly very highly mineralized. This indicates that the sandstone lenses within the Dakota are imperfectly interconnected, and to some extent, function as separate aquifers. The old Carrington city well penetrated two water-bearing beds, the first at 1,847 feet, which yielded soft water that stood 100 feet below the surface, and the second at 1,927 feet, which yielded hard water that flowed at land surface (Simpson, 1929, p. 131-132). These are the only data on more than one "flow" in the two counties.

Chemical analyses of water from the Dakota wells now in use are given in table 1. The water samples from these wells are of the same type-dissolved solids of about 3,000 ppm, high in sodium, sulfate, bicarbonate, and chloride, and soft. By U.S. Public Health Service drinking water standards, the water contains excessive concentrations of dissolved solids, sulfate, chloride, fluoride, and iron. It is unsuitable for use in irrigation because of the high dissolved solids, sodium, and boron concentrations. It has been used for livestock without apparent ill effects, and is satisfactory for bathing and laundry if the iron is removed. Its

# TABLE 1. Chemical analyses of water from consolidated rock aquifers.

[Analytical results in parts per million except as indicated]

| Location | Depth of well (feet) |  | Date of collection | Temperature (°F) | Silica (SiO$_2$) | Total iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) | Bicarbonate (HCO$_3$) | Carbonate (CO$_3$) | Sulfate (SO$_4$) | Chloride (Cl) | Fluoride (F) | Nitrate (NO$_3$) | Boron (B) | Dissolved solids |  | Hardness as CaCO$_3$ |  | Percent sodium | Sodium-adsorption-ratio | Specific conductance (micromhos at 25°C) | pH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Sum | Residue on evaporation at 180°C | Calcium, magnesium | Noncarbonate |  |  |  |  |
| DAKOTA SANDSTONE |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Foster County** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 145-65-31aba | 1,960 |  | 10- 8-64 | 50 | 7.0 | 1.0 | 4.0 | 4.9 | 1,020 | 16 | 494 | 0 | 1,250 | 402 | 2.8 | 4.6 | 3.5 | 2,950 | 2,940 | 30 | 0 | 98 | 81 | 4,420 | 8.1 |
| 145-66-1dcc | 1,849 |  | 10- 8-64 | 54 | 6.8 | 1.1 | 8.0 | 6.1 | 1,000 | 40 | 553 | 0 | 1,160 | 431 | 7.0 | 5.0 | 4.9 | 2,930 | 2,960 | 45 | 0 | 96 | 65 | 4,490 | 8.1 |
| 145-66-13aaa | 1,900 |  | 10- 1-64 | 48 | 10 | 1.0 | 12 | 5.8 | 1,060 | 11 | 554 | 0 | 1,190 | 475 | 3.1 | 5.5 | 4.2 | 3,040 | 3,080 | 55 | 0 | 97 | 62 | 4,480 | 7.9 |
| PIERRE SHALE |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Foster County** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 145-63-32bba | 186 |  | 10-14-64 | 49 | 21 | .26 | 11 | 6.8 | 848 | 15 | 925 | 0 | 37 | 794 | .6 | 11 | 4.4 | 2,200 | 2,230 | 55 | 0 | 96 | 50 | 3,610 | 8.2 |
| 146-65-24ccb1 | 180 |  | 10-30-64 | 45 | 19 | .97 | 37 | 18 | 418 | 12 | 759 | 0 | 266 | 137 | .4 | 1.5 | .50 | 1,280 | 1,310 | 165 | 0 | 83 | 14 | 1,990 | 8.0 |
| 146-67-19bab | 150 |  | 9- 3-64 | .. | 15 | 12 | 12 | 7.5 | 920 | 18 | 861 | 0 | 110 | 904 | .3 | 1.0 | 4.6 | 2,420 | 2,360 | 60 | 0 | 96 | 52 | 4,010 | 8.1 |
| 147-62-5dbd1 | 95 |  | 9-30-64 | .. | 25 | .94 | 12 | 3.2 | 464 | 10 | 732 | 19 | 115 | 222 | .5 | 2.0 | 4.2 | 1,230 | 1,200 | 43 | 0 | 95 | 31 | 2,020 | 8.4 |
| 147-62-5dbd2 | 110 |  | 9-30-64 | 48 | 25 | .90 | 14 | 5.4 | 724 | 12 | 644 | 0 | 99 | 726 | .6 | 1.0 | 4.2 | 1,920 | 1,940 | 58 | 0 | 96 | 41 | 3,070 | 7.8 |
| 147-65-8baa2 | 199 |  | 10-16-64 | 46 | 21 | .68 | 18 | 11 | 582 | 13 | 468 | 0 | 70 | 620 | .5 | 9.3 | 3.7 | 1,620 | 1,650 | 85 | 0 | 93 | 27 | 2,570 | 8.1 |
| **Eddy County** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| 148-66-24bcc2 | 170 |  | 1-20-65 | 46 | 24 | .18 | 18 | 6.8 | 302 | 9.0 | 573 | 0 | 205 | 44 | .4 | .0 | 2.6 | 891 | 890 | 74 | 0 | 88 | 15 | 1,320 | 8.1 |
| 150-63-14bac2 | 207 |  | 3-10-65 | 48 | 22 | 1.0 | 30 | 46 | 1,620 | 23 | 754 | 0 | 212 | 2,120 | .2 | .0 | 5.3 | 4,450 | 4,080 | 266 | 0 | 92 | 43 | 6,950 | 8.0 |
| 150-64-7bab | 90 |  | 4-15-65 | .. | 26 | .11 | 8.8 | 2.2 | 566 | 14 | 581 | 7 | 105 | 483 | 2.0 | 4.0 | 4.2 | 1,510 | 1,510 | 31 | 0 | 96 | 44 | 2,380 | 8.3 |
| 150-66-17adc2 | 114 |  | 10-15-64 | 45 | 17 | 3.8 | 99 | 62 | 2,720 | 43 | 556 | 0 | 272 | 4,070 | .3 | 1.0 | 5.2 | 7,550 | 7,590 | 502 | 46 | 91 | 53 | 12,400 | 8.0 |

temperature, which exceeds 50°F in flowing wells in nearby areas, makes it more desirable for stock water in winter than in summer, and makes it a possible source of heating by means of heat pumps. The practicality of its use for heating largely depends on the cost of drilling the well and disposing of the used water without waste, or contamination of other water supplies.

The Dakota probably can yield substantial quantities of water anywhere in Eddy and Foster Counties, but because of its depth, mineralized water, and the availability of water in shallower aquifers, it is likely to supply only a small part of the water needs of the area for the foreseeable future. A well penetrating the first water-bearing sand in the Dakota might be less than 1,400 feet deep if drilled in the eastern part of the area at a low surface elevation, or more than 2,000 feet deep if drilled on the edge of the Missouri Coteau in southwestern Foster County.

The piezometric surface in the existing Dakota wells in southwestern Foster County was about 1,568 feet above sea level in 1963. Wells drilled at surface elevations lower than 1,568 would flow, while those at higher elevations would not. The piezometric surface is believed to slope gently eastward so that wells drilled east of the existing wells would have to be at progressively lower surface elevations in order to flow. However, it is possible that there are Dakota Sandstone lenses that are poorly connected with the depleted parts of the formation, and retain more of their original pressure.

## PIERRE SHALE

The Pierre Shale supplies only small quantities of water to wells in Eddy and Foster Counties, but it is important locally where no better source of water is available. Earlier reports state that water in the Pierre comes from sandy beds in the upper part of the formation (Wenzel and Sand, 1942, p. 14), but test holes drilled in Eddy and Foster Counties do not support this view. Rather, the water probably comes from fractures and bedding planes in the upper part of the Pierre.

Dry holes and wells with very low yields are occasionally obtained in the Pierre. There are two principal explanations: either the well was drilled in an area where the Pierre does not have open fractures, or it may have been drilled in an area where the Pierre is fractured, but by chance failed to penetrate a fracture of sufficient size. The former explanation may apply where the Pierre is a soft clay or silt rather than a fissile, brittle shale. Under these circumstances, all the nearby shale wells are likely to be poor producers. The second explanation probably applies where a dry hole is drilled near productive wells.

Most of the water in the Pierre enters by seeping down through the overlying glacial drift. This recharge is probably greatest where permeable drift aquifers directly overlie the Pierre, or where the drift is thin.

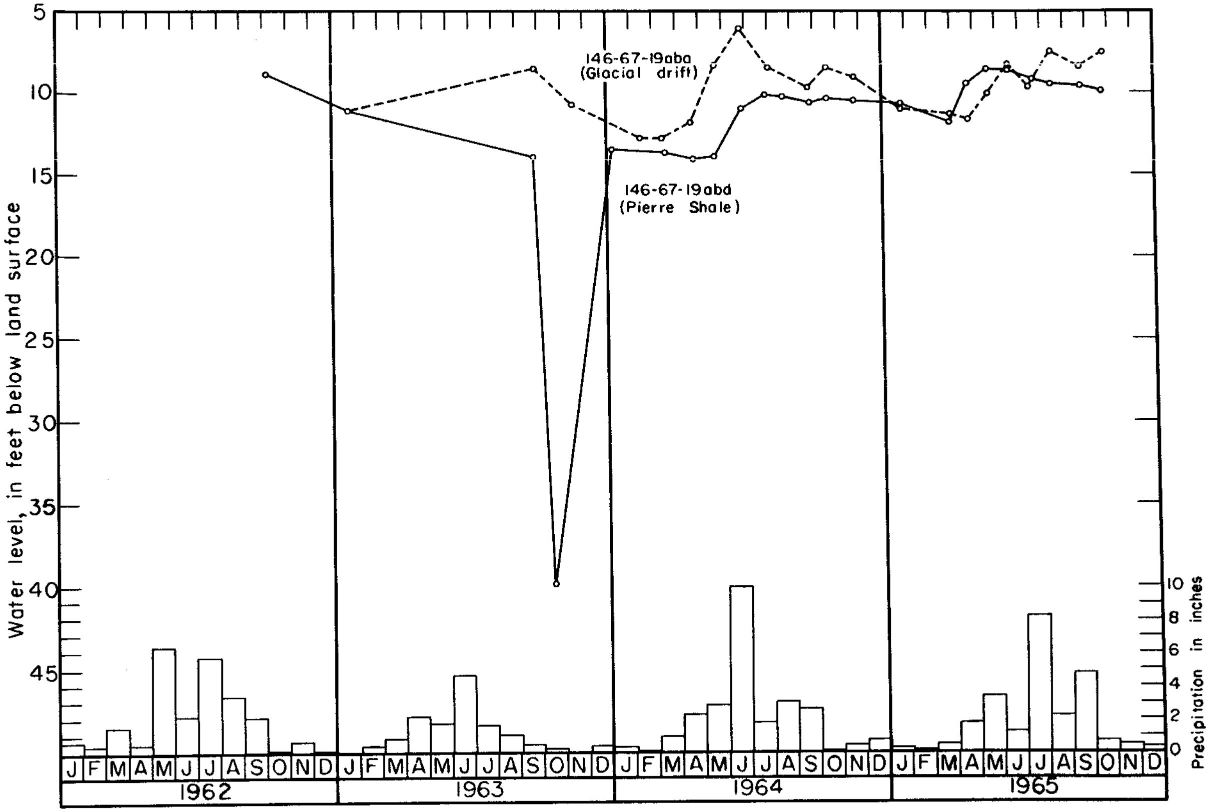


FIGURE 7. Hydrographs of a Pierre Shale well and a shallow glacial drift well.

Periodic water-level measurements were made in a Pierre well in western Foster County (146-67-19abd) and in a shallow glacial drift well nearby (146-67-19aba). Figure 7 shows the water-level fluctuations in the two wells from late 1962 to the fall of 1965. The water level in the drift well responds more sharply to changes in precipitation. Water-level changes in the Pierre well lagged the changes in the drift well through 1963 and 1964, which is to be expected if its recharge comes from the drift. In the spring of 1965, on the other hand, the level in the Pierre well rose first. This may be because the shale well is at about 10 feet lower surface elevation and closer to Pipestem Creek and its level may have been influenced by high water in the creek.

Chemical analyses of water from Pierre wells are listed in table 1, and are shown in graphic form, in terms of equivalents per million, in figure 8. The equivalents per million of a given ion equal its concentration in parts per million divided by its combining weight. Thus, the composition of a solution is expressed in terms of the proportions in which the ions combine, as well as their concentration in terms of weight. Figure 8 shows that the least mineralized Pierre waters are the sodium bicarbonate type, and that the more mineralized waters are the sodium chloride type.

The most mineralized Pierre waters are several times as hard as the least mineralized, but there does not seem to be a direct relationship between dissolved solids concentrations and hardness. As mentioned earlier in this report (p. 29) the cation-exchange reaction

$$2\ \mathrm{Na\ X} + \mathrm{Ca}^{++} \rightleftharpoons \mathrm{Ca\ X}_2 + 2\mathrm{Na}^{+}$$

tends to shift to the left in the presence of a high concentration of sodium ions so that there would be more calcium ions in solution (more hardness) with the moderately saline water.

There is a wide variation in the quality of water from the Pierre. It is usually highly mineralized and salty, yet the water from well 148-66-24bcc2 has only 44 ppm chloride and 205 ppm sulfate, in comparison with the U.S. Public Health Service recommended limits of 250 ppm of chloride or sulfates. This water exceeds the recommended limits for drinking water only in dissolved solids (891 ppm as opposed to 500 ppm). The depth of the well and the softness of its water tend to confirm that it is a Pierre well, as reported. At this locality, most of the connate water seems to have been flushed out of the Pierre, which still retains its cation-exchange capacity, so that the water is a soft, sodium bicarbonate type, rather than a hard, calcium bicarbonate type, as in the glacial drift. Wells 147-62-5dbd1 and 147-62-5dbd2 are on adjoining town lots in McHenry. Both yield relatively soft waters, but, whereas the water from the first had only 222 ppm chloride and did not taste salty to the author, water from the second had 726 ppm chloride and was definitely salty. The second well, which is 15 feet deeper, may be getting water from a different set of fractures in the Pierre. Residues of connate water are more

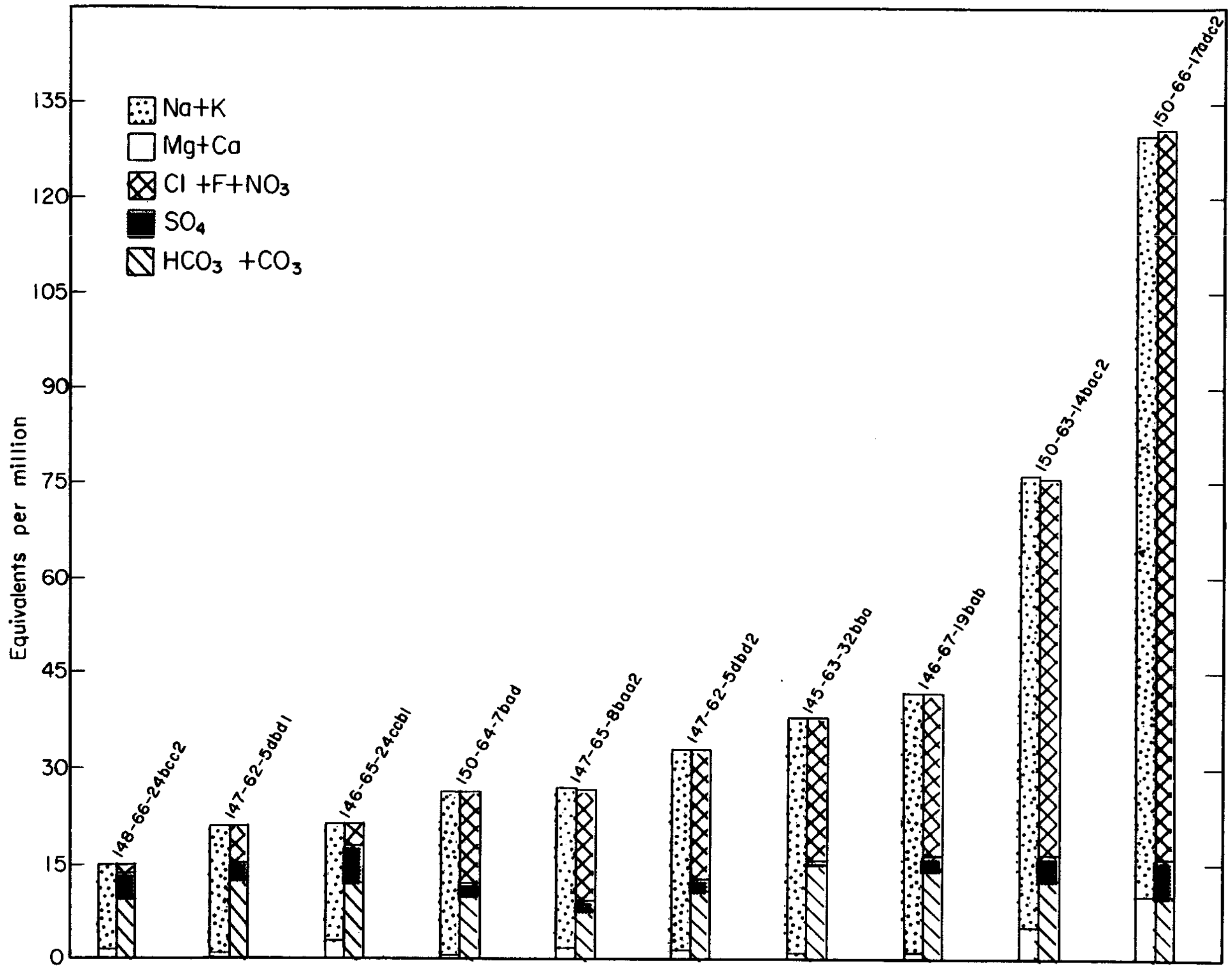


FIGURE 8. Graph showing equivalents per million of selected water samples from wells in the Pierre Shale.

likely to be found deeper in the Pierre than near its upper surface.

Well 150-66-17adc2 yielded highly mineralized water from the Pierre--4,070 ppm chloride and 7,550 ppm dissolved solids. It was also a very hard water with 502 ppm hardness as calcium carbonate. In the same township in sections 10, 17, 21, and 32, water from other Pierre wells had high specific conductance values, suggesting that the water from the Pierre through most of this township is similar.

The water from the Pierre is commonly slightly saline and high in chloride, but it does not appear to be extremely corrosive. There are a number of wells in the area that are 40 years old or more with the original steel casing. The owner of a 329 foot Pierre well in southwestern Eddy County (148-67-5ddd) stated that the cylinder pump and drop pipe were removed from the well after 30 years and were not noticeably corroded. The well produced salty water and had not been used much for several years before the pump was pulled.

Inflammable gas, probably methane, has been reported from water wells constructed in the Pierre in northwestern Eddy County (150-65-12bdc2, 150-66-10ada2, 150-67-12ddc2). In some cases, the gas exploded, damaging the well fittings. There has been no report of gas occurring in useful amounts in the Pierre Shale in this part of the State. The nearest commercial gas production from Pierre equivalents is on the Cedar Creek anticline about 275 miles to the west.

Although Pierre wells usually have low yields of water too highly mineralized to be palatable, they supply an important part of the stock water in areas where yields from glacial drift wells are low. They also supply some domestic needs, chiefly as sources of soft water for laundry and washing, and, in a few localities, the Pierre water is less mineralized than much of the glacial drift waters.

Several assumptions may be made concerning the occurrence of water in the Pierre:

(1) The water-bearing fractures are largely concentrated in the upper part of the shale, and resulted from preglacial weathering and glacial erosion acting on the Pierre surface.

(2) Salinity in water from the Pierre, except for that derived by the percolation of recharge through the overlying drift, probably originates in part from incompletely flushed connate water. This is more likely to be encountered deep in the Pierre than near its upper surface.

(3) Therefore, the deeper a well penetrates into the shale, the less likely it is to find additional water per foot drilled, and such water is increasingly likely to be saline.

# Ground water in the glacial drift

Most of the wells in Eddy and Foster Counties obtain water from the glacial drift. The drift is made up of particles ranging in size from colloidal (clay) to large boulders, with a wide variation in degree of sorting. Within the drift, various bodies of material (sand, gravel, till, etc.) may be mapped as separate aquifers, although they are interconnected hydrologically. However, before studying the individual glacial drift aquifers, the hydrology of the drift as a whole may be considered. Some of the hydrologic characteristics include the elevation and configuration of the water table and the saturated thickness, lithology, transmissibility, and potential yield of the drift.

## CONFIGURATION OF THE WATER TABLE

Plate 1 (in pocket) shows the elevation of the water table above sea level as of 1964. The water table in most of the area is in the glacial drift, although there are places where it is below the top of the Pierre Shale. Its elevation was derived from observation wells measured on or about October 15, 1964, plus water levels measured at other times and adjusted to the same date by comparison with observation well records. Also, the elevations of the land surface and of surface bodies of water were used as control. Water levels in wells believed to be constructed in leaky artesian aquifers were assumed to approximate the water table, provided that the wells were not affected by recent pumping. In a few localities where artesian heads in the drift are a few feet above land surface (as in part of Rocky Run valley in southwestern Eddy County and part of Bald Hill Creek valley in northeastern Foster County), the water table was contoured arbitrarily at approximately land surface elevation.

The use of the elevation of the surfaces of ponds and sloughs as control points for the water-table map may have introduced some error. The elevations of the water surfaces shown on the topographic maps probably do not coincide with the elevations of October 15, 1964, because the maps were prepared earlier and the levels fluctuate. However, considering the scale of the map and its 20-foot contour interval, the error possible from this source seems relatively small. A more serious error may be the assumption that the ponds and sloughs are continuous with the water table. Some of them may be "perched" above the regional water table -- that is, the bottom material may be of such low permeability that water cannot seep through fast enough to maintain contact with the regional water table. Given time, contact should be made, but most of the ponds go dry at times and freeze solid in the winter, interrupting downward seepage. However, the majority of water levels in wells measured for this project were less than 20 feet below land surface, and because the water table tends to be shallower under depressions, probably the water levels in most of the ponds in Eddy and Foster Counties are continuous with the water table. Thus, in the absence of contrary evidence, the author has assumed continuity.

The water-table map reflects topography, but the water table has less relief than the land surface. The highest point of the water table in the area is near the highest topographic point, or more than 1,900 feet above sea level in southwestern Foster County. The lowest point is below 1,380 feet where the Sheyenne River leaves eastern Eddy County. However, ground water does not flow simply from the highest point in the area to the lowest; most of it is intercepted by surface drainage and by aquifers in buried channels. In Eddy and Foster Counties, the James and Sheyenne Rivers and their tributaries are effluent or "gaining" streams; that is, ground water helps to sustain their flow. The water table on each side is higher than the level of the streams, so that ground water moves toward the streams. This is verified by the presence of numerous springs in the bluffs above both rivers and short tributaries behind the bluffs. Probably there are also springs in the beds of the rivers.

The courses of buried channels do not show up well on the water-table map except where they are expressed by topographic lows. One of these would be the valley occupied by Lake George and Dry Lake in southern Foster County near Bordulac. Potentially good aquifers may be expressed by the areas of low relief shown on the water-table map. This may be explained by considering Darcy's Law in the form:

$$Qd = TIL$$

in which Qd is the discharge, in gallons per day

T is the coefficient of transmissibility, in gallons per day per foot

I is the hydraulic gradient, in feet per foot

L is the width, in feet, of the cross section through which the discharge occurs.

If this formula is applied to a system consisting of material that varies laterally in transmissibility, with a fixed discharge area and a constant rate of discharge, it could be expressed as:

$$I = \frac{K}{T}$$

where K is a constant.

In other words, the hydraulic gradient is inversely proportional to transmissibility. Applying this concept to plate 1, areas underlain by good aquifers (high transmissibility) would have low hydraulic gradients. However, low relief on the water-table map locally may result from low topographic relief and lack of integrated surface drainage.

## THICKNESS OF SATURATED DRIFT

The thickness of the drift below the water table is shown on plate 2 (in pocket). The control for this map was derived by subtracting the depth to the water table (as of October 15, 1964) from the depth to bedrock. The general configuration of the lines is somewhat similar to the contour pattern of bedrock topography (Bluemle, 1965, pl. 2). However, the bedrock topography map shows the elevation of the bedrock surface above a plane (mean sea level), while the saturated drift thickness map shows the depth to bedrock below a sloping, undulating surface (the water table). Low areas on the bedrock topography map generally correspond to areas of thick saturated drift, except where the bedrock lows are also topographic lows. For example, the bedrock low occupied by the Sheyenne River in T. 150 N., Rs. 64 and 65 W., corresponds to an area of thin drift rather than to thick drift as might be expected.

One of the more conspicuous features in the area is the narrow band of thick drift extending southeast from T. 149 N., R. 67 W., to T. 146 N., R. 62 W. This represents glacial drift filling a bedrock channel that extends at least from northern Wells County to western Griggs County, where apparently it joins the Spiritwood channel near Sutton. The channel is discussed more fully under the heading "New Rockford aquifer."

Test drilling in the Sheyenne River valley at Sheyenne disclosed a steep, narrow, outwash-filled trench underlying or slightly north of the present stream in secs. 4 and 5, T. 150 N., R. 66 W. (Froelich, 1964, figs. 5a, 5b). Bedrock elevation in the center of this trench is at or below 1,345 feet above sea level, or at least 70 feet below the present level of the stream. Elsewhere in the Sheyenne valley in Eddy County, the available logs indicate only a thin cover of either outwash or alluvium on the Sheyenne valley floor. It is likely that the trench found at Sheyenne is part of the valley of an older outwash channel, locally followed by the present Sheyenne River. The course of the trench at Sheyenne is roughly east-west, but elsewhere its course is not known. It evidently diverges from the Sheyenne valley between Sheyenne and the site of the proposed Warwick Siphon crossing in sec. 18, T. 150 N., R. 64 W., where test drilling for the Garrison Diversion Units proposed Warwick Siphon crossing disclosed no deep trench.

The greatest drift thickness penetrated was 423 feet in test hole 150-65-5adc in northern Eddy County; about 360 feet of this drift is saturated. This was about 1 mile west of a Pierre Shale outcrop in sec. 4. Bluemle (1965, p. 19-20) interpreted the drift-filled bedrock low as trending to the southwest. This interpretation is uncertain because of lack of control; the low might take a more southerly course and join the New Rockford channel east of New Rockford instead.

Along the eastern border of Eddy County, the drift thickens, indicating a north-south trending bedrock low which may be the Spiritwood channel (Huxel, 1961,

p. 179-181; Kelly, 1966, p. 26). A northwest-trending area of thick saturated drift area south of Hamar in T. 150 N., R. 62 W., may represent the main channel or its tributary. These bedrock channels and associated aquifers are discussed more fully under Spiritwood (?) aquifer and Hamar aquifer.

At the north end of South Washington Lake, test hole 149-63-11ccc penetrated 172 feet of saturated drift. The area of thick drift indicated by this test hole is interpreted to trend southeast to 148-62-18acd where the log of a private well shows 171 feet of saturated drift thickness. This relatively thick drift may occupy a channel tributary to the Spiritwood channel, but the relationship is obscure. The scanty subsurface data do not indicate any substantial thickness of buried outwash.

In central Eddy County, a large area in T. 148 N., Rs. 64-65 W., T. 149 N., Rs. 64-66 W., and T. 150 N., R. 65 W., has a fairly uniform saturated drift thickness of about 50 feet. The drift in this area has a greater water-bearing potential than its saturated thickness would suggest since its upper part is outwash sand and gravel (Bluemle, 1965, pl. 1). The potential yields of wells in this area are determined more by the saturated thickness of outwash rather than by the total saturated drift thickness. This surficial outwash is discussed further in the Northwest Eddy and Central Eddy aquifers.

It may be seen in plate 2 that the valley of the James River in southern Foster County occupies an area of comparatively thin drift; however, greater thicknesses of drift are on either side of the valley. Three test holes in the areas of thicker drift penetrated mostly till, but it is possible that more intensive exploration might reveal sand or gravel aquifers.

In the area west, northwest, and south of Carrington in Tps. 145, 146, and 147 N., R. 67 W., the saturated drift is less than 100 feet thick. The valley bottom of Pipestem Creek, at least above the confluence of Little Pipestem Creek, has a saturated drift cover as thin as 11 feet, as shown by records of private wells. However, test hole 145-67-16ccb, drilled in the valley of Little Pipestem Creek, penetrated 99 feet of saturated drift, which included 39 feet of sand near the surface.

## TRANSMISSIBILITY OF THE DRIFT

While a knowledge of the position of the water table and the thickness of the drift is useful in studying the movement of ground water and for identifying favorable areas for aquifer exploration; it is not sufficient to predict potential yields of water from the drift. The lithology of the drift, which determines its porosity and permeability, is of at least equal importance. Although a thick channel fill might appear favorable as a source of ground water, the potential yield would be disappointingly low if it should consist of till or clay. On the other hand, wells constructed in a comparatively thin saturated drift cover composed of sand or gravel might produce large quantities of water.

Plate 3 (in pocket) expresses the saturated thickness of the drift and its estimated permeability in terms of transmissibility. Generally, more accurate values of transmissibility may be determined by means of aquifer tests, but it is not feasible to cover a large area with them. Transmissibility equals field permeability multiplied by saturated thickness. The permeability may be estimated from lithology by using permeability values determined for similar material. The coefficient of permeability is calculated in the laboratory for water passing through the material at 60°F. If the temperature of the water in the aquifer is not 60°F, the laboratory values of permeability must be corrected to field permeability because water becomes more viscous with decreasing temperature, and therefore will flow at a decreased rate through a given permeable medium at a given gradient. In Eddy and Foster Counties, temperatures of waters in the glacial drift generally range from 40° to 45°F. Todd(1959, p. 50-51, fig. 33) shows that the ratio of laboratory to field permeability for the field temperature of 42° is about 1.33. Therefore, laboratory values of permeability, or estimated permeabilities based on laboratory determinations of similar material, were divided by 1.33 to obtain the estimated field permeabilities for this area.

Keech (1964, p. 16-17) lists ranges of laboratory coefficients of permeabilities determined for outwash and alluvium in the Platte River valley in Nebraska.

These are:

| Material | Gallons per day per square foot | Material | Gallons per day per square foot |
|---|---|---|---|
| Clay and silt | 0-100 | Sand, coarse | 800-900 |
| Sand, very fine, silty | 100-300 | Sand, very coarse | 900-1,000 |
| Sand, fine to medium | 300-400 | Sand and gravel | 1,000-2,000 |
| Sand, medium | 400-600 | Gravel | 2,000-5,000 |
| Sand, medium to coarse | 600-700 | | |

Ackroyd (1967) used a similar set of permeability values, based on Keech, in mapping potential yields in the Little Muddy aquifer in Williams County, N. Dak. These are:

| Material | Gallons per day per square foot | Material | Gallons per day per square foot |
|---|---|---|---|
| Till or clay | 1 | Sand, coarse | 900 |
| Till or clay, silty | 50 | Lignite | 900 |
| Till or clay, sandy | 100 | Sand and gravel | 1,500 |
| | | Gravel | 3,000 |
| Sand, fine | 200 | Gravel, very coarse | 5,000 |
| Sand, medium | 500 | | |

In this report, Ackroyd's values of standard coefficients of permeability were assigned to materials in logged holes, with the addition of values of 100 gpd per square foot for silt and 100 for gravelly till. Some of the values assigned were adjusted upward or downward within the ranges indicated by Keech where the description of the lithologic unit in the log was qualified by such adjectives as "very clean, well-sorted," or "very silty, dirty."

The coefficient of transmissibility for each logged hole was estimated by multiplying the saturated thickness of each lithologic unit by its assigned permeability and adding the results, then dividing the total by 1.33 to correct for temperature.

Three aquifer tests (described in more detail later in this report) were made during the course of the project. The average transmissibility values derived by various aquifer test analysis methods are listed below for the Carrington, Northwest Eddy, and New Rockford tests. These may be compared with transmissibilities estimated from lithology by the above method:

| Aquifer test | T (estimated gpd per foot) | T (aquifer test, gpd per foot) |
|---|---|---|
| Carrington (147-66-31) | 110,000 | 120,000 |
| New Rockford (148-66-6) | 130,000 | 260,000 |
| Northwest Eddy (150-65-22) | 30,000+ | 67,000 |

Transmissibilities estimated by the above method may differ from transmissibilities as determined from aquifer tests for several reasons:

1. Inadequate control--in many parts of the area, test holes are widely separated.
2. The section penetrated by each hole is assumed to be representative of the surrounding area, although in fact glacial deposits are highly variable.
3. The permeabilities assigned to lithologies may, in places, be inappropriate because they do not take into account factors other than average grain size.
4. The sample and mechanical logging methods used on the test holes are not ideally suited for quantitative determinations of permeability.
5. The test holes were logged by different people, so that lithologic descriptions used on one hole may not be exactly the same as those used on another.
6. Calculated coefficients of transmissibility from aquifer tests depend on the method of analysis used. Each method involves assumptions; the assumptions are only approximately true.
7. Transmissibilities derived from lithology apply only to the site of the logged hole; aquifer test transmissibilities apply to all of the aquifer affected by the pumped well during the test.

Despite the limitations involved in estimating transmissibility from lithology, it seems to be the best means of presenting the data collected to show the capacity of the glacial drift in various parts of the two-county area to transmit ground water.

Transmissibilities also were estimated by the above method for the sections penetrated in holes that did not reach bedrock, but these are used as minimum values. In the absence of logged holes, the performance of wells was used as an indication of transmissibility. Listed in the well inventory in Part II (Trapp, 1966, table 1), are a few wells with reported drawdowns for specified pumping rates. These can be used to approximate transmissibility, but the accuracy of the results depends on how long the well was pumped, whether it was fully penetrating, and on the efficiency of the well. In areas where drift wells for domestic and stock use were reported to pump dry and one or more wells had reached the Pierre Shale, the transmissibility of the drift was assumed to be less than 1,000 gpd per foot. Over most of the area, where no other data were available, the transmissibility was assumed to be 1,000-10,000 gpd per foot.

## POTENTIAL YIELD OF THE DRIFT

Plate 4 (in pocket) shows the estimated potential yield from glacial drift aquifers in Eddy and Foster Counties. This is based on the transmissibility map (pl. 3) and the reported performance of wells from the inventory (Trapp, 1966, table 1).

Meyer (1963, p. 338-340, fig. 100) published a chart relating well diameter, specific capacity, and coefficients of transmissibility and storage. This shows that, for coefficients of storage less than 0.005, and for transmissibilities within the range of 2,000 to 100,000 gpd per foot, the ratio of transmissibility to specific capacity is about 2,000:1, where specific capacity is given in gallons per minute per foot of drawdown after 24 hours pumping. The ratio is larger for transmissibilities outside the range of 2,000-100,000 gpd per foot. In most artesian aquifers, the storage coefficient falls within the range of 0.00005 to 0.005, and the graph shows that, within this range, large changes in the storage coefficient correspond to relatively small changes in specific capacity. Therefore, in artesian aquifers having transmissibilities of up to 100,000 gpd per foot, the yield, in gallons per minute, of an efficient, fully penetrating well with 10 feet of drawdown after 24 hours pumping may be approximated by dividing the transmissibility by 200. The diameter of the well will also affect the yield, but this effect is small compared to the uncertainty of estimating transmissibility from lithology. The same chart shows that, for aquifers having a greater coefficient of storage, the specific capacity will be greater, with the ratio of transmissibility to specific capacity approaching 1,000:1 for low values of transmissibility and high values of the storage coefficient. Storage coefficient values of more than 0.005 apply to water-table aquifers. For these, yields of efficient wells would be up to twice as great as for similar wells constructed in artesian aquifers with the same transmissibility.

The principles described above were applied in preparing plate 4. Wherever geologic and well data indicated that artesian or leaky artesian conditions predominated, the estimated transmissibility was divided by 200 to arrive at a yield value. Where an aquifer was known to be very narrow, so that boundary conditions would affect the yields of wells, or where a comparatively high transmissibility resulted from a large thickness of material of poor permeability, yield values on the map were arbitrarily reduced. Where water-table conditions predominate, yields were adjusted upward.

The yield map has all the limitations of the transmissibility map resulting from the method used, imprecision of lithologic logs, and insufficient control in relation to the variability of the glacial drift, plus the added element of interpretation involved in deriving yield from transmissibility. Also, drawdowns of more than the 10 feet assumed in this method would often be acceptable, and under these conditions, greater yields would be possible. Nevertheless, the map should be useful in showing potential ground-water yields of the various parts of Eddy and Foster Counties. The interpretation is based on all geologic and hydrologic data relevant to it in Part I (Bluemle, 1965) and Part II (Trapp, 1966) of this report.

## AQUIFERS IN THE DRIFT

Plate 4 shows the location and extent of the principal glacial drift aquifers in Eddy and Foster Counties together with patterns indicating other less well-defined areas that show promise of yielding 50 gpm or more to wells. Buried glaciofluvial aquifers include areas where 20 feet or more of buried sand and gravel are present. Surficial aquifers are arbitrarily limited to those parts of the surficial outwash and alluvium having 10 feet or more of water-saturated sand and gravel. The buried aquifers are artesian or leaky artesian, and the surficial ones are water-table type. A discussion of individual aquifers follows, with the buried aquifers first.

### New Rockford aquifer

The New Rockford channel and its associated aquifer have been previously known as the "Heimdal channel" and "Heimdal channel aquifer" (Bluemle, 1965, p. 19). However, this term is subject to confusion with the Heimdal diversion channel of Lemke (1958, p. 89-90; 1960, p. 112, 115), a surface channel that carried overflow from Lake Souris and outwash from the Leeds ice lobe when the ice stood at the position now occupied by the Heimdal moraine. It is hereby proposed to restrict application of the term "Heimdal channel" to the surface channel described and mapped by Lemke, and to rename the buried channel the New Rockford channel because it lies near the city of New Rockford in Eddy County, and is defined by a line of test holes drilled south of the city.

The New Rockford channel is earlier in origin than the Heimdal diversion channel of Lemke. Although the landforms of Eddy and Foster Counties and adjoining areas, including the Heimdal diversion channel, date from the recession of the late Wisconsin ice front, the New Rockford channel was formed prior to or during the advance of these ice sheets. It has no surface expression except where it is overlain locally by later drainage channels, and it is covered in various places by all the drift sheets exposed in the area except the McHenry drift (Bluemle, 1965, fig. 9). Its origin is obscure, as is the reason for the geographic proximity of the Heimdal channel.

The aquifer occupying the New Rockford channel at New Rockford was described briefly by Sayre (1935, p. 112). He reported that Victor Hegg, a local driller, stated that it extended 60 miles east and west and 2 miles north and south. The early association of the aquifer with New Rockford provides additional justification for naming it after the city.

dimensions

*Location and extent.*--In Eddy and Foster Counties, the New Rockford buried channel extends in an east-southeasterly direction from the James River Valley on the Eddy-Wells county line to east of Glenfield on the Foster-Griggs county line, a distance of about 43 miles (pl. 5, in pocket). At New Rockford and Brantford, lines of test holes indicate that the buried channel is about 2 miles wide, although subsurface data elsewhere suggest that the width may vary from 1 to 3 miles. The aquifer underlies about 82 square miles in Eddy and Foster Counties.

~~[illegible]~~
1-3 mi wide
43 long

area

*Thickness and lithology.*--The drift in the New Rockford channel probably

Saturated thickness of drift 260-320 ft

thickens to the southeast as the channel deepens. The water-saturated drift thickness in the center of the channel generally ranges from 260 to 320 feet. Much of the drift filling the channel is outwash, comprising one of the more important aquifers, or system of aquifers, in the area.

The outwash consists of sand and gravel. The greatest thickness of sand and gravel penetrated was 161 feet in test hole 146-61-19ccc. Near the center of the channel, grain size generally increases with depth (test holes 146-61-19ccc, 148-66-3ddc, 148-66-6ccb, and 149-67-17bbb) although the coarse gravel near the bottom may be a poorly sorted shale gravel (pl. 5, sections B-B' and F-F'). However, in test hole 148-66-7bbc, gravel and medium coarse sand in the upper part of the aquifer grade downward into medium fine sand. In the deep part of the channel, the base of the aquifer generally overlies Pierre Shale. Till commonly underlies the aquifer on the flanks of the channel (test hole 146-62-30ccc; pl. 5, section E-E'). From 50 to 200 feet of till overlie the aquifer.

periodic damming fill silt clay within aquifer ↓ low T zones?

Masses of till and layers of clay and silt within the aquifer were penetrated in some test holes (for example: 146-61-19ccc, 146-62-36bbb, and 147-65-11cbb). These materials suggest that the outwash channel was ice marginal during at least part of its history. From time to time, local advances of the ice front must have overridden the channel, depositing till and damming the flow so as to permit the deposition of quiet water sediments (clay and silt) upstream. The damming probably caused diversion of the melt water, either in the form of small-scale detours, which may explain certain buried outwash deposits high on the south flank of the channel (test hole 146-62-30ccc), or the formation of new channels taking a substantially different course from the old. The deposits making up the Eastman aquifer may have resulted from such a diversion of the New Rockford channel melt water.

At Juanita, test holes 146-63-4aaa and 146-63-10bbb (pl. 5, section D-D') indicate either local damming of the main channel or a major diversion. Test hole 146-63-10bbb, although in the deep part of the channel, penetrated mostly gravelly till. The other test hole, 1 mile north but still in the deep part of the channel, penetrated till in the lower 110 feet above bedrock, but the till is overlain by 24 feet of gravel, 6 feet of till, and 20 feet of gravel. The evidence suggests that an outwash channel was eroded into bedrock by melt water, then advancing ice scoured out any outwash in the channel at the time, leaving till in its place, which dammed the flow. Flow was later reestablished over the site of the old channel, as evidenced by the gravel in test hole 146-63-4aaa, but it did not extend as far south as section 10.

Interruptions in the continuity of the aquifer, such as previously described, would restrict the flow of ground water. Other possible hydrologic boundaries within the aquifer may have originated from post-depositional glacial erosion, cut-off meanders, terraces, and changes in grain size within the outwash sediments. Subsurface data are presently insufficient to define the barriers to ground-water movement within the New Rockford aquifer, but evidence that they exist is provided by anomalous piezometric levels and variations in water quality.

k specific

*Storage and movement of water.*--Assuming an area of 90 square miles, an average thickness of 100 feet, and a porosity of 30 percent, the aquifer holds about 1,700,000 acre-feet of water in Eddy and Foster Counties.

In estimating the movement of water through the aquifer, Darcy's Law may be applied in the form:

$$Q = TIL \quad \text{(see p. 34)}$$

Using an average coefficient of transmissibility of 260,000 gpd per foot (from the aquifer test at New Rockford), a hydraulic gradient of 5 feet per mile (between observation wells 149-67-17bbb and 148-66-3ddc), and an aquifer width of 1.7 miles, the quantity of water passing through the aquifer at New Rockford is about 2,200,000 gpd. Of this amount, about 150,000 gpd is withdrawn by the city of New Rockford.

The rates of flow at various points along the aquifer cannot be calculated from existing data with sufficient precision to show gains or losses.

*Water levels and their fluctuations.*--Water in the New Rockford aquifer is under artesian or leaky artesian conditions. The water levels in wells penetrating the aquifer range from 1-1/2 to 50 feet below land surface. The water levels generally correspond fairly closely to the levels in nearby water-table wells.

Hydrographs of observation wells in and adjoining the New Rockford channel show water levels plotted with respect to sea level. The period of record extends from the summer of 1963 to early 1966. Two wells (149-66-31cadl and 146-61-19ccc) were equipped with automatic water-level recorders during part of this period.

Figure 9 shows that, in general, water levels in the New Rockford aquifer become lower toward the southeast. Therefore, the direction of flow within the aquifer is primarily toward the southeast. The water levels do not fit the general pattern perfectly. The level in 146-62-30ccc is about 25 feet higher than would be expected from the position of the well in the channel. The probable explanation for this anomaly is that the aquifer penetrated by the observation well is, to some extent at least, cut off from the main body of the New Rockford aquifer. The well is located on the south edge of the channel, and may have penetrated buried outwash that was deposited in a diversion of the main channel. (See pl. 5). The water level in this well also changed differently in the latter half of 1964 than did the levels in wells 146-62-36bbb or 146-61-19ccc.

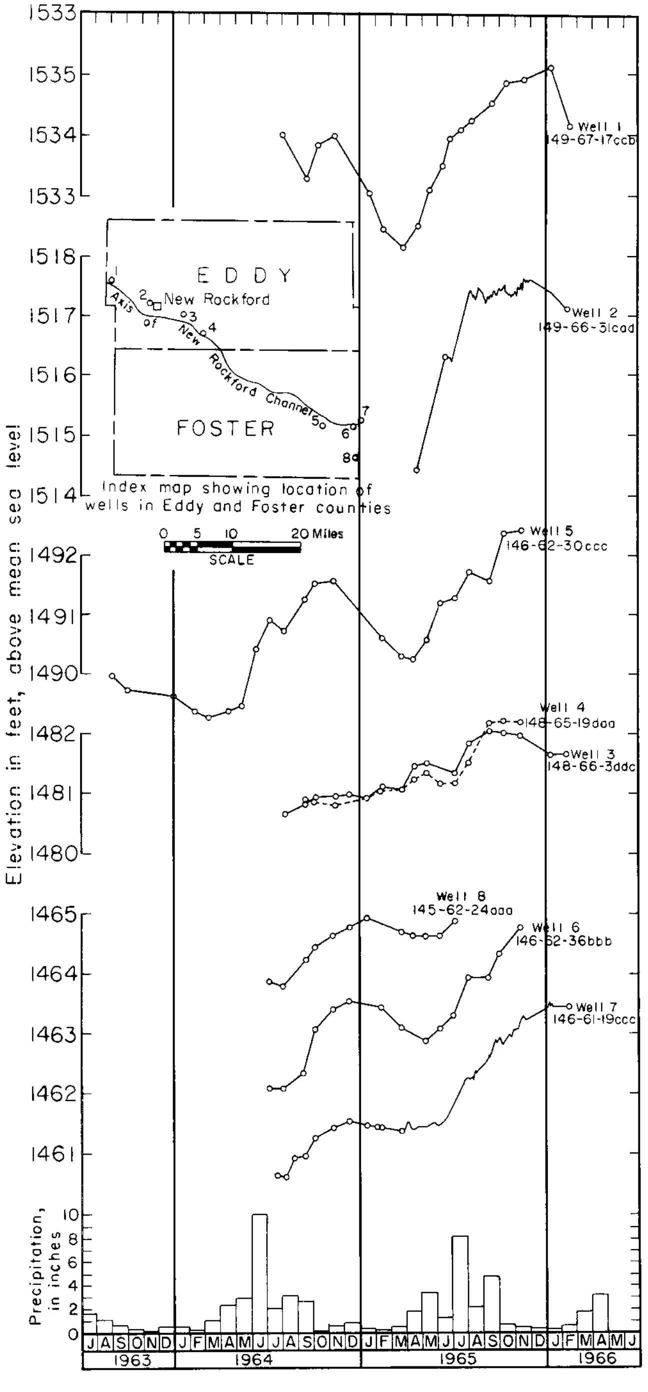


FIGURE 9. Hydrographs of observation wells in and adjoining the New Rockford aquifer.

Wells 148-65-19daa and 148-66-3ddc have almost the same level, although 148-66-3ddc is about 4 miles "upstream." Part of the answer may be that the surface elevations at the well sites were not determined with sufficient precision to show small differences in elevation of the piezometric surface. Another reason may be that well 148-66-3ddc may be affected to some extent by pumping at the New Rockford municipal well in sec. 6, less than 4 miles to the west. Also, 148-66-3ddc may be in an aquifer in a channel branching off from the New Rockford channel, and with a northward hydraulic gradient.

Well 145-62-24aaa had water levels anomalously higher than those in 146-62-36bbb and 146-61-19ccc, indicating that this well is in a separate aquifer (Eastman aquifer), which may have originated from a southward diversion of the New Rockford channel. Its level appears to be too low to have a close hydrologic connection with 146-62-30ccc.

There are insufficient test-hole and water-level data to show the relationship between the main body of the New Rockford aquifer (as penetrated in 146-62-36bbb and 146-61-19ccc), the Eastman aquifer (145-62-24aaa), and the aquifer penetrated at 146-62-30ccc.

Water levels in observation wells along the channel in the northwestern part of the area responded promptly to increased spring precipitation and thawing in 1965 (the year with the most nearly complete water-level records). The rise began in April in 149-67-17ccb, 148-66-3ddc, and 148-65-19daa. Near each of these, the present valley of the James River overlies the aquifer, and the James may furnish recharge to the New Rockford aquifer in this area, even though 60 feet or more of till separates the buried aquifer from the river and associated saturated surficial outwash.

On the other hand, water levels in observation wells along the channel in eastern Foster County did not begin a major rise until about 1 to 3 months after the rise began in western Eddy County. The water level in recorder-equipped 146-61-19ccc did not begin a major rise until late June. The hydrograph for 146-62-36bbb is similar. Both hydrographs show no abrupt changes in water levels in response to large amounts of precipitation. This type of behavior is to be expected in a leaky artesian aquifer overlain by 50-100 feet of drift having low permeability. It suggests that the aquifer receives less local recharge in eastern Foster County than it does in western Eddy County, where it underlies the James River.

*Aquifer test.*--An aquifer test was run on the city of New Rockford's present public supply well (148-66-6bcc3) during April 26-30, 1965. The production well is a partially penetrating well that is located near the north edge of the New Rockford aquifer.

Pairs of observation wells, with one constructed in the upper part of the aquifer and one in the lower part, were drilled at radii of 100 and 300 feet (observation wells 2S-2D and 3S-3D, fig. 10). The paired observation wells provided draw-

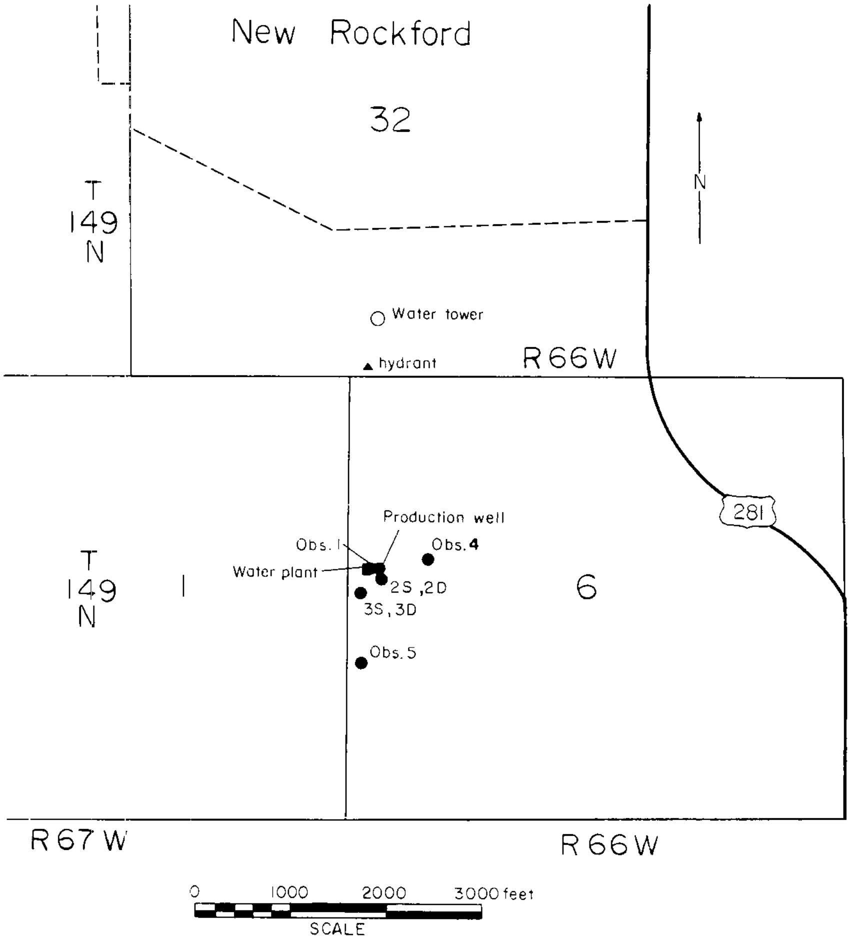


FIGURE 10. Map showing New Rockford aquifer test site.

down values that were averaged to compensate for the effect of the partially penetrating production well on drawdowns in close-in observation wells. Single observation wells were drilled at radii of 500 (observation well 4) and 980 (observation well 5) feet from the production well. An old city well, 99 feet away (observation well 1), was also measured. The paired observation wells were equipped with continuous water-level recorders and electric water-level sensing devices to monitor water-level fluctuations. Water levels in the production well were measured periodically with a steel tape. The locations of the production and observation wells are shown in figure 10.

The well was pumped at a rate of 460 gpm for 3,390 minutes, with the rate measured by a flowmeter coupled to a chart recorder. The water was pumped into the municipal water system and the surplus drained off through a hydrant nearly half a mile north of the production well. There was little chance of any of it reentering the aquifer during the test. Following the pumping, measurements continued during a recovery period of 2,000 minutes. The recovery time was limited by the storage capacity of the city's water system and the need to resume pumping when the water in storage was depleted.

In the following discussion, no attempt is made to provide the reader with a background knowledge of aquifer test analysis, but standard references include Ferris and others (1962) and Walton (1962).

Because test hole 148-66-6bbc indicated that the production well is probably within 1,200 feet of the edge of the aquifer, and because semilog time-drawdown plots showed line segments interrupted by breaks in slope, the limitations imposed by geohydrologic boundaries had to be recognized. Therefore, only the early drawdown data, which was obtained before the boundary affected the data, could be used for the calculation of the coefficients of transmissibility and storage. Thus, the Jacob method could not be used because it is applicable only to drawdown data collected after a substantial pumping time has elapsed.

The methods used were applications of the nonleaky artesian formula to distance-drawdown and time-drawdown field data curves.

Figure 11 is a distance-drawdown plot. Observation wells 2S-2D, 3S, and 5 were drilled south of the production well, or away from the northern barrier boundary of the aquifer. The drawdowns for these wells may be aligned with segments of the Theis type curve, as shown. (Data are missing for the first 70 minutes of the test for observation well 3D, but later data show the average drawdown value for 3S and 3D to be about 0.05 foot less than the drawdown for 3S.) Observation well 4 was east of the production well and was nearest the northern barrier boundary of the aquifer. Its drawdown values fall above the trace of the type curve when the curve is aligned with the other values, evidently because barrier boundary effects appeared here first.

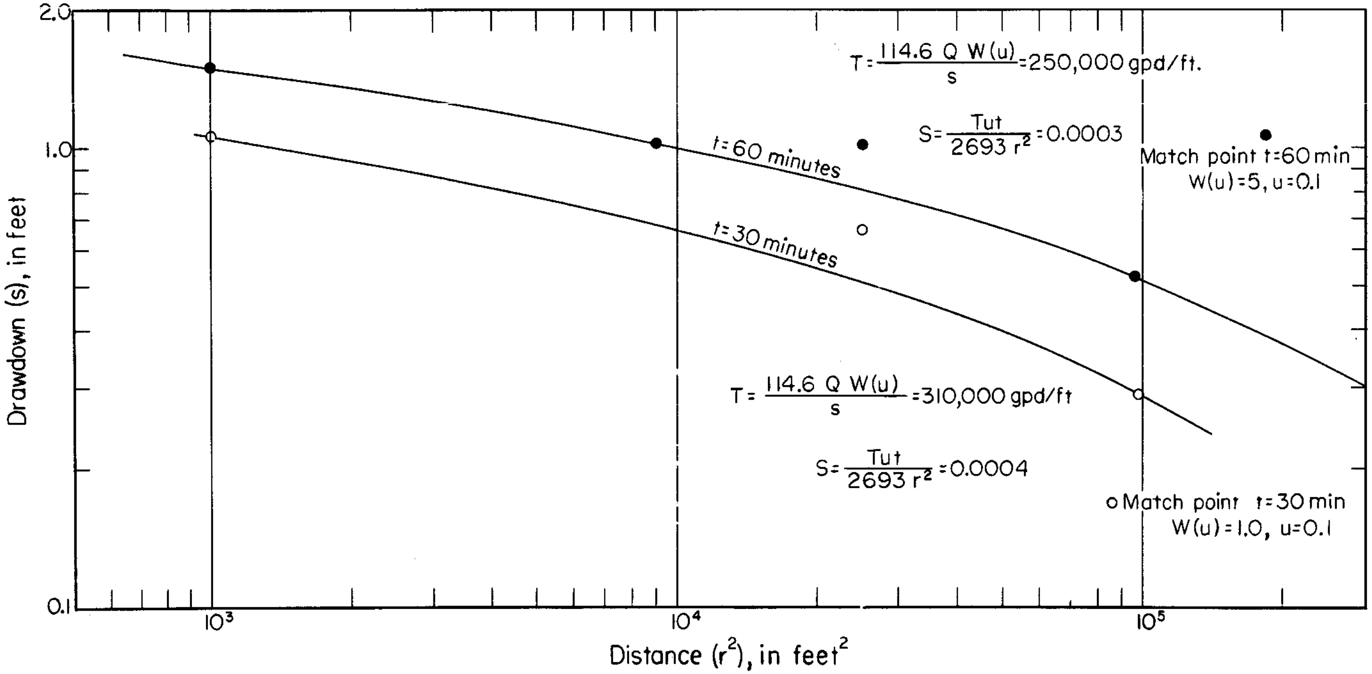


**FIGURE 11.** Logarithmic plot of distance-drawdown data for observation wells 2S-2D, 3S, 4 and 5, New Rockford aquifer test.

When the type curve is matched with the data curve, the coordinates of a random point (match point) common to both graphs are recorded and substituted into the Theis equation in the form:

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

Where:

$T$ = transmissibility in gallons per day per foot

$Q$ = discharge of a well, in gallons per minute

$W(u)$ = well function of u, coordinate of type curve

$s$ = drawdown in feet

$u = \frac{1.87\, r^2\, S}{Tt}$

$r$ = distance, in feet, from discharging well to the point of observation

$S$ = storage coefficient

$t$ = time in days. (When t is expressed in minutes, $u = \frac{2{,}693\, r^2\, S}{Tt}$.)

After solving for transmissibility, the storage coefficient is derived by means of the equation defining u.

Figure 12 is a time-drawdown plot for observation well 4. Similar plots were made for observation wells 2S-2D (average drawdown) and 5. The type curve was matched to the early drawdown data and the coefficients of transmissibility and storage derived by a procedure similar to that used on the distance-drawdown plot. The results are listed in table 2, along with the coefficients derived by the distance-drawdown method. The production well was omitted from the analysis because of its partial penetration and the unknown factor of entrance losses. Observation well 1 also was omitted because it is evidently partially penetrating; its construction details and condition at the time of the test were unknown, and it is close to the partially penetrating production well. Early drawdown data for the paired 3S-3D observation wells are missing, and so they, too, are omitted from the tabulation.

Leaky artesian methods (Walton, 1962, p. 4-6) were also applied to the New Rockford aquifer test data. Using Walton's modified Theis method with a family of leaky artesian curves for nonsteady state, it was found that no definitive match could be made with the early parts of the test curves, and that the flat part of the plotted curve most closely matched the nonleaky curve (standard Theis curve). The steady-state leaky artesian method of Jacob, as described by Walton (1962, p. 5-6), using the Bessel function curve, also was applied. Early drawdown data matched the Bessel function curve fairly well, and gave transmissibility values similar to those obtained by the nonleaky artesian methods, but the assumption of steady-state conditions is incompatible with the boundary effect increasing with

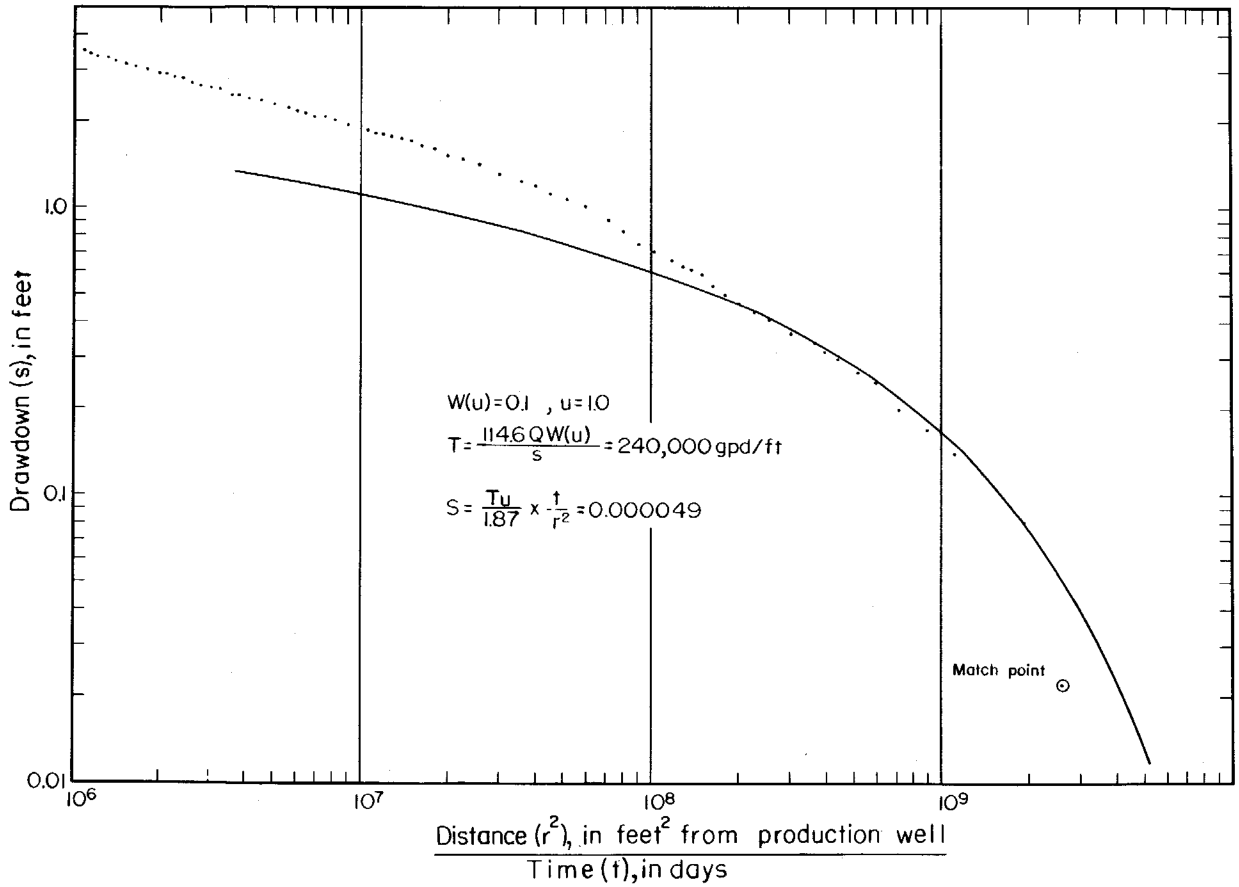


FIGURE 12. Logarithmic plot of time-drawdown data at observation well 4, New Rockford aquifer test.

**TABLE 2. New Rockford aquifer test, summary of test results.**

| Time after pump started (minutes) | Observation wells | Distance from production well (feet) | Coefficient of transmissibility (gpd per foot) | Average field coefficient of permeability (gpd per square foot) | Coefficient of storage |
|---|---|---|---|---|---|
| Distance-drawdown method: | | | | | |
| 30 | 2S-2D, 5 | .... | 310,000 | 2,800 | 0.0004 |
| 60 | 2S-2D, 3S, 5 | .... | 250,000 | 2,200 | .0003 |
| <u>Average</u> | | | 280,000 | 2,500 | .00035 |
| Time-drawdown method: | | | | | |
| .. | 2S-2D (averaged) | 100 south | 290,000 | 2,400 | .00093 |
| .. | 4 | 500 east | 240,000 | 2,400 | .000049 |
| .. | 5 | 980 south | 230,000 | 2,100 | .00047 |
| <u>Average</u> | | | 250,000 | 2,300 | .00048 |
| <u>Average of all values</u> | | | 260,000 | 2,400 | .00043 |

34,760 ft²/day

K ~ 290

5:/20

time, and so these values are omitted from table 2.

The average field permeability coefficient of 2,400 gpd per square foot (table 2) indicates an aquifer composed predominantly of gravel. However, sample logs of observation wells drilled for the aquifer test and nearby test holes show the aquifer to be composed largely of sand, which would have a lower permeability. This apparent discrepancy might be explained by the limitations of rotary drill samples. The coarser pebbles tend to remain in the hole during drilling, especially when the drilling mud is diluted and thinned or being lost to the aquifer.

Because of the boundary, drawdowns in the production well and the observation wells are greater than would be expected in an infinite homogeneous aquifer having the same aquifer coefficients. The effect ofthe boundary may be represented by image wells — imaginary wells discharging at the same rate as the real production well (Ferris and others, 1962, p. 144-167; Walton, 1962, p. 15-22). When using image wells, the aquifer is assumed to be infinite and homogeneous, with its constants being those determined at the aquifer test site. In a simple image well system, the effective hydrologic boundary perpendicularly bisects lines drawn between the production well and the image well.

Any number, or an infinite number, of image wells may be used, and in various combinations of discharge and recharge wells, depending on the complexity of the hydrologic system and the need to account for observed water-level changes. For the New Rockford aquifer test, two image wells satisfactorily accounted for the departure of observed drawdowns from those expected with ideal infinite aquifer conditions. The map at the left side (A) of plate 6 (in pocket) shows the observed drawdowns at the aquifer test site after 3,200 minutes of pumping (near the end of the test). Drawdowns for the production well and observation well 1 are corrected for partial penetration.

On the map at the right side (B) of plate 6, ideal drawdowns were computed for the production well and two image wells, each pumping 460 gpm for 3,200 minutes in an infinite aquifer having a transmissibility of 260,000 gpd per foot and a coefficient of storage of 0.00043.

The relationship:

$$u = \frac{2{,}693\, r^2 S}{Tt} \quad \text{(where } t = 3{,}200 \text{ minutes, } S = 0.0043\text{, and } T = 260{,}000 \text{ gpd per foot)}$$

and the Theis equation in the form:

$$s = \frac{114.6\, Q\, W(u)}{T} \quad \text{(where } Q = 460 \text{ gpm)}$$

were used to derive theoretical drawdowns for the image well solution. The first step was to solve for u, using a convenient value of r. Then, using the corresponding value of W(u) (Ferris and others, 1962, table 2), the value of s was computed. When the drawdowns were plotted against logarithms of r on semilog paper (pl. 6, C), the points fell along a straight line except for large values of r, where $u > 0.01$. The equation of the straight line segment is:

$$\Delta S = \frac{528\,Q}{T}$$

where $\Delta S$ is the drawdown difference per log cycle, in feet (Walton, 1962, p. 8-9). The line was extended as a curve to r = 4,000 feet, into the area where $u > 0.01$, by plotting additional points calculated from the Theis equation (pl. 6).

Part C of plate 6 may be used to determine the drawdown after 3,200 minutes pumping 460 gpm at any radius up to 4,000 feet from a well in an ideal aquifer having a transmissibility of 260,000 gpd per foot and a storage coefficient of 0.00043. It was used to determine the radii of circles of equal drawdown around the image wells and production well, and to compute the drawdown resulting from the production well and image wells at each well. The combined effects of the production well and image wells have been added at the production well and at each observation well, and the sums may be compared with the observed drawdowns shown in part A of plate 6. The theoretical drawdowns at the production well and image wells were computed by using r = 0.71 foot, as the inside diameter of the production well casing is 17 inches. The sums of the computed values at each well are within 0.2 foot of the observed drawdown, or corrected observed drawdown, except for the production well in which the corrected observed drawdown is 2.2 feet greater. This discrepancy may be explained by entrance losses.

Ideal drawdowns were also computed for t = 60 minutes, using the same image wells, with about the same degree of agreement with the observed data. This interpretation is omitted from the plate.

The position of the effective hydrologic boundary was determined by bisecting lines drawn from the image wells to the production well. The position of the boundary may be compared to the geologic cross section (part D of pl. 6, line of cross section shown on map, part A). Effective hydrologic boundaries do not correspond exactly to the geologic boundaries, but there is a fairly close correspondence here. Subsurface data are insufficient to show whether or not the channel has a bend in it corresponding to that of the hydrologic boundary.

Additional stratigraphic control or more intensive development of groundwater supplies probably would necessitate changes in this interpretation of the hydrologic system. However, the aquifer constants derived from the early data of the aquifer test are consistent with the presently known facts.

# TABLE 3. Selected chemical analyses of water from glacial drift aquifers.

[Analytical results in parts per million except as indicated]

| Location | Aquifer | Depth of well (feet) | Date of collection | Temperature (°F) | Silica ($SiO_2$) | Total iron (Fe) | Calcium (Ca) | Magnesium (Mg) | Sodium (Na) | Potassium (K) | Bicarbonate ($HCO_3$) | Carbonate ($CO_3$) | Sulfate ($SO_4$) | Chloride (Cl) | Fluoride (F) | Nitrate ($NO_3$) | Boron (B) | Dissolved solids |  | Hardness as $CaCO_3$ |  | Percent sodium | Sodium-adsorption-ratio | Specific conductance (micromhos at 25°C) | pH | Irrigation classification |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | Sum | Residue on evaporation at 180°C | Calcium, magnesium | Noncarbonate |  |  |  |  |  |
| 148-66-6bcc3 | New Rockford | 140 | 4-28-65 | .. | 22 | 1.5 | 98 | 26 | 356 | 13 | 975 | 0 | 222 | 76 | 0.1 | 0.0 | 0.80 | 1,290 | 1,270 | 350 | 0 | 68 | 8.3 | 1,910 | 8.1 | C3-S2 |
| 146-66-18adal | Carrington | 89.9 | 12- 4-64 | 45 | 18 | 1.2 | 94 | 26 | 26 | 5.1 | 376 | 0 | 86 | 11 | .1 | .0 | .00 | 452 | 478 | 344 | 36 | 14 | .6 | 714 | 8.0 | C2-S1 |
| 148-67-28bda2 | Rosefield | 65 | 10- 1-64 | 46 | 29 | 4.0 | 64 | 34 | 180 | 13 | 575 | 0 | 193 | 24 | .4 | 2.0 | 1.0 | 826 | 840 | 300 | 0 | 55 | 4.5 | 1,250 | 7.4 | C3-S1 |
| 147-63-27bac | Bald Hill Creek | 108 | 11- 6-64 | 45 | 27 | .28 | 55 | 25 | 213 | 8.0 | 560 | 0 | 151 | 73 | .5 | 2.0 | .30 | 830 | 836 | 242 | 0 | 65 | 5.9 | 1,280 | 8.0 | C2-S2 |
| 145-62-24aaa | Eastman | 166 | 7- 9-64 | 48 | 21 | .37 | 121 | 48 | 239 | 20 | 454 | 0 | 457 | 98 | .3 | 80 | .00 | 1,310 | 1,340 | 502 | 130 | 50 | 4.6 | 1,890 | 8.0 | C3-S1 |
| 148-62-25acc2 | Spiritwood(?) | 112 | 9-30-64 | 44 | 20 | 4.6 | 97 | 60 | 116 | 14 | 566 | 0 | 275 | 5.5 | .3 | 1.0 | 1.0 | 872 | 929 | 490 | 26 | 33 | 2.3 | 1,350 | 7.8 | C3-S1 |
| 150-62-24dca2 | Hamar | 161 | 6- 8-65 | .. | 28 | .11 | 90 | 23 | 10 | 3.5 | 338 | 0 | 58 | 2.6 | .2 | .4 | .00 | 383 | 354 | 320 | 43 | 6.3 | .2 | 591 | 7.9 | C2-S1 |
| 148-62-15cdd | Johnson Lake | 147 | 7-21-64 | 46 | 22 | .73 | 17 | 4.2 | 236 | 10 | 460 | 7 | 110 | 54 | .5 | 2.0 | .30 | 690 | 719 | 60 | 0 | 88 | 13 | 1,090 | 8.3 | C3-S3 |
| 150-65-22bdb | Northwest Eddy | 46 | 8-27-64 | 47 | 20 | .18 | 48 | 23 | 14 | 3.7 | 259 | 0 | 32 | 3.0 | .2 | 2.0 | .00 | 274 | 277 | 216 | 1 | 12 | .4 | 468 | 7.9 | C2-S1 |
| 149-64-19ddd | Central Eddy | 12 | 10-23-64 | 48 | 20 | .09 | 104 | 54 | 37 | 14 | 406 | 0 | 168 | 48 | .4 | 11 | .15 | 656 | 660 | 480 | 148 | 14 | .7 | 1,070 | 8.2 | C3-S1 |
| 150-63-1ada | Warwick | 20 | 1-18-51 | .. | .. | 2.2 | 42 | 25 | 35 |  | 318 | 0 | 1 | 2 | 0 | 4.3 | ... | 267 | ... | 208 | ... | 27 | 1.1 | ... | ... | C2-S1[1] |
| 145-64-21dba | James River | 33 | 8-29-63 | .. | 23 | .69 | 40 | 33 | 95 | 8.0 | 410 | 0 | 84 | 12 | .3 | 0 | 1.65 | 500 | 530 | 236 | 0 | 46 | 2.8 | 837 | 7.7 | C2-S1 |
| 147-64-25add | Juanita Lake | 63 | 7- 8-64 | 51 | 24 | .17 | 70 | 27 | 76 | 12 | 366 | 0 | 156 | 3.0 | .5 | .0 | .00 | 548 | 612 | 288 | 0 | 35 | 1.9 | 892 | 7.9 | C2-S1 |
| 145-67-16ccb | Pipestem Creek | 37 | 8-27-63 | .. | 23 | .38 | 75 | 102 | 85 | 12 | 372 | 0 | 472 | 14 | .6 | 0 | .15 | 966 | 1,076 | 610 | 305 | 23 | 1.5 | 1,623 | 7.8 | C3-S1 |
| 150-66-9cab | Sheyenne Village | 25 | 10-25-63 | .. | 16 | .64 | 56 | 17 | 135 | 15 | 444 | 0 | 115 | 20 | .3 | 2.0 | 0 | 597 | ... | 212 | 0 | 56 | 4.0 | 1,000 | 7.6 | C3-S1[2] |
| 148-63-11ccb | Cherry Lake | 38 | 7-17-64 | 46 | 18 | .17 | 76 | 23 | 39 | 8.2 | 376 | 0 | 59 | 5.5 | .3 | 4.5 | .00 | 419 | 428 | 284 | 0 | 22 | 1.0 | 689 | 8.0 | C2-S1 |
| 145-66-32baa | Russell Lake | 88 | 8-23-63 | .. | 26 | 1.13 | 72 | 39 | 104 | 14 | 508 | 0 | 132 | 14 | .3 | 2.0 | 1.00 | 654 | 654 | 340 | 0 | 38 | 2.5 | 1,068 | 7.7 | C3-S1 |
| 148-65-35bbd | Glacial till | 25 | 10- 8-64 | .. | 10 | 12 | 138 | 108 | 34 | 10 | 348 | 0 | 574 | 2.9 | .3 | .0 | .00 | 1,060 | 1,140 | 790 | 506 | 8 | .5 | 1,640 | 7.6 | C3-S1 |
| 150-67-21cab1 |  | 26 | 11- 6-64 | 45 | 22 | .80 | 334 | 465 | 644 | 24 | 903 | 0 | 2,290 | 426 | 1.9 | 548 | .00 | 5,200 | 5,640 | 2,750 | 2,010 | 33 | 5.3 | 6,120 | 7.6 | C4 |

[1] From Paulson and Akin, 1964, table 4.
[2] From Froelich, 1964. table 2.

*Quality of water.*--A chemical analysis of water from the New Rockford aquifer at New Rockford is given in table 3 and shown graphically in figure 13. However, the quality of the water varies considerably from place to place and with depth. Trapp (1966, table 4) listed 25 analyses from the New Rockford aquifer. The dissolved solids content (sum) ranged from 386 ppm (148-66-13dac) to 2,680 ppm (146-63-9ccd2). Sodium and bicarbonate are the major constituents in most of the samples.

Near the north edge of the aquifer, the samples from 148-66-6bcc5 and 148-66-6bcc6 differ markedly although they were collected on the same day from wells 3 feet apart. The first well is 103 feet deeper than the second. The sample from the shallower well had the lowest dissolved solids concentration, but it had the highest hardness. Water from the deeper well had about twice as much sodium, and was higher in bicarbonate, sulfate, and chloride and lower in calcium. The probable explanation is that the upper part of the aquifer is receiving recharge from the overlying drift and the lower part is receiving recharge from the underlying Pierre Shale, which contains water high in sodium, bicarbonate, sulfate, and chloride. At this site, the water from those two sources is incompletely mixed.

Another sample (149-67-17bbb) from the deep part of the channel shows the probable effect of admixture of Pierre Shale water. Although predominately a sodium bicarbonate water, the chloride content (425 ppm) is the highest of all the New Rockford aquifer samples. Three miles to the southeast, at the south edge of the aquifer, sample 149-67-33aba had only 624 ppm total solids and 18 ppm chloride, yet had almost three times as much calcium as sample 149-67-17bbb. The water in this part of the aquifer evidently has not been modified by passing through the Pierre Shale.

Differences in water quality within the aquifer may be caused by differences in quality of recharge water entering the aquifer at different points, by local differences in aquifer lithology, or by varying times of residence of the water in different parts of the aquifer. The upper part of the aquifer is most likely to receive recharge with a low mineral content — recharge that has taken the most direct route to the aquifer from its origin as precipitation. Water in the lower part of the aquifer is likely to receive recharge from underlying aquifers — in this case, the Pierre Shale. Local accumulations of such materials as carbonate and gypsum pebbles, lignite fragments, or clay in the aquifer are likely to alter the composition of water contacting them.

Variations in water quality within an aquifer are likely to be intensified by the presence of barrier boundaries, which would impede mixing. Abrupt changes in quality in short distances are possible indications of barrier boundaries within an aquifer. However, test drilling and water sampling in the New Rockford aquifer are not sufficiently detailed to locate barriers within the aquifer, although variations in both lithology and water quality suggest their presence.

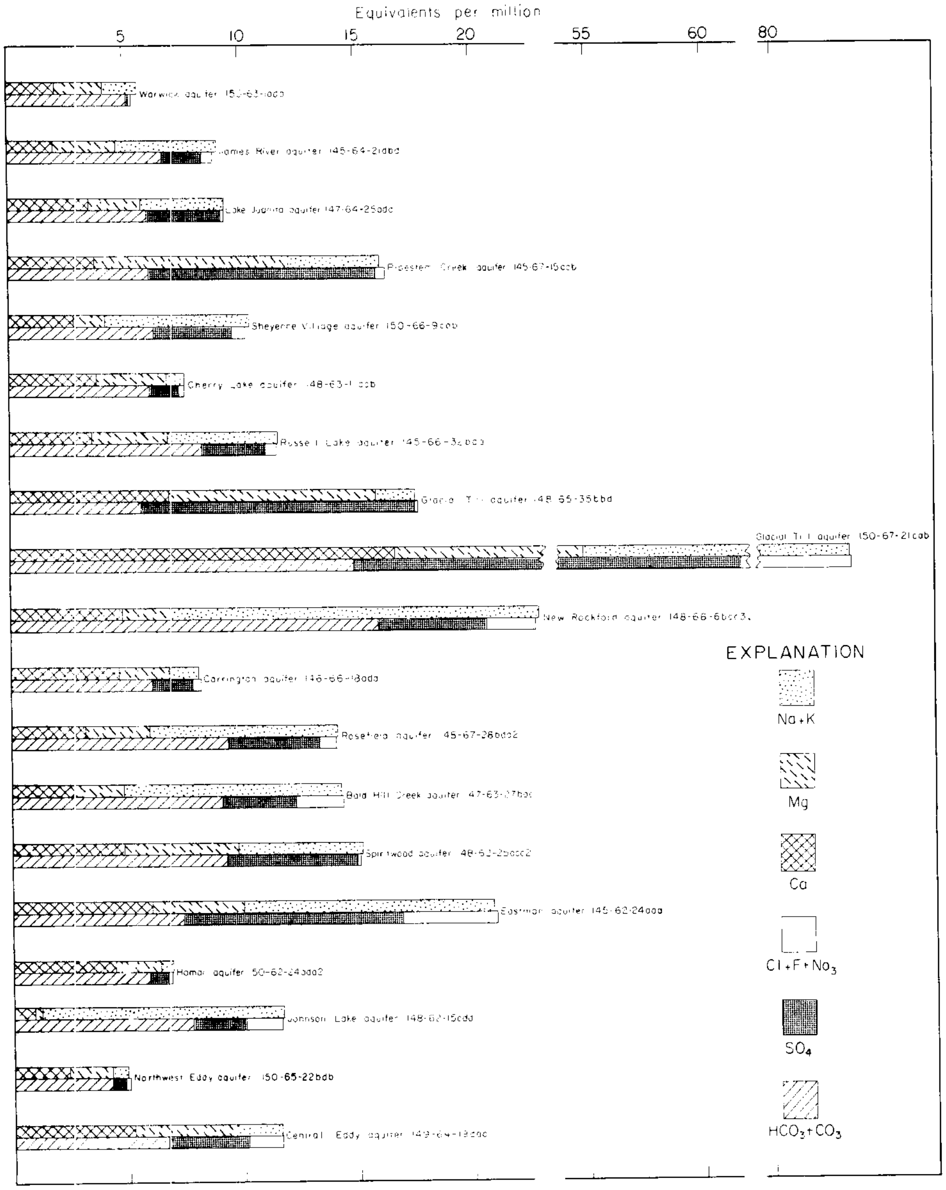


FIGURE 13. Graphs showing equivalents per million of selected water samples from glacial drift aquifers.

Analyses from only 2 (148-66-13dac and 149-66-35dbdl) of the 25 wells sampled in the aquifer had dissolved solids below the limit of 500 ppm recommended for drinking water by the U.S. Public Health Service (1962a, p. 7), and 13 had dissolved solids in excess of 1,000 ppm. The latter waters are classed as slightly saline (Robinove and others, 1958, p. 3).

Six of the samples had sulfate in excess of the Public Health Service recommended limit of 250 ppm, and 1 exceeded the chloride limit of 250 ppm. Most of the samples contained iron in excess of the recommended limit of 0.3 ppm. A sample from 1 well (146-63-9ccd2) had a nitrate content of 377 ppm, substantially above the recommended limit of 45 ppm.

The calcium-magnesium hardness of the samples ranged from 73 ppm to 2,010 ppm as calcium bicarbonate. Most of the samples had hardness in excess of 200 ppm, and all but 2 had O noncarbonate hardness.

Most of the samples were in the irrigation water classification C3, or high salinity (fig. 5). Two samples fell into the very high salinity (C4) class, and 2 were medium salinity (C2).

The sodium-hazard classification (fig. 5) of the sampled New Rockford aquifer water ranged from S1 (low sodium) to S3 (high sodium).

Residual sodium carbonate concentrations (RSC) ranged from 0 (146-63-9ccd2 and 146-63-15aba) to 15.7 meq per liter{ 149-67-17bbb). Of samples from 26 wells for which the RSC could be determined, 4 had values of less than 1.25 meq per liter, or probably safe for irrigation with respect to RSC; 7 were in the range 1.25 to 2.50 meq per liter, or marginal for irrigation; and 15 had RSC concentrations above 2.50 meq per liter, or unsuitable for irrigation.

The boron content of the New Rockford aquifer water samples ranged from 0.000 to 0.95 ppm.

Persons planning to construct wells in the New Rockford aquifer should consider the different qualities of water that it contains. Analyses indicate that the quality varies both with depth and laterally. Therefore, water samples should be taken from wells as they are drilled in order to determine the part of the aquifer that contains the water most suitable for its intended use. Water users having a choice of several well sites, such as municipalities, industries, and irrigators, should consider drilling several test holes for water-sampling purposes as well as for information on the aquifer thickness and lithology. Where feasible, well sites near the edge of the aquifer should be compared to those near its center.

The present limited data suggest that wells constructed in the upper part of the aquifer, and those drilled near the edge of the channel, yield water having a lower mineral content (although at the price of lower potential yields) than fully penetrating wells near the center of the channel. Under continued heavy pumping, however, the quality of water produced by a well could change. There is no evidence that the quality has changed substantially at the New Rockford municipal well field between 1921 (Simpson, 1929, p. 285) and 1965 (Trapp, 1966, table 4).

### Carrington aquifer

The Carrington aquifer, a buried outwash deposit, is the most extensively exploited aquifer in the area; it supplies the city of Carrington, the Carrington Irrigation Branch Station, several privately owned irrigation wells, and a number of domestic and stock wells.

*Location and extent.*--The aquifer underlies about 48 square miles in northwestern Foster County and about 10 square miles west of Foster County in Wells County (F. Buturla, oral communication). In most places, the aquifer is covered by about 40 feet of till, but it crops out in the bottom of Scotts Slough, 3 miles north of Carrington. No distinctive surface feature is associated with the aquifer.

*Thickness and lithology.*--The Carrington aquifer consists of sand, gravel, and lignite fragments, with lenses of till, clay, and silt. The average thickness of sand and gravel encountered in test holes in Foster County is 44 feet, with a maximum thickness of 79 feet in 147-67-19cbc (pl. 5). The lithology changes abruptly in very short distances. The aquifer generally overlies the Pierre Shale. The surface of the Pierre is nearly level under much of the central part of the aquifer. Test hole 147-66-33dad (pl. 5, H-H') shows that the aquifer overlies till. However, although plate 5 shows the buried outwash in 147-66-33dad to be connected with the Carrington aquifer to the west, it may actually be a separate body since it lies at a lower elevation.

*Storage.*--Assuming an area of 48 square miles, an average thickness of 44 feet, and a porosity of 30 percent, the aquifer holds about 400,000 acre-feet of water.

*Water-level fluctuations.*--Figure 14 shows water-level fluctuations in four wells constructed in the Carrington aquifer, and also in a shallower well in the overlying till. Well 146-66-6aad is a water-table well on the bank of Scotts Slough, dug into the aquifer near its outcrop. The hydrograph shows water levels to be higher in the spring than in winter from 1963-65, but the time at which the rise takes place is unknown because the well freezes and there are no measurements made between early winter and the spring thaw. Fluctuations during the summer correlate with those in 147-66-31accl, an irrigation well three-quarters of a mile north on the Carrington Irrigation Branch Station. These fluctuations are due primarily to natural causes rather than pumping since the first sharp decline in the summer of 1964 took place before the beginning of the year's irrigation pumping (June 1). During the aquifer test run at the irrigation station June 1-10, there was no observed correlation between pumping and recovery on 146-66-31accl and water levels in 146-66-6aad. Ordinarily Scotts Slough receives discharge from the aquifer, and therefore serves as a hydrologic boundary.

The difference between the high and low monthly measurements of 146-66-6aad is 1.42 feet for 1964 and 0.61 feet for 1965.

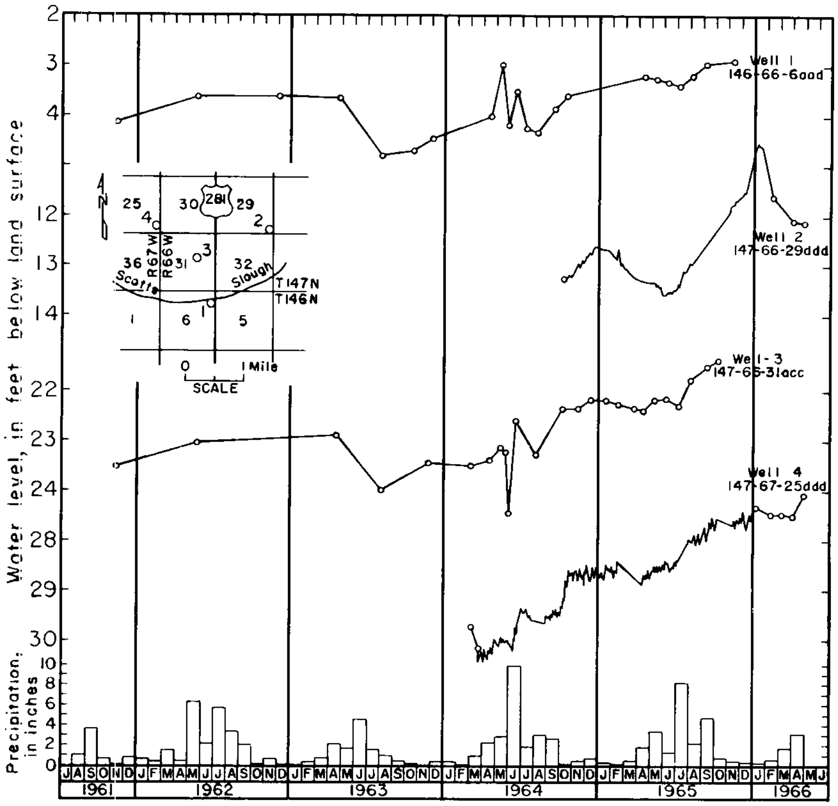


FIGURE 14. Hydrographs of observation wells in and adjoining the Carrington aquifer.

Well 147-66-31accl shows recovery in the late fall at the close of the irrigation season each year. A yearly decline in midwinter occurs because frozen ground prevents recharge. During 1965, there was very little pumpage for irrigation, and the record of monthly measurements principally reflects natural changes. The water level was still rising between September 21 and October 21, at which time the high for the period of record was reached. An adjoining well, 147-66-31acc2 (not shown on hydrograph), continued to rise into November. The reasons for the high levels at the close of 1965 were the succession of two wet years (1964-65), the wet late summer and early fall of 1965, which were also cool enough so that evapotranspiration demands were reduced, and the curtailment of irrigation pumpage.

Well 147-67-25ddd is a recorder-equipped shallow observation well dug into the till overlying the Carrington aquifer, and located a little more than half a mile from 147-66-31accl. Its hydrograph is roughly similar to 147-66-31accl. During the aquifer test June 1-10, 1964, the water level in 147-67-25ddd continued to rise as 147-66-31accl was being pumped. This indicates either that the distance was too great for the effects of pumping to influence water levels in the observation well, or that the reduced artesian pressure in the Carrington aquifer has a delayed influence on water levels in the overlying till.

Well 147-66-29ddd is a recorder-equipped observation well about 1-1/2 miles northeast of 147-66-31accl. Its hydrograph shows a pattern generally similar to the others, but with greater variations. This may be because, at this location, the aquifer approaches true artesian conditions more closely than at 147-66-31accl and therefore has a lower coefficient of storage. Although the Carrington aquifer outcrops in Scotts Slough south of 147-66-31accl, where it must be under water-table conditions, there probably is till separating it from the surficial outwash in Scotts Slough southeast of 147-66-29ddd (pl. 5 sections G-G' and H-H').

*Aquifer test.*--An aquifer test was run June 1-10, 1964, on well 147-66-31accl at the Carrington Irrigation Branch Station.

Four observation wells, at radii of 200, 450, 660, and 980 feet were drilled for the test. Their locations are shown in figure 15A. They were equipped with automatic water-level recorders and sensing devices. Water levels were measured periodically by tape on the production well, and at irregular intervals on several outlying wells. Well 147-67-25ddd, a shallow well a little over half a mile northwest of the production well, had a recorder on it, also.

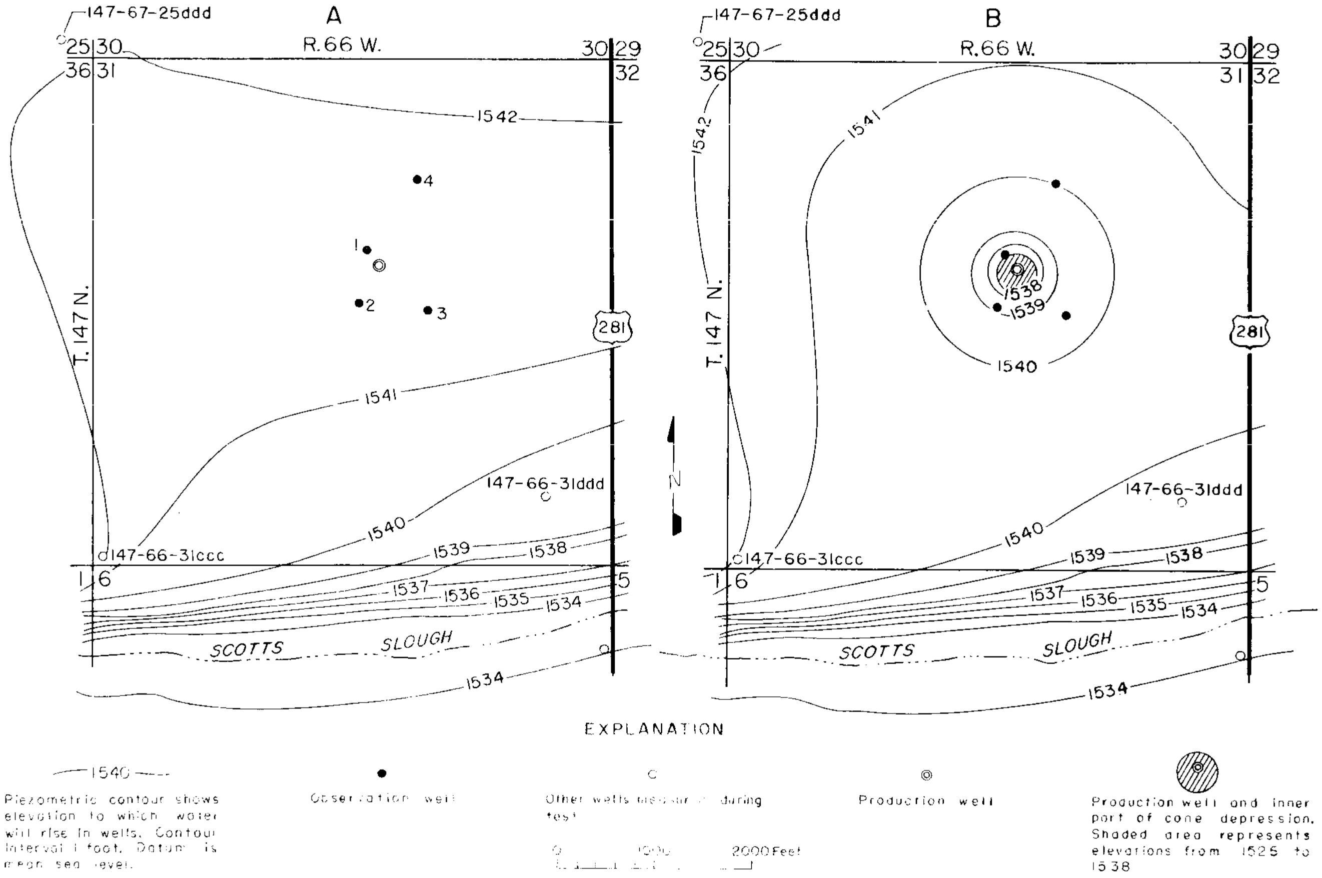
The production well was pumped at a rate of 1,260 gpm for 97 hours, with the rate measured by means of a discharge orifice. The water was discharged into an irrigation ditch, which was lined for the first 200 feet with waterproof plastic. It is believed that little, if any, of the discharged water returned to the aquifer during the test.

Figure 15B shows the configuration of the piezometric surface at the test site after 5,600 minutes pumping. It may be seen from this that the water levels in Scotts Slough at the end of the test were still below piezometric levels between the slough and the pumped well, so that the slough was not a source of recharge during the test.

Water-level measurements were continued for 5,400 minutes following the cessation of pumping, but the recovery data were affected by atmospheric pressure changes resulting from thunderstorm activity. There were no barometric readings to compensate for the effect of the atmospheric pressure changes.

The geologic setting suggests that leaky artesian conditions exist at the test site, but time-drawdown plots of the production well and observation well 1 failed to fit nonsteady-state leaky artesian type curves (Walton, 1962, pl. 1).

Using a distance-drawdown plot applied to the steady-state leaky artesian curve (Walton, 1962, pl. 2), a good fit was obtained for observation wells 1, 2 and 3 at 1,000 and 5,600 minutes, but a comparatively poor fit at 60 minutes (fig. 16). The plotted points for observation well 4 fell above the type curve,



(A) Configuration of the piezometric surface before pumping, Carrington aquifer test.
(B) Configuration of the piezometric surface after 5,600 minutes pumping, Carrington aquifer test.

FIGURE 15. Map of Carrington aquifer test site, showing configuration of piezometric surface.

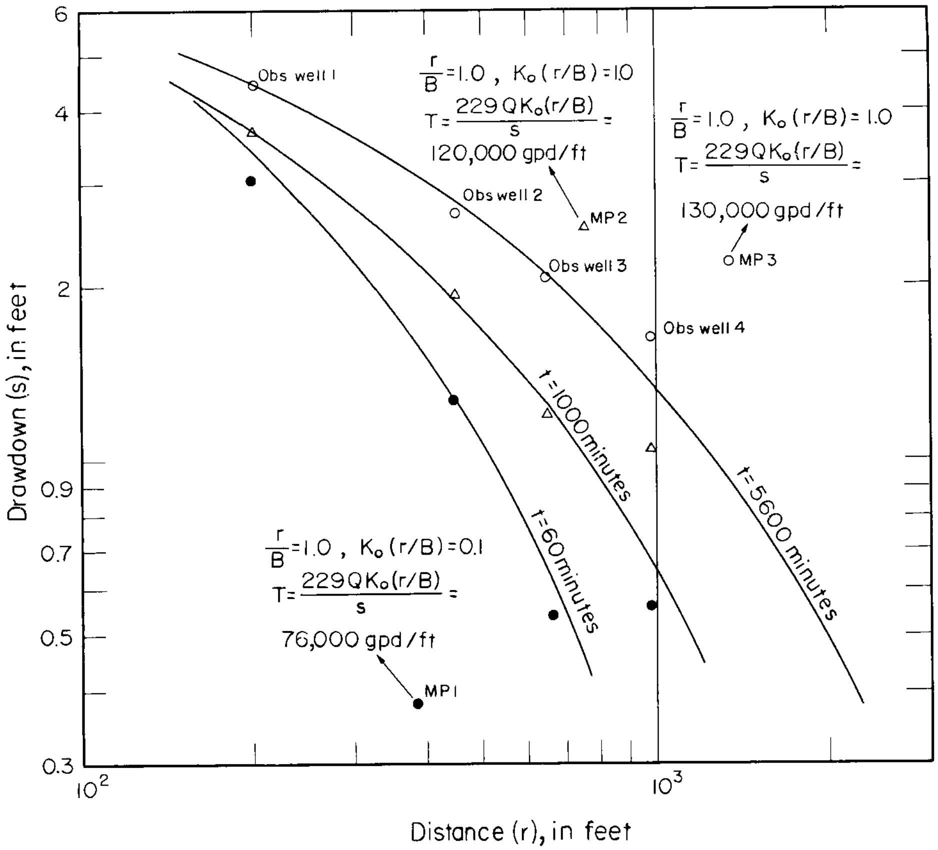


**FIGURE 16. Logarithmic plot of distance-drawdown data and steady-state leaky artesian type curve, Carrington aquifer test.**

indicating either that pumping was not continued long enough for steady-state leaky artesian conditions to be established at a radius of 980 feet, or that a recharge boundary affected the results of this well. There is no geologic evidence for a recharge boundary. Data for observation well 4 were not used in the compilation and averages of table 4.

The steady-state leaky artesian method does not permit calculation of the storage coefficient. Where two distinct aquifers are separated by a confining bed, the vertical permeability of the confining bed may be derived by this method. At the Carrington site, however, where the overlying till is both the confining bed and second aquifer, the vertical permeability of the confining bed cannot be determined by this method because the effective thickness of the confining bed continually changes during the test as the till is drained (G.A. LaRocque, Jr., 1966, written communication).

TABLE 4. Carrington aquifer test, summary of test results.

| Time after pump started (minutes) | Observation wells | Coefficient of transmissibility (gpd per foot) | Average field coefficient of permeability (gpd per square foot) | Coefficient of storage |
|---|---|---|---|---|
| Leaky artesian method: | | | | |
| 60 | 1, 2, 3 | 76,000 | 2,000 | ..... |
| 1,000 | 1, 2, 3 | 120,000 | 3,000 | ..... |
| 5,600 | 1, 2, 3 | 130,000 | 3,500 | ..... |
| Distance-drawdown method: | | | | |
| 60 | 1, 2, 3 | 110,000 | 2,800 | 0.014 |
| 1,000 | 1, 2, 3 | 120,000 | 3,200 | .027 |
| 5,600 | 1, 2, 3 | 140,000 | 3,800 | .056 |
| Average | | 120,000 | 3,100 | .032 |

A logarithmic plot of drawdown versus distance squared was also prepared (not shown), and the computed transmissibility values were of the same order of magnitudes as those determined by the leaky artesian method. Drawdown values for observation well 4 again fell above the type curve.

Rather poor matches could be made between the Theis type curve and logarithmic plots of the time-drawdown data from the individual observation wells. Typically, the curves would match for the early part of the test, but the time-drawdown curve would flatten below the type curve, then turn up at the end. High calculated values of transmissibility resulted from matching either early or middle-of-the test data, and the parts of the curves representing late data were not long enough to make a positive match.

Applying Jacob's method of plotting drawdowns against the logarithm of time resulted in gradual curves, segments of which seemed to approach straight lines. Using the latest data (the steepest parts of the curves), transmissibilities calculated by Jacob's formula were substantially higher than those calculated by the distance-drawdown methods, but there is no reason to believe that the curves would not have become steeper (and the calculated transmissibilities lower) if pumping had been continued.

Application of the Theis recovery method (Ferris and others, 1962, p. 100-102) to the Carrington test results led to extremely high values of calculated transmissibility, which are much higher than the distance-drawdown determinations, and much higher than could be expected from the known thickness and lithology of the aquifer.

Possible explanations for the deviation from ideal conditions in the attempted applications of the Theis curve and the Jacob method to time-drawdown data, and of the Theis recovery method, include leaky artesian conditions, boundaries, and partial dewatering of the aquifer in the vicinity of the pumped well. Although the aquifer is known to be nonhomogeneous, meaning that local boundaries must exist, the principal boundary affecting the system is probably Scotts Slough, which acts as a discharge boundary, and also marks a local transition to water-table conditions.

Since the results calculated by the time-drawdown method and recovery method diverge from the generally more reliable (Walton, 1962, p. 5) distance-drawdown methods, they are omitted from the compilation and averages of table 4.

The column showing permeability is based on approximate average aquifer thickness of 38 feet in the vicinity of the test.

*Quality of water.*--A representative chemical analysis of water from the Carrington aquifer is given in table 3. The dissolved solids content of the samples from the aquifer ranged from 452 to 1,134 ppm (Trapp, 1966, table 4). Calcium and bicarbonate were the major constituents of most of the samples. The waters with relatively high sodium, sulfate, or chloride probably contained admixtures of

Pierre Shale water. Some of the more mineralized waters were from wells near the edge of the aquifer (147-66-29ddd, 147-66-33dad, and 147-66-10dda), but one sample from the southwest edge of the aquifer (147-67-19cbc) had only 496 ppm dissolved solids. This low dissolved solids content may be related to the proximity of the well to Scotts Slough, which locally may furnish recharge to the aquifer at certain times.

Except for an increase in iron, no great change in quality was noted between the samples taken near the beginning and end of pumping in the aquifer test at the Carrington Irrigation Branch Station (samples 147-66-33accl, 6-1-64 and 6-5-64). The well had been pumped very little since the previous fall before the first of these samples was taken.

Only three of the wells in the aquifer sampled during the course of this study, 146-66-18adal, 146-66-18ada2 (city of Carrington wells), and 147-67-19cbc, had dissolved solids contents below the limit of500 ppm recommended by the U.S. Public Health Service for drinking water. Two of the samples (147-66-33dad and 147-67-10dda) had dissolved solids concentrations in excess of 1,000 ppm, and would be classed as slightly saline. The average dissolved solids content of 728 ppm for the 10 wells sampled is probably lower than the solids content of most waters from buried glacial drift aquifers in North Dakota.

Seven of the 10 wells sampled yielded water containing iron in excess of the recommended limit of 0.3 ppm. One sample (147-67-10dda) had sulfate in excess of the recommended limit of 250 ppm.

The calcium-magnesium hardness of the samples ranged from 324 to 456 ppm as calcium carbonate (very hard).

All but one of the samples were in irrigation water classification C3, or high salinity. The sodium-hazard classification oftheCarrington aquifer water sampled was S1 (low sodium), except for two samples (147-66-33dad and 147-67-10dda) which were S2 (medium sodium).

The boron content of the Carrington aquifer water samples ranged from 0 to 1.80 ppm. The waters containing boron in excess of 1 ppm could damage sensitive crops, but the principal crops grown in North Dakota are semitolerant to boron.

All the waters sampled from the Carrington aquifer had residual sodium carbonate concentrations below 1.25 meq per liter, except for the sample from 147-67-10dda which had an RSC of 6.7.

### Rosefield aquifer

Rasmussen (1945, p. 2-3) described the Rosefield aquifer as a low-pressure artesian aquifer, consisting of gravel outwash, following the valley of Rocky Run in Rosefield Township (T. 148 N., R. 67 W.) in Eddy County. He concluded that its area of recharge was in Wells County to the west.

*Location and extent.*--The extent and thickness of the aquifer are inferred from inventory data, with limiting control provided by outlying test holes. It underlies about 8 square miles in western Eddy and Foster Counties. Wells drilled into the aquifer range from 40 to 80 feet in depth. In Wells County, test hole 148-68-10ada penetrated 48 feet of sand, with pebbles, from 11 to 61 feet below land surface. At this site, the aquifer overlies till; bedrock is 99 feet below land surface (F. Buturla, 1966, oral communication).

The Rosefield aquifer may connect with the Carrington aquifer in the NW cor, T. 147 N., R. 67 W. and in the adjoining part of Wells County.

*Storage.*--Assuming an area of about 7 square miles, an average thickness of 35 feet, and an average porosity of 30 percent, the aquifer holds about 47,000 acre-feet of water in Eddy and Foster Counties.

*Discharge fluctuations.*--Measurements were made at irregular intervals from 1942-55 on a flowing well at 148-67-28ddb (Trapp, 1966, table 2). The measured rates of flow ranged from 6 to 15 gallons per minute. The measurements were not at close enough intervals to show a seasonal pattern and there is no evidence for a long-term decline.

*Quality of water.*--The chemical analysis of a water sample (148-67-28bba2) from the Rosefield aquifer, which is included in table 3, indicates that the water is a sodium bicarbonate type. The dissolved solids (826 ppm) and iron (4.0 ppm) concentrations of the sample exceeded the U.S. Public Health Service limits and the water was very hard. The irrigation classification was C3-S1.

### Bald Hill Creek aquifer

Lemke (1960, pl. 15) showed the Heimdal diversion channel following the present course of Bald Hill Creek. Bluemle (1965, p. 35-37, pl. 1, fig. 13) mapped and described Bald Hill Creek valley as a large melt-water channel. Low-pressure artesian flows are obtained by several wells in the valley, including 147-63-22bdd, which is 63 feet deep and reported to bottom in coarse gravel. The buried gravel in the Bald Hill Creek valley is designated the Bald Hill aquifer.

The aquifer is evidently buried outwash. It may be related in origin to the surficial outwash in the Bald Hill Creek valley, perhaps with less permeable material such as silt or till separating the surficial and buried outwash and serving as a confining bed.

An alternate explanation is that the aquifer was deposited during a phase in the development of the New Rockford channel. This is suggested by the fact that the aquifer lies within 3 miles of the New Rockford channel and appears to trend parallel to it. If this is the case, the aquifer may be hydrologically connected to the New Rockford aquifer.

*Location and extent.*--The extent and thickness of the aquifer are inferred from inventory data, with limiting control provided by outlying test holes. Test hole 147-62-26add showed that the aquifer is not present in this location in the Bald Hill Creek valley; it may extend southeast of T. 147 N., R. 63 W. As interpreted in plate 4, it underlies about 3 square miles in T. 147 N., R. 63 W.

A well (147-63-22bdd) constructed in the aquifer in the valley is reported to be 63 feet deep and another well (147-63-27bac) at the south edge of the valley, where the land surface is 21 feet higher, is 108 feet deep. These wells suggest that the top of the aquifer is about 60 feet below the surface in the valley bottom and that the aquifer may exceed 25 feet in thickness.

*Quality of water.*--The chemical analysis of a sample from 147-63-27bac is given in table 3. The water had 830 ppm dissolved solids, and was a sodium bicarbonate type. The specific conductance of water from 147-63-22bdd (flowing well) suggests that the water is similar to the sample from 147-63-27bac.

The dissolved solids concentration of water from 147-63-27bac exceeded the limits recommended by the U.S. Public Health Service. The water was very hard but not unusually so for North Dakota ground water.

The irrigation classification of the water was C3-S2 (high salinity, medium sodium). However, the residual sodium carbonate was 4.4 meq per liter which is substantially above the recommended limit of 2.5 for water to be used in irrigation. The boron concentration (0.20 ppm) was too low to be a hazard.

### Eastman aquifer

The Eastman aquifer is defined as the buried outwash body penetrated by test hole 145-62-24aaa in Eastman Township in southeastern Foster County (pl. 4). The outwash may have been deposited in a diversion of the New Rockford channel, but there is no definite evidence that it is a channel deposit or that it is continuous with the New Rockford channel outwash.

*Location and extent.*--The extent of the aquifer is not known. It is interpreted as extending southwestward to a test hole in 145-62-27bbb, and possibly northwestward to 146-62-30ccc. As interpreted in plate 4, the aquifer underlies about 14 square miles.

*Thickness and lithology.*--Test hole 145-62-24aaa penetrated 28 feet of sand, 8 feet of till, 14 feet of sand, and 25 feet of gravel, which overlie the Pierre Shale. Test hole 145-62-27bbb penetrated 42 feet of sand and gravel. Test hole 146-62-30ccc penetrated 40 feet of sand and 12 feet of gravel, with 12 feet of till separating the aquifer from bedrock.

*Water-level fluctuations.*--The hydrographs of 145-62-24aaa and 146-62-30ccc are shown on figure 9 where they may be compared to hydrographs in the New Rockford aquifer. The hydrograph for 145-62-24aaa shows a 1.1 feet maximum variation during the period of record, as compared to 1.4 feet for 146-62-36bbb, the nearest observation well in the New Rockford aquifer. The record for 145-62-24aaa also shows a delay of about 1 month in the appearance of highs and lows as compared to 146-62-36bbb. The water level in 146-62-30ccc is about 10 feet higher than in 145-62-24aaa, a gradient of about 1.4 feet per mile.

*Quality of water.*--The chemical analysis of a water sample from 145-62-24aaa is listed under the Eastman aquifer in table 3. This may be compared with water from 145-62-27aaa and 146-62-30ccc in table 4 of part II of this report (Trapp, 1966). Their dissolved solids concentrations were 1,310, 1,000, and 850 ppm, respectively. The most abundant ions were sodium, calcium, bicarbonate, and sulfate, but each of the samples had a different combination of dominant ions.

All three of the samples contained dissolved solids in excess of the limits recommended by the U.S. Public Health Service for drinking water, and the water from 145-62-24aaa would be classed as slightly saline. This water also contained nitrate in excess of the recommended limit of 45 ppm, which would make it hazardous for infant feeding. Nitrate is usually an indication of pollution, and in this area, is seldom encountered in deep, properly constructed wells. The samples from 145-62-24aaa and 145-62-27aaa contained sulfate in excess of the recommended limit, but the sample from 146-62-30ccc had a much lower sulfate content, which makes the connection between the aquifer penetrated by this well and the one penetrated by the other two wells appear less certain. All three of the samples contained iron in excess of the recommended limit.

All three of the samples were very hard, but 145-62-24aaa and 145-62-27aaa were much harder than 146-62-30ccc.

The irrigation classification of the water was C3-S1 (high salinity, low sodium hazard), except for 146-62-30ccc, which was C3-S2 (high salinity, medium sodium hazard). The boron content (in 145-62-27aaa and 146-62-30ccc only) was not likely to damage any but the more sensitive crops.

### Spiritwood (?) aquifer

The Spiritwood aquifer was named by Huxel (1961, p. 179-181) in Stutsman County, was further described by Huxel and Petri (1965, p. 35-36), and was traced into Barnes County and northward by Kelly (1964, p. 161-165). Kelly (1966, p. 26-38) further described it, determined aquifer coefficients, reported water-level fluctuations, and estimated the amount of water contained by the aquifer in Barnes County.

*Location and extent.*--The location and extent of the Spiritwood aquifer in Eddy County is imperfectly known. T.E. Kelly (1966, oral communication) tentatively has traced the channel north to northwestern Griggs County near Binford, about 5 miles east of the Foster county line. Along the east border of Eddy County, test holes 149-62-1aaa and 148-62-25add indicate a north-south trending bedrock low, which may be the Spiritwood channel. As interpreted in plate 4, the Spiritwood aquifer covers about 4 square miles in eastern Eddy County.

*Thickness and lithology.*--Test hole 148-62-25add penetrated 67 feet of gravel, which was overlain by 37 feet of silt and underlain by bedrock; but test hole 149-62-1aaa penetrated only 16 feet of gravel, overlain by 176 feet of silt and clay. The association of silt and clay with a bedrock low indicates that a lake occupied the low during part of its history. Subsurface data are insufficient to show how much of the low is filled by unproductive fine lake sediments and how much by coarse outwash deposits suitable for an aquifer.

*Quality of water.*--The chemical analysis of a sample from a private well in 148-62-25acc2 is given in table 3. The water had 872 ppm dissolved solids and was a mixed bicarbonate type with sodium the predominate cation by a slight margin. Dissolved solids, sulfate, and iron concentrations exceeded the limits recommended by the U.S. Public Health Service, and the water was very hard.

The irrigation classification of the one sample of Spiritwood(?) aquifer water was C3-S1 (high salinity, low sodium hazard). The boron content of 1.0 ppm might damage certain sensitive plants.

### Hamar aquifer

*Location and extent.*--The Hamar aquifer in Eddy County consists of buried outwash in a bedrock channel near Hamar (pl. 4). Control for the channel and associated aquifer includes a test hole in 150-62-15baa, the log of the Great Northern Railway well at Hamar (150-62-3aba), and well 150-62-25dca2. The southwestern limit of the channel is partly defined by test hole 150-62-22ddd, which encountered bedrock at 13 feet. Depth to bedrock is at least 168 feet in the channel. The outwash in the channel is as much as 40 feet thick. It is reported that relatively deep farm wells obtaining water from buried gravel lie along a trend extending southeast from sec. 24, T. 150 N., R. 62 W., into Nelson County.

The Hamar channel may be a tributary of the Spiritwood channel, which is known to extend northward from Stutsman and Barnes Counties, or it may be the Spiritwood channel itself. Subsurface data indicate a bedrock low extending along the east line of Eddy County south of the Sheyenne River. The Hamar aquifer is probably connected with the overlying Warwick aquifer in Benson County, but the test holes in Eddy County indicate that till and clay 100 feet thick separate the two aquifers.

*Quality of water.*--A water sample from 150-62-24dca2 contained only 383 ppm dissolved solids and 2.6 ppm chloride. The hardness of the water was 320 ppm. It was one of the least mineralized water samples collected for the study, and was a calcium bicarbonate type similar in character to the water from the surficial outwash (Warwick aquifer) in the same area.

The irrigation classification of the water was C2-S1 (medium salinity, low sodium hazard).

### Sheyenne Channel aquifer

Froelich (1964, p. 19-21) reported that outwash sand and gravel deposits occur in a steep, narrow bedrock depression partly underlying the present bed of the Sheyenne River at Sheyenne. They are evidently not connected to the terrace deposits of the Sheyenne Village aquifer because of the exposure of the terrace face.

*Location and extent.*--The saturated thickness of the Sheyenne Channel aquifer is about 60 feet, and it lies in a buried channel locally followed by the present Sheyenne River. The course of the buried channel at Sheyenne is roughly east-west, but outside the Sheyenne area, its course is not known. It evidently diverges from the Sheyenne River valley between Sheyenne and 150-65-11aaa where a test hole drilled in the valley bottom encountered the Pierre Shale at 6 feet.

The Sheyenne Channel aquifer is not known to be exploited at present. If heavy withdrawals were made, presumably recharge from the Sheyenne River would be induced. The aquifer appears to have a much higher potential yield than the Sheyenne Village aquifer.

### Johnson Lake aquifer

The Johnson Lake aquifer is defined as the buried outwash penetrated from 99 to 147 feet in test hole 148-62-15cdd, Eddy County.

*Location and extent.*--Test hole 148-62-15cdd was drilled in a surface channel extending southwest from Johnson Lake. It is assumed that the aquifer is approximately coextensive with the surface channel in the interpretation shown in plate 4. In this case, the aquifer underlies about 3 square miles.

*Thickness and lithology.*--The buried outwash includes 14 feet of sand and 34 feet of gravel, which overlies bedrock in 148-62-15cdd. A surficial sequence of outwash and silt was separated from this buried aquifer by 39 feet of till at this location.

*Water levels.*--The water level in test hole 148-62-15cdd was about 1 foot above land surface, but the hole was destroyed before a record of water-level fluctuations could be made.

*Quality of water.*--A chemical analysis of a sample from 148-62-15cdd is listed in table 3. The sodium bicarbonate type water had a dissolved solids concentration of 690 ppm. Dissolved solids and iron concentrations exceeded the limits recommended by the U.S. Public Health Service for drinking water.

The irrigation classification of the water from 148-62-15cdd was C3-S3 (high salinity, high sodium hazard). In addition, its residual sodium carbonate concentration of 6.6 meq per liter exceeded the recommended limit of 2.5 for irrigation water.

### Northwest Eddy aquifer

Bluemle (1965, pl. 1) mapped an outwash plain about 150 square miles in area between the James and Sheyenne Rivers in west-central Eddy County, and extending into northern Foster County. The deposits underlying the outwash plain may constitute a single aquifer; however, only locally does the aquifer have sufficient saturated thickness for large-scale use. Two areas within the outwash plain are underlain by a saturated thickness of more than 10 feet of sand and gravel and have sufficiently distinct boundaries to define two separate aquifers. One of these, centered in T. 150 N., R. 65 W., is here defined as the Northwest Eddy aquifer.

*Location and extent.*--In secs. 15, 16, and 22, T. 150 N., R. 65 W., logs of private test holes and wells show that the maximum water-saturated thickness of surficial outwash is about 35 feet. The aquifer is partly bound on the south and southeast by an east-west disintegration ridge in secs. 21 and 22, T. 150 N., R. 65 W. (Bluemle, 1965, pl. 1), and thins to less than the arbitrary limiting thickness of 10 feet in other directions. As thus defined, the effective area of the aquifer is about 2.4 square miles (pl. 4).

*Thickness and lithology.*--A well (150-65-22bdb) on the Berglund farm penetrated fine sand from 12 to 31 feet, and gravel from 35 to 47 feet. This is an irrigation well capable of producing over 750 gpm (see aquifer test). Other nearby test holes and observation wells encountered till below the surficial outwash at depths of 35 to 55 feet, but none reached the bedrock, which is Pierre Shale in this area.

*Aquifer test.*--An aquifer test was run on the Berglund well (150-65-22bdb) on August 24-30, 1964.

Four observation wells were drilled at radii of 100, 200, 300, and 440 feet (fig. 17). The observation wells were equipped with automatic water-level recorders and electric water-level sensing devices. The water level in the production well was measured with a steel tape.

The well was pumped at a rate of 766 gpm for 4,260 minutes. The discharge was measured by a flowmeter and was recorded on a chart recorder. The water was discharged beyond the glacial disintegration ridge about 1,000 feet to the south so that probably only the slight leakage at the pipe joints returned to the aquifer.

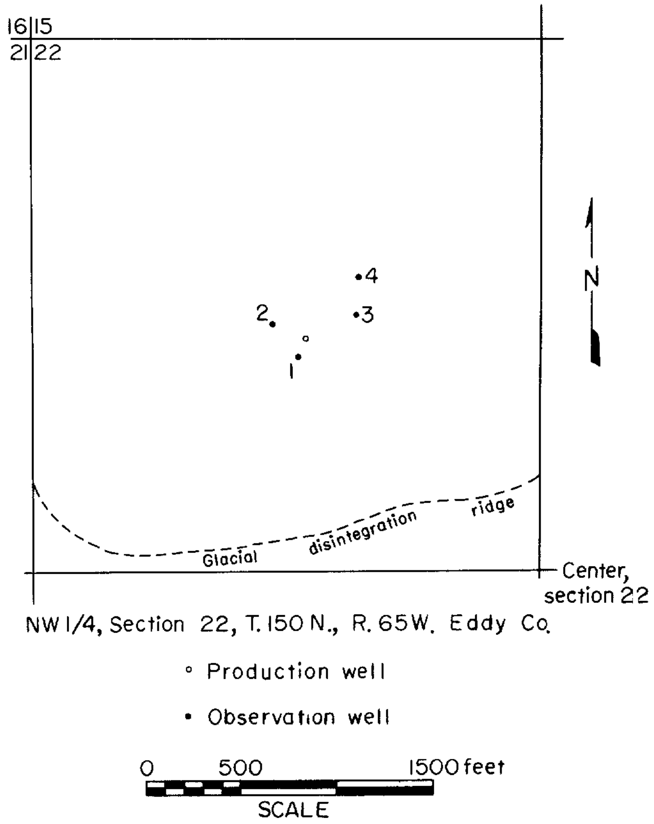


**FIGURE 17. Map showing test site, Northwest Eddy aquifer test.**

Recovery measurements were continued for 4,380 minutes after cessation of pumping. About 0.6 inches of rain fell toward the end of the recovery period, but this had no observable effect on the recovery hydrographs.

The Theis equation was derived for artesian conditions, with the assumption that water is released from storage instantaneously with decline in head. A water-table aquifer is characterized by slow gravity drainage from the pore spaces, and the drawdown data begin to fit the Theis curve only after sufficient time has elapsed for drainage. The time required for this depends on the discharge and the distance from the pumped well, with complete drainage taking place first in the center of the cone of depression.

The Northwest Eddy aquifer is under water-table conditions. Figure 18 is a distance-drawdown plot showing drawdowns at the end of the pumping period when drainage of pore spaces reached its maximum. The drawdowns were corrected for the reduction in the coefficient of transmissibility during pumping, re-

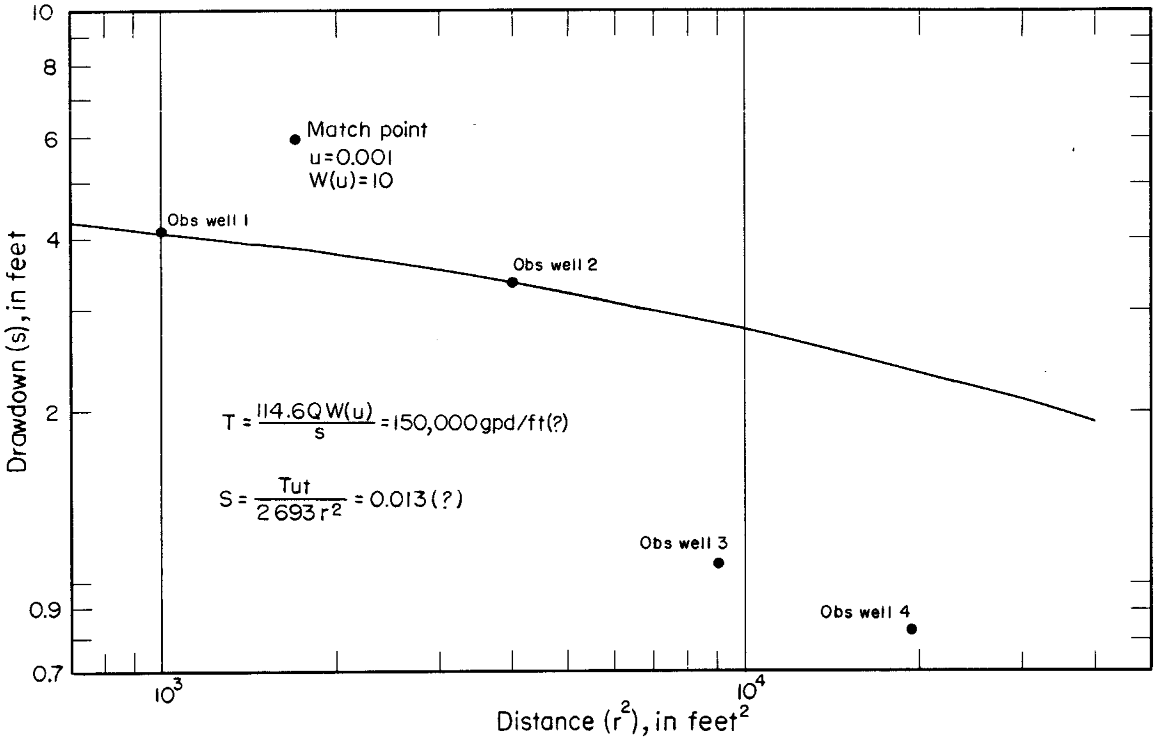


**FIGURE 18. Logarithmic plot of distance-drawdown data, Northwest Eddy aquifer test.**

sulting from the decrease in saturated thickness ofthe aquifer, according to Jacob's method as given by Walton (1962, p. 7):

$$s' = s-(s^2/2m)$$

where:

$s'$ = drawdown that would occur in an equivalent nonleaky artesian aquifer, in feet

$s$ = observed drawdown under water-table conditions, in feet

$m$ = initial saturated thickness of aquifer, in feet.

Only observation wells 1 and 2 fall on the type curve. This suggests that observation wells 3 and 4 are at too great a distance (r) from the pumped well for their drawdowns to respond in accordance with the Theis equation within the time of the pumping test. An alternative explanation is that a barrier separates them from the pumped well. In either case, the data from wells 3 and 4 were not used in solving for aquifer constants.

In figure 18, the curve fit to only two points is not definitive, and also, if the data from observation wells 3 and 4 were not valid for application of the Theis equation because of insufficient time, it is possible that the data from well 2 were not either. The computed transmissibility of 150,000 gpd per foot seems high considering what is known of the aquifer thickness and lithology. The calculated coefficient of storage, on the other hand, is lower than is usual for a permeable water-table aquifer.

A method of estimating the transmissibility of a water-table aquifer from the specific capacity of a well is given by Theis and others (1963, p. 332-336). This may be used as a check for the validity of the distance-drawdown solution above. For water-table aquifers, T' approximately equals $\frac{Q}{s}K$, where:

$K$ = $-66-264 \log_{10} (3.74\, r^2 \times 10^{-6})$

$r$ = effective radius of the well

$Q$ = pumping rate in gallons per minute, and

$s$ = drawdown after 24 hours.

The transmissibility (T) may be derived from T' by means of a chart (Theis and others, 1963, p. 334, fig. 99). Theis (p. 335) suggests using r = 5 feet for the effective radius of a large-capacity well in sand or gravel, whose yield has been increased by development.

Applying this method to the pumped well at the Berglund farm test:

$$T' \approx \frac{Q}{s}K = \frac{766}{10.75} \times 996 = 71{,}000$$

$T \approx 69{,}000$ gpd per foot.

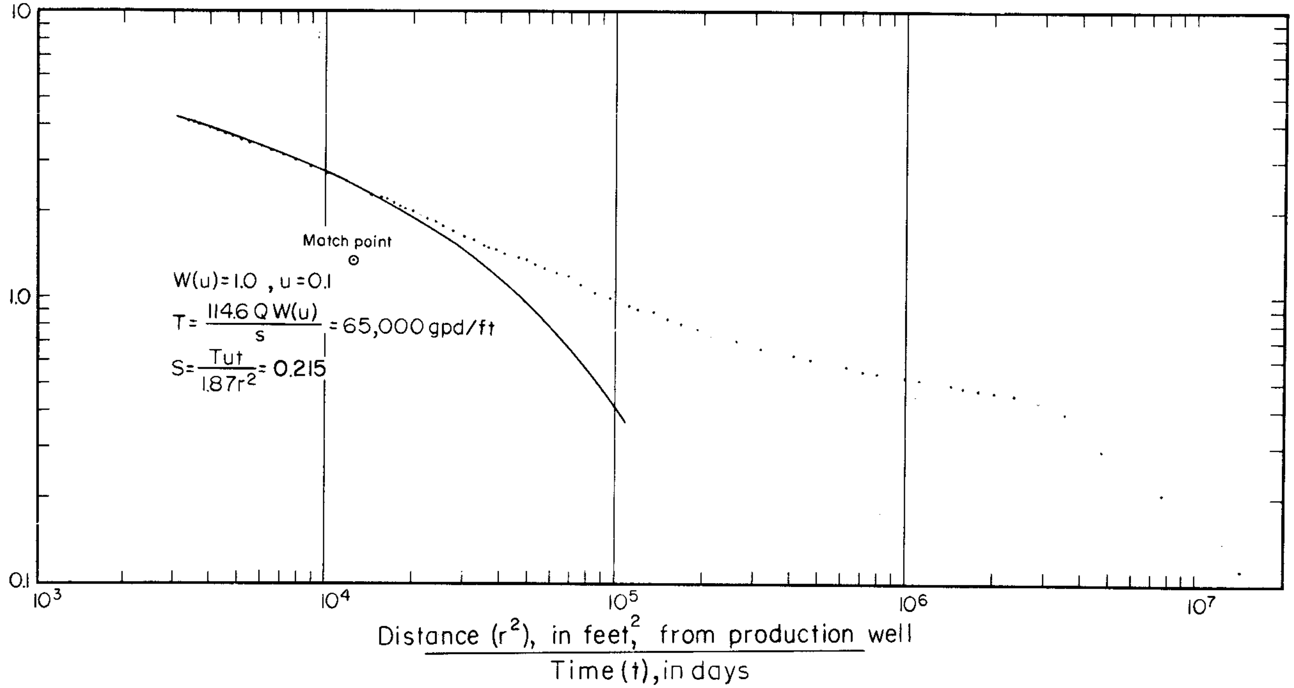


FIGURE 19. Logarithmic plot of time-drawdown data, observation well 1, Northwest Eddy aquifer test.

Applying the same method to observation well 1, with r = 100 feet distance from pumped well:

$$T' \cong \frac{Q}{s}K = \frac{766}{2.87} \times 311 = 83,000$$

$$T \cong 77,000 \text{ gpd per foot.}$$

Figure 19 is a logarithmic time-drawdown plot of data from observation well 1.

Drawdowns have been corrected by the method described above for the distance-drawdown method. Because of the effect of slow drainage under water-table conditions, emphasis should be placed on late time-drawdown data. Using this and the type curve, the calculated transmissibility is 65,000 gpd per foot, which checks closely with the Theis estimate method results, and the coefficient of storage is 0.22, which is in the usual range for water-table aquifers.

Jacob's method solutions for the pumped well and observation well 1 agree reasonably well with the Theis curve solution for observation well 1.

It is therefore concluded that the distance-drawdown solution is invalid, because the water levels in the more distant observation wells did not represent the conditions assumed for application of the Theis curve solution. From this it follows that data from observation wells 2, 3, and 4 are invalid for time-drawdown solutions.

Milton Lindvig (1964, written communication) calculated aquifer constants by the Theis recovery method (Ferris and others, 1962, p. 100-102), as well as by drawdown methods. The results agree reasonably well for the pumped well and observation well 1 with the results obtained by other methods. However, according to LaRocque (1966, written communication), the application of the recovery method to water-table conditions is questionable because of the unknown effects of:

1. Degree of drainage
2. Entrainment or entrapment of air
3. Changing aquifer thickness.

Table 5 lists the aquifer constants as calculated by time-drawdown and recovery methods for the pumped well and observation well.

*Storage.*--Using an area of 2.4 square miles, and assuming an average thickness of 25 feet and average porosity of 30 percent, the aquifer holds about 12,000 acre-feet of water in storage. Of this amount, using a specific yield of 0.24, about 9,000 acre-feet could be drained from the aquifer by gravity.

*Quality of water.*--Chemical analyses of the water sample from 150-65-22bdb, taken at the end of the aquifer test, is listed in table 3. The water had 274 ppm dissolved solids, and was calcium magnesium bicarbonate type. There was no significant change in water quality during the aquifer test (Trapp, 1966, table 4).

TABLE 5. Northwest Eddy aquifer test, summary of test results.

| Well | Method | Distance from pumped well (feet) | Coefficient of transmissibility (gpd per foot) | Average field coefficient of permeability (gpd per square foot) | Coefficient of storage |
|---|---|---|---|---|---|
| Observation | | | | | |
| well 1 | Theis curve | 100 | 65,000 | 1,900 | 0.22 |
| Do. | Jacob | 100 | 64,000 | 1,900 | .25 |
| Do. | Theis recovery | 100 | [a]/60,000 | 1,800 | .... |
| Pumped well | Jacob | ... | 78,000 | 2,300 | .... |
| Do. | Theis recovery | ... | [a]/68,000 | 2,000 | .... |
| Average of drawdown method results | | | 69,000 | 2,000 | .24 |
| Average of recovery method results | | | 65,000 | 1,900 | .... |
| Overall average | | | 67,000 | 2,000 | .24 |

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[a]/ M. O. Lindvig, written communication, 1964.

The analyzed constituents fell within the limits recommended by the U.S. Public Health Service for drinking water. The water was very hard. The irrigation classification of the water was C2-S1 (medium salinity, low sodium hazard).

### Central Eddy aquifer

Bluemle (1965, pl. 1) mapped an outwash plain about 150 square miles in area between the James and Sheyenne Rivers in west-central Eddy County and extending into northern Foster County. Test-hole data indicate that much of the central part of the outwash plain has a water-saturated thickness of 10 feet or more, and has a potential for large-scale use. At present, it supplies water only for domestic and stock purposes.

*Location and extent.*--The effective limits of the aquifer are defined arbitrarily by a minimum saturated thickness of 10 feet of surficial outwash. As interpreted in plate 4, the aquifer underlies about 16 square miles in central Eddy County. More intensive exploration probably would show parts of the area now included within the aquifer to have less than 10 feet of saturated outwash, and parts of the outwash outside the present boundary to have more than 10 feet of saturated thickness.

*Thickness and lithology.*--The maximum known thickness of the aquifer is about 28 feet in test hole 149-64-22ddd, and the aquifer is composed of fine to coarse sand with a small proportion of gravel, and a thin layer of till. In this test hole, the aquifer overlies 5 feet of till, which rests on Pierre Shale bedrock. In test hole 149-65-9bbb, the aquifer contains 11 feet of gravel overlain by about 6 feet of saturated sand. Throughout the area of the aquifer, overall saturated drift thickness remains fairly constant, but the relative proportions of surficial outwash and underlying till vary.

The Bureau of Reclamation made sieve analyses from samples taken in several test holes in the Central Eddy aquifer. The median grain size and sorting coefficient for each of these is listed in table 6.

The median grain size is the size such that 50 percent of the material is coarser and 50 percent is finer, by weight. The sorting coefficient is defined as:

$$So = \sqrt{Q3/Q1}$$

where:

$Q3$ = third quartile; the size such that 75 percent of the material is finer

$Q1$ = first quartile; the size such that 25 percent of the material is finer (Pettijohn, 1949, p. 23-24.

The smaller the sorting coefficient, which has a lower limit of 1, the more uniform the grain size of the sediment. Pettijohn (1949, p. 24) states that, while a sorting coefficient of 2.5 or lower has been considered to represent a well-sorted sediment, this value may be too high.

TABLE 6. Median grain-size and sorting coefficients of samples from the Central Eddy aquifer (derived from U.S. Bureau of Reclamation sieve analysis cumulative curves.

| Location | Depth (feet) | Median size (millimeters) | Sorting coefficient |
|---|---|---|---|
| 149-64-6ddd | 10-14 | 0.5 (medium sand) | 2 |
| Do. | 18-30 | .2 (fine sand) | 1.33 |
| Do. | 30-39 | .27 (fine sand) | 1.55 |
| Do. | 39-42.6 | .59 (medium sand) | 2.44 |
| 149-64-8ddd | 2-9.8 | .25 (fine sand) | .... |
| Do. | 9.8-21.1 | .37 (medium sand) | 1.52 |
| 149-64-18bbb | 10-15 | .43 (medium sand) | 1.86 |
| Do. | 15-21 | .44 (medium sand) | 1.7 |
| 149-64-21aaa | 5-10 | .43 (medium sand) | 1.81 |
| Do. | 10-17.8 | .47 (medium sand) | 1.78 |
| Do. | 17.2-21.7 | .33 (medium sand) | 1.67 |
| Do. | 21.7-29.2 | .44 (medium sand) | 2.55 |
| 149-64-27bbb | 9-15 | .36 (medium sand) | 1.55 |
| Do. | 15-27 | .55 (medium sand) | 1.8 |
| 149-65-10bbb | 8-9.5 | .16 (fine sand) | .... |
| Do. | 9.5-23.8 | .5 (medium sand) | 1.73 |
| 150-65-35bbb | 14-20 | .25 (fine sand) | 1.64 |

Grain size and sorting are two of the factors determining the permeability of a sedimentary aquifer. The coarser the grain size, and the lower the sorting coefficient, the more permeable the aquifer. Since most of the samples in table 6 are in the medium grain-size range, and are fairly well sorted, an average coefficient of permeability (at 60°F) of about 500 gpd per square foot seems reasonable (p. 62 this report). This indicates a transmissibility of about 11,000 gpd per foot in the thickest known part of the aquifer at 149-64-22ddd, and higher where the aquifer contains gravel.

*Storage.*--Using an area of 15 square miles, and assuming an average thickness of 20 feet and average porosity of 30 percent, the aquifer holds about 58,000 acre-feet of water in storage. Of this amount, assuming a specific yield of 0.24, about 46,000 acre-feet could be drained theoretically from the aquifer by gravity.

*Water-level fluctuations.*--A hydrograph (fig. 20) of an observation well (149-64-18bbb) in the Central Eddy aquifer shows that annual recoveries began in March in 1965 and 1966, but that less-frequent measurements in 1952 and 1953 suggest that recovery began later in the year. The annual low occurs just before the annual high. For most of the period of record, the annual variation is a little over 1 foot. The high for the period is 6.2 feet below land surface (June 14, 1951), and the low is 9.59 feet (May 21, 1964).

*Quality of water.*--Water in the Central Eddy aquifer is generally of calcium magnesium bicarbonate type. The analysis of a typical sample (from 149-64-19ddd) is given in table 3. Analyses of water from 149-64-8dcd, 149-65-1bba, and 149-65-29baa2 are given in part II of this report (Trapp, 1966, table 4). The dissolved solids concentrations of the samples ranged from 322 to 1,350 ppm. Two of the samples contained dissolved solids in excess of the limit recommended by the U.S. Public Health Service for drinking water, and one sample contained sulfate in excess of the recommended limit. The determined constituents in the other samples fell within the recommended limits.

Two of the samples were in the irrigation classification C2-S1 (medium salinity, low sodium hazard) and two were C3-S1 (high salinity, low sodium hazard).

### Warwick aquifer

Paulson and Akin (1964, p. 30-36) described the Warwick outwash deposits as extending from the North Viking moraine in Benson and Ramsey Counties, south to the Sheyenne River valley in Eddy and Nelson Counties.

*Location and extent.*--Although the Warwick outwash deposits extend to the Sheyenne River, the effects of thinning and the slope of the water table limit the Warwick aquifer (arbitrarily restricted to 10 feet or more of water-saturated outwash thickness) approximately to the north halves of T. 150 N., Rs. 62 and 63 W. in Eddy County. However, the thinner outwash to the south conveys discharge

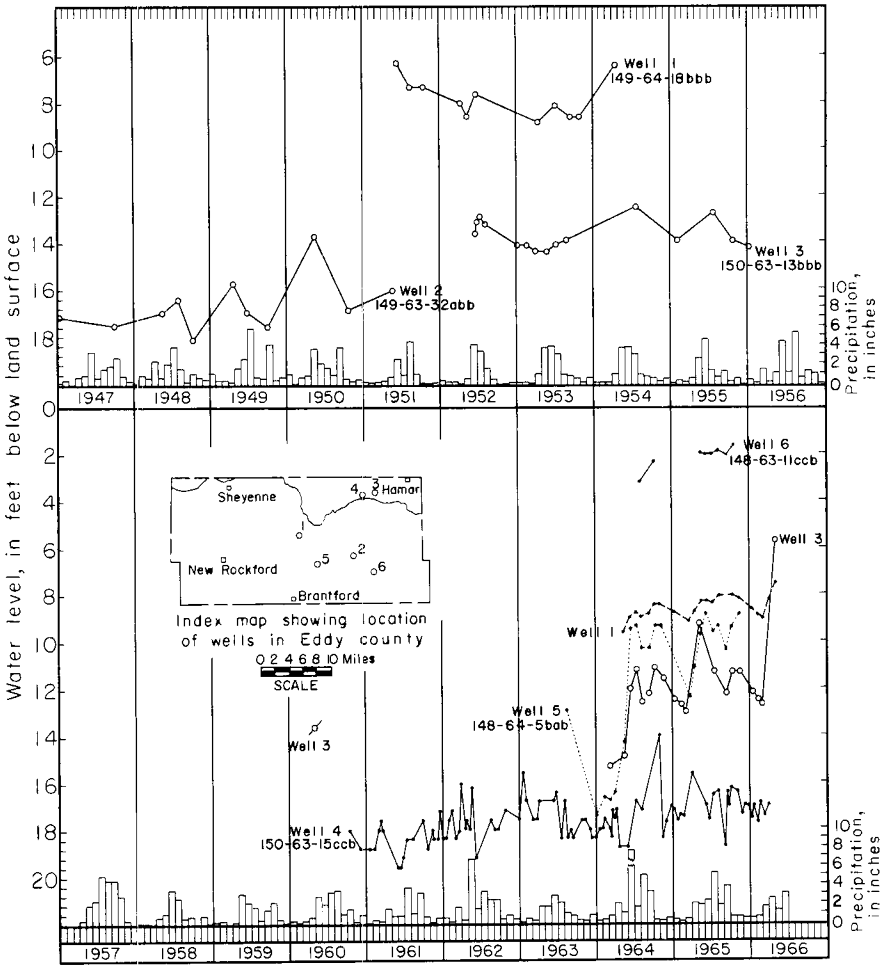

FIGURE 20. Hydrographs of observation wells in Eddy County.

to springs in the Sheyenne River bluffs.

As interpreted in plate 4, the aquifer underlies about 24 square miles in northeastern Eddy County.

*Thickness and lithology.*--In the vicinity of the Devils Lake municipal well field northwest of Warwick, in Benson Bounty, Paulson and Akin (1964, p. 34-36) reported a water-table aquifer and a lower, leaky-artesian aquifer separated locally by less-permeable silty and clayey layers. The lower aquifer supplies the Devils Lake wells. Both are considered within the Warwick outwash. Over most of its extent in Eddy County, the Warwick aquifer is a water-table aquifer. At Hamar, the surficial outwash is about 20 feet thick, and at test hole 150-62-22ddd it is only 10 feet thick, with most of this above the water table. Its maximum known thickness in Eddy County is 90 feet in test hole 150-63-10dda (Paulson and Akin, p. 63).

In the northeastern part of T. 150 N., R. 63 W., where it reaches its maximum known thickness in Eddy County, the aquifer consists largely of gravel. At 150-63-13bbb, the aquifer is sand and loamy sand. Farther east, near Hamar, it is predominantly sand. It evidently thins and becomes less permeable south and east of Hamar.

*Storage.*--Assuming an average porosity of 30 percent, and an average saturated thickness of 40 feet, the aquifer holds about 180,000 acre-feet of water in Eddy County. Assuming a specific yield of 0.24 (same as coefficient of storage determined in the Northwest Eddy aquifer test), about 140,000 acre-feet of water could be drained from the aquifer by gravity.

*Water-level fluctuations.*--Observation well 150-63-13bbb in the Warwick aquifer was measured from 1952 to 1956 and from 1964 to 1966, with one measurement in 1960 (fig. 20). The high-water level for the period of record was reached on May 10, 1966, when the water level was 5.61 feet below land surface. This high level is probably the result of the two wet years, 1964 and 1965, which raised water levels and increased soil moisture, combined with an unusually large amount of water for recharge from the heavy snow in the spring of 1966.

The lowest known water level was recorded in March 1964, when it was more than 15 feet below land surface. The previous year (1963) was unusually dry. The spread of almost 10 feet between high and low readings, with a difference of more than 7 feet between the high and low in the spring of 1966, indicates a low coefficient of storage. Since the observation well is near the southern limit of the aquifer, where it becomes finer grained, the range in water levels may not be typical of the main body of the aquifer.

Flow measurements of a spring (150-63-15ccb) in Sheyenne River alluvium south of the Warwick aquifer, when plotted on the same time base, roughly parallel water levels in 150-63-13bbb (fig. 20). The Warwick outwash is in contact with the alluvium and probably discharges through it into the river. The spring is flooded at high river stages, which probably nearly coincide with high discharge rates, so that the maximum measured flows probably are less than the true maximum discharge rates. Also, the stage of the river is likely to affect spring discharge.

*Quality of water.*--The water analysis from the Warwick aquifer listed in table 3 was selected from four analyses of Paulson and Akin (1964, p. 205). These analyses show that calcium bicarbonate type water is present in the Warwick aquifer in Eddy County. The water samples had dissolved solids concentrations of 118 and 357 ppm. The total hardness of the samples ranged from 85 to 280 ppm. The iron concentration was determined for one sample and was 2.2 ppm, which exceeds the upper limit of 0.3 ppm recommended by the U.S. Public Health Service. The irrigation classification of the water was C2-S1 (medium salinity, low sodium hazard).

### James River aquifer

*Location and extent.*--The James River aquifer comprises valley train outwash in the James River valley, its tributaries, and associated abandoned channels in south-central Foster County. On either side of the valley are end moraines (Grace City and Kensal), which limit the surficial aquifer on its east and west sides. However, the aquifer may be continuous with buried outwash in channels that carried melt waters from the Grace City and Kensal ice sheets before they reached their maximum extent. The aquifer probably extends southward into Stutsman County, where it may be covered by Arrowwood Lake. The northern extent of the aquifer is not known, but scattered subsurface control indicates a broad bedrock high to the north, which probably means a shallow valley fill.

As interpreted in plate 4, the aquifer covers about 6.5 square miles in Foster County.

*Storage.*--Assuming an average thickness of 50 feet, a porosity of 30 percent, and an area of about 6.5 square miles, as shown on plate 4, the aquifer would hold about 62,000 acre-feet of water.

*Thickness and lithology.*--The maximum known thickness of the aquifer is the 78 feet penetrated in 145-64-22da. The upper part of the aquifer at this site consists predominantely of sand, the lower part of gravel, separated from bedrock by 3 feet of till. The upper part of the aquifer includes 7 feet of clay, which indicates that the outwash channel was ponded for a time during deposition. In a melt-water channel at 145-64-21dba, the aquifer consists of 27 feet of gravel, separated from bedrock by 5 feet of till.

*Water-level fluctuations.*--Hydrographs of 145-64-22da and 145-64-21dba parallel each other fairly closely (fig. 21). However, 145-64-22da, in the main valley of the James River, has a greater range of fluctuation that does 145-64-

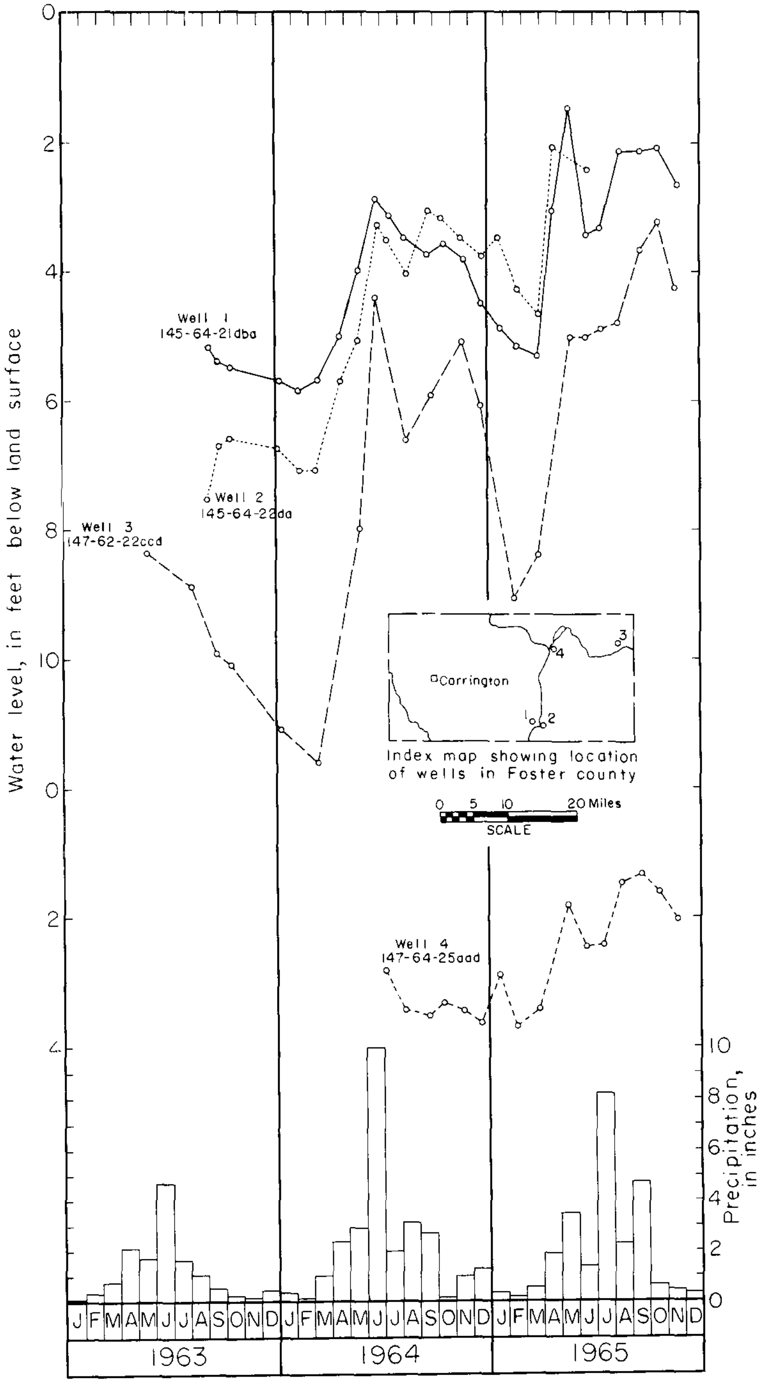

FIGURE 21. Hydrographs of observation wells in central and eastern Foster County.

21dba. The highest water level measured in 145-64-22da was 2.08 feet below land surface (April 22, 1965), and the lowest was 7.53 feet (September 5, 1963), as compared to a high of 1.44 feet below land surface (May 18, 1965), and a low of 5.84 (February 13, 1964) in 145-64-21dba.

One possible explanation for the greater range of fluctuation in 145-64-22da is that it is more directly affected by changes in stage of the James River. The well was drilled within 400 feet of the river. Another possible explanation for the greater range in fluctuation is that the storage coefficient in the aquifer at 145-64-22da is lower than at 145-64-21dba. At the first location, the aquifer, although thicker, has a lower gravel-to-sand ratio than at the latter. The coarseness of the sediment may control the range of water-level fluctuations at various points within the aquifer.

*Quality of water.*--The analysis of a sample of water from 145-64-21dba is listed in table 3. It contained 500 ppm total solids and was a sodium magnesium bicarbonate type water. The constituents fell within the limits recommended by the U.S. Public Health Service for drinking water, except for iron. The water was very hard.

The irrigation classification was C2-S1 (medium salinity, low sodium hazard). The boron content of 1.65 ppm may damage sensitive crops.

### Juanita Lake aquifer

Lemke (1960, pl. 15) showed that the Heimdal diversion channel follows the present course of the James River from Eddy County southwest to near Grace City, where it jogs north in the Juanita Lake depression and then follows the present course of Bald Hill Creek. Bluemle (1965, p. 33, pl. 1) mapped an outwash channel partly occupied by Juanita Lake and described it as a "deep channel which formerly carried melt water from the nearby glacier" (Grace City phase). Test hole 147-64-25add, Foster County, penetrated two bodies of outwash separated by 15 feet of clay and till. The two outwash bodies are assumed to be a single aquifer, which is named the Juanita Lake aquifer.

The Juanita Lake aquifer supplies water for local domestic and livestock requirements. It probably is connected hydrologically to the James River and Juanita Lake.

*Location and extent.*--The aquifer is assumed to coincide approximately with the outwash deposits in the channel partly occupied by Juanita Lake, although the effective aquifer (10 feet or more water-saturated thickness) is probably of somewhat smaller area. As interpreted in plate 4, the aquifer underlies about 5 square miles.

*Thickness and lithology.*--The upper outwash, as penetrated in 147-64-25add, consists of 27 feet of sand and gravel, of which 17 feet are water-saturated.

The lower outwash consists of 14 feet of medium sand and 11 feet of gravel with some very coarse sand.

*Storage.*--Assuming that the aquifer has an average effective thickness of 40 feet, an average porosity of 30 percent, and an area of 5 square miles, it would hold about 38,000 acre-feet of water.

*Water-level fluctuations.*--Water levels in 147-64-25add (fig. 21) varied between 1.36 (September 20, 1965) and 3.73 feet (February 18, 1965) below land surface during the period of record (July 10, 1964 to November 23, 1965). The period of record was unusually wet; lower levels could be expected in drier years.

*Quality of water.*--A water sample from 147-64-25add contained 548 ppm dissolved solids and was calcium sodium bicarbonate type (table 3). Its analyzed constituents fell within the limits recommended by the U.S. Public Health Service for drinking water, except for the dissolved solids concentration which was slightly above the limit. The water was very hard. The irrigation classification of the water was C2-S1 (medium salinity, low sodium hazard).

### Pipestem Creek aquifer

The Pipestem Creek aquifer consists of water-saturated outwash in the valleys of Pipestem Creek and Little Pipestem Creek. Bluemle (1965, p. 30) described Pipestem Creek as occupying a former melt-water channel, with a valley bottom covered with alluvium.

The Pipestem Creek aquifer supplies local domestic and stock needs.

*Location and extent.*--Test hole 145-67-16ccb penetrated the aquifer in the valley of Little Pipestem Creek. Five miles northwest of the confluence of Pipestem and Little Pipestem Creeks, well inventory data show that only thin drift covers bedrock in the Pipestem Creek valley. To the east, test hole 145-67-23baa struck Pierre Shale bedrock at 13 feet. Accordingly, the aquifer boundaries in plate 4 were drawn to coincide approximately to the mapped surficial outwash in Little Pipestem Creek valley and the alluvium-covered valley of Pipestem Creek below the confluence of the Little Pipestem. Test holes in Wells County indicate that the aquifer extends along Little Pipestem Creek about 15 miles west of the Foster-Wells county line to Heaton (F. Buturla, oral communication). The aquifer may extend into Stutsman County to the south, but a test hole in the Pipestem Creek valley at 143-66-4aaa, Stutsman County, penetrated 51 feet of alluvium and glacial drift, of which only 15 feet was sand and gravel (Huxel and Petri, 1963, table 2).

As interpreted in plate 4, the Pipestem Creek aquifer underlies about 9 square miles in Foster County.

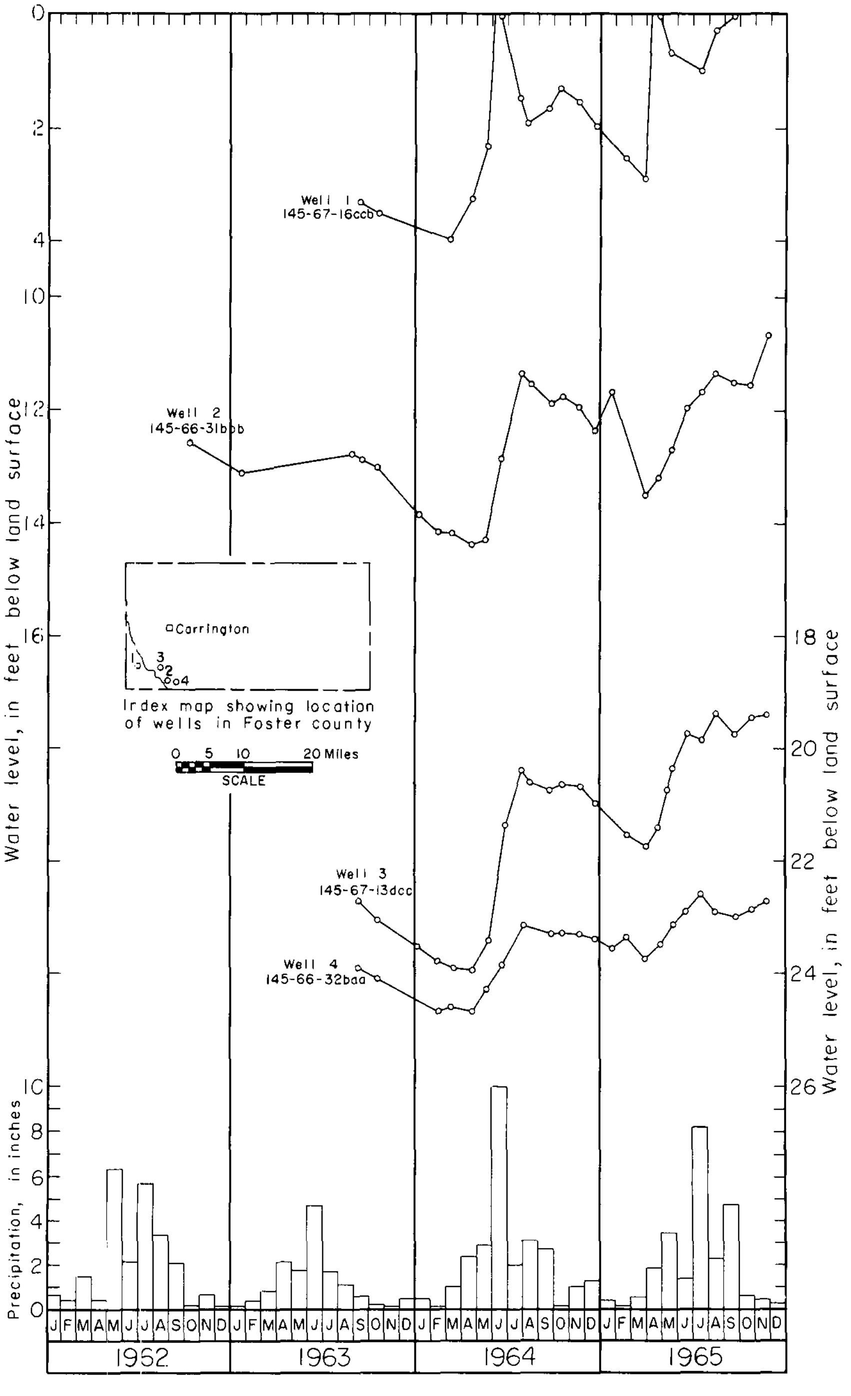

FIGURE 22. Hydrographs of observation wells in southwestern Foster County.

*Thickness and lithology.*--In test hole 145-67-16ccb, the aquifer comprises 21 feet of medium to coarse sand with gravel, which is underlain by till and overlain by 18 feet of sand and silt. At 145-68-12add, in Wells County, 31 feet of medium to very coarse sand with gravel was penetrated, of which about 21 feet is water saturated (F. Buturla, oral communication).

*Storage.*--Using an average aquifer thickness of 21 feet, and an average porosity of 30 percent, the aquifer should hold about 36,000 acre-feet of water in Foster County.

*Water-level fluctuations.*--Between 1963 and 1965, the water level (fig. 22, well 145-67-16ccb) varied from land surface or above (flooded) to 4 feet below land surface. Since the well is in a low spot subject to flooding, the water levels may not be generally representative of the aquifer. Seasonal high and low points in the well hydrograph appear about a month earlier than in other observation wells in the area that are not in the valley bottom. A possible explanation for this is that the aquifer is hydrologically connected to Pipestem and Little Pipestem Creeks, and that water levels in the creeks respond more promptly to precipitation and snowmelt than do most aquifers.

*Quality of water.*--A sample of water from 145-67-16ccb had a dissolved solids concentration of 996 ppm, and was magnesium sulfate type. Dissolved solids, sulfate, and iron concentrations exceeded the limits recommended for drinking water by the U.S. Public Health Service. The water was very hard. In comparison, three water samples from Pipestem Creek in 1964 (U.S. Geol. Survey, 1964, p. 71) had dissolved solids concentrations ranging from 155 ppm, at a discharge rate of 35 cfs (cubic feet per second), to 781 ppm at 5.8 cfs. This water contained more sodium, calcium, and bicarbonate, relative to its concentration, than the Pipestem Creek aquifer water from 145-67-16ccb. Residence in the aquifer either modifies recharge coming from the creek , or this recharge is mixed with recharge from glacial till. A change in water quality might occur if the aquifer were pumped long enough to induce additional recharge from the creek.

The irrigation classification of the Pipestem Creek aquifer water was C3-S1 (high salinity, low sodium). The boron concentration of 0.15 ppm was too low to injure crops.

### Sheyenne Village aquifer

Sayre (1935, p. 118, 127) first investigated the aquifer at Sheyenne, with emphasis on water levels. Froelich (1964) delineated the aquifer through detailed test drilling. He described it as a terrace of the Sheyenne River, composed of sand and gravel, and overlying an undulating surface of Pierre Shale (eastern part of Sheyenne) and till (western part).

Bluemle (1965, p. 61-62, pls. 3-4) also mapped and described the Sheyenne River terraces. The terrace deposits that contain the Sheyenne Village aquifer coincide with the Gates fill-terrace deposits underlying Sheyenne west of Warsing Reservoir. The Gates fill-terrace of Bluemle corresponds to terrace 2 of Froelich (fig. 3).

The aquifer receives recharge directly from precipitation, and also probably from the adjoining and underlying till and Pierre Shale. Its natural discharge is through springs issuing at the contact between the terrace deposits and underlying Pierre Shale and till in the exposed terrace face in the south bluffs of the Sheyenne River and west bank of the tributary containing Warsing Reservoir.

*Location and extent.*--The aquifer underlies about 370 acres in secs. 4, 5, 8, and 9, T. 150 N., R. 66 W. It is bounded on the north by the intersection of the water table with the base of the terrace deposit near the Sheyenne River bluffs; on the east by the tributary containing Warsing Reservoir (since the tributary has cut through the terrace); and on the south and west by the limits of the water-saturated terrace deposits.

*Thickness and lithology.*--The Sheyenne Village aquifer consists of fine to coarse sand with gravel. The saturated thickness averages about 9 feet, with a maximum of about 31 feet of 150-66-8baa1 (Froelich, 1964, tables 3-4). Froelich (p. 18-19 emphasized the importance of minor depressions in the surface of the Pierre Shale and till underlying the aquifer in controlling the saturated thickness.

*Storage.*--Assuming an area of 370 acres, an average saturated thickness of 9 feet, and a porosity of 30 percent, the aquifer should hold about 1,000 acre-feet of water.

*Water-level fluctuations.*--Because of the dependence by the village of Sheyenne on the aquifer as a source of water, its water-level fluctuations are of greater importance than its size and water-bearing potential would indicate. Sayre (1935, p. 127) established 9 observation wells, and measurements on 4 were continued into the 1950's. Also, the Bureau of Reclamation had observation wells in connection with the experimental irrigation farm at the west edge of the village (Trapp, 1966, table 2).

Hydrographs of three wells in the Sheyenne Village aquifer, for the period 1935 through 1966, are shown in figure 23. The precipitation record shown on the hydrograph through 1964 is from Maddock Agricultural School, about 21 miles northwest of Sheyenne. For 1965 and 1966, measurements at Sheyenne were available, except that there was no record for March 1966, and the Maddock reading was used.

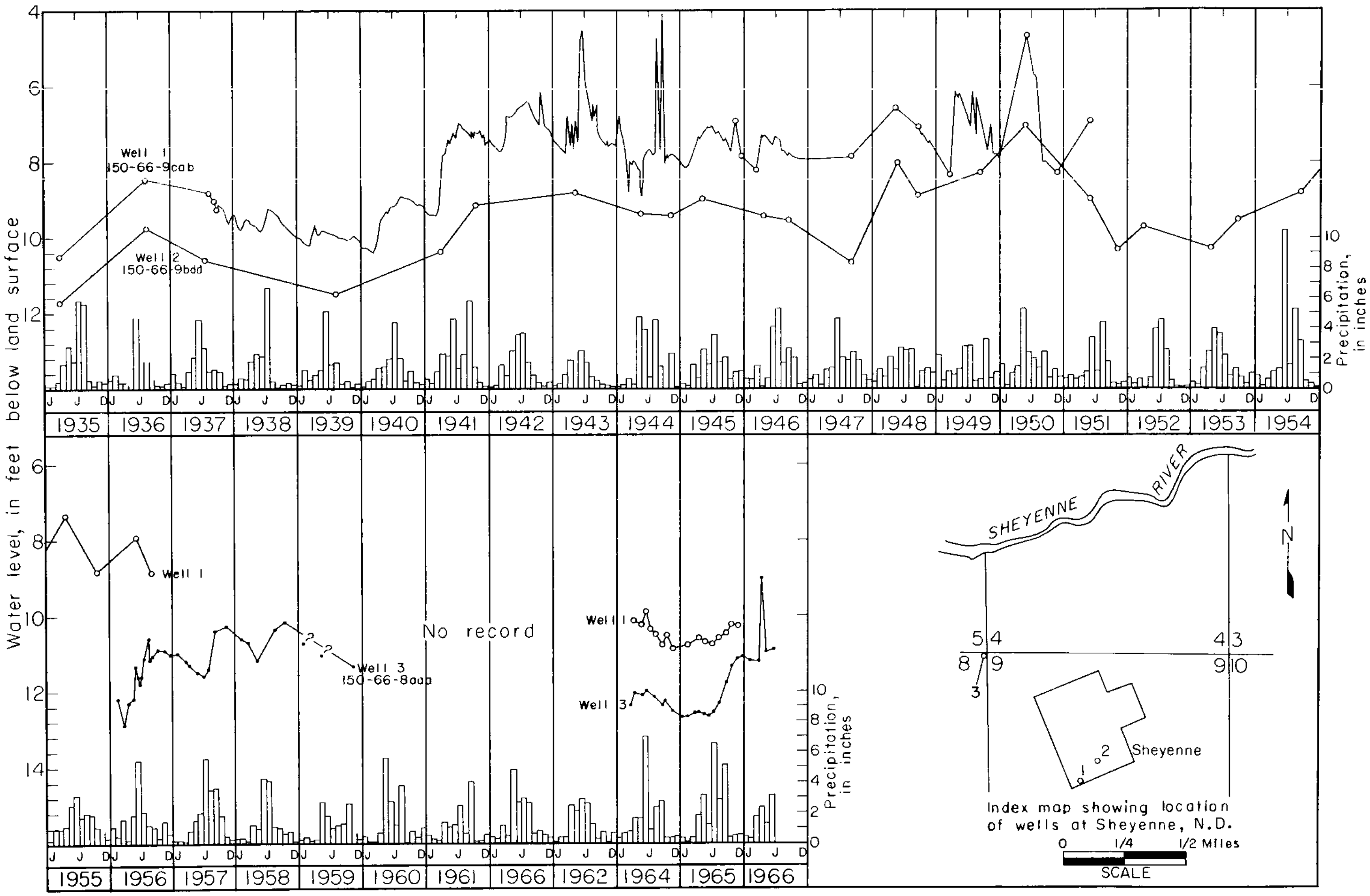

FIGURE 23. Hydrographs of observation wells in the Sheyenne Village aquifer.

From 1935 to 1951, the hydrographs of two wells are given: 150-66-9cab2 and 150-66-9bdd (Trapp, 1966, table 2). Well 150-66-9cab2 was later destroyed. Its record includes weekly measurements of water levels. The water levels in well 150-66-98bdd were measured only once or twice a year until 1956; monthly measurements were made in 1964 and 1965 as part of the Eddy-Foster study. The U.S. Bureau of Reclamation measured the water levels for well 150-66-8aaa from 1956 to 1959. From 1964, a monthly record of the water levels in this well was obtained as part of this project.

The beginning of the record, 1935, shows water levels just after the worst years of the 1930's drought. The water level in 150-66-9bdd was almost 12 feet below land surface. From 1941 to 1956, however, water levels usually were less than 10 feet below surface. During this period Sheyenne had no public water supply; however, private wells withdrew water from the aquifer.

Water-level measurements were made on 150-66-8aaa from 1956-1959 in connection with the Bureau of Reclamation's irrigation experiment farm. Water for irrigation was pumped from the Sheyenne River. The hydrograph indicates that some of this water percolated through the soil and recharged the aquifer. The water level in 150-66-8aaa was about 11 feet below land surface during this period.

In 1959, a public water supply was installed in Sheyenne, using a former railroad well constructed in the Sheyenne Village aquifer, as a source of supply. A sewage lagoon was installed about a quarter of a mile east of the village, beyond the limits of the aquifer. The water supply was evidently adequate at this time despite probable increased withdrawals. Irrigation operations were discontinued after the 1961 season.

No water-level measurements are available for 1960 through 1963. In the latter part of 1963, however, the water level in the village well dropped below the base of the aquifer, resulting in a severe water shortage. The village installed collecting galleries at the well and began artificial recharge of the aquifer by pumping river water to an infiltration pond near the well. The water level in the well rose to an adequate level. In spite of this artificial recharge and increased precipitation throughout most of 1964, the water level in observation well 150-66-8aaa remained more than 12 feet below land surface throughout most of 1964. Through 1964 and 1965, despite high precipitation, recorded water levels in 150-66-9bdd did not rise above 9.90 feet below surface, a level that had been exceeded in 16 out of 22 years of record.

The evidence, although incomplete, suggests that water levels in the Sheyenne aquifer now tend to be lower, for a given amount of precipitation, than they were in the early part of the period of record. This may be explained by increased withdrawals and decreased recharge. Sheyenne's population has not changed much--the 1930 census listed 417 and the 1960 census 423 inhabitants --but the installation of a modern public supply system and the resulting availability of running water probably caused greatly increased consumption. The concentration of withdrawals in one large well rather than spread out in many private wells must have caused a steeper cone of depression. The discontinuance of pumpage of river water for irrigation on land overlying the aquifer, and, to a lesser extent, the removal of waste to the sewage lagoon, reduced recharge.

*Quality of water.*--A sample of untreated water from the Sheyenne village well had a dissolved solids concentration 597 ppm and was sodium bicarbonate type (table 3). Dissolved solids and iron concentrations exceeded the limits recommended by the U. S. Public Health Service for drinking water and the water was very hard.

The irrigation classification of the water was C3-S1 (high salinity, low sodium hazard).

### Tokio aquifer

Paulson and Akin (1964, p. 28-30, figs. 3,7) showed the Tokio outwash as extending south and eastward from the North Viking end moraine, and southwestward from the Heimdal end moraine in Benson County to the Sheyenne River valley. They reported that the outwash served as an aquifer, supplying rural domestic and stock needs, and that its potential for more intensive development of ground-water supplies appeared to be less than that of the Warwick aquifer to the east.

Bluemle (1965, p. 45, pl. 1) mapped the part of the Tokio outwash in Eddy County as pitted outwash in front of the largely collapsed McHenry end moraine. He included some surficial sand and gravel, described as Tokio outwash by Paulson and Akin, as part of the collapsed end moraine.

For purposes of this report, the Tokio aquifer is defined as the water-saturated part of the surficial sand and gravel penetrated in test hole 150-64-5aaa (Paulson and Akin, 1964, table 1), and those sand and gravel deposits continuous with it that are capable of yielding substantial quantities of water, whether mapped as outwash or end moraine.

*Location and extent.*--The Tokio aquifer in Eddy County underlies about 1 square mile in T. 150 N., R. 64 W.

*Thickness and lithology.*--Test hole 150-64-5aaa penetrated 28 feet of fine to coarse sand mixed with gravel, which is coarser with depth. About 20 feet of this sand and gravel may be water saturated.

*Storage.*--Assuming an area of about 1 square mile, an average porosity of 30 percent, and an average thickness of 20 feet, the Tokio aquifer contains about 3,800 acre-feet of water in storage in Eddy County.

## Oberon aquifer

Paulson and Akin (1964, p. 26-28, fig. 3) showed the Oberon outwash as extending southward from the North Viking moraine in Benson County to the Sheyenne River valley, and covering a small area in northwestern Eddy County. They reported that the outwash served as an aquifer, supplying water for domestic and stock needs, but, judging from the lithology and thickness of the outwash, it was doubtful whether large-capacity wells could be developed in it.

Bluemle (1965, pl. 1) mapped drift corresponding to the Oberon outwash as pitted outwash.

The aquifer is not important in Eddy County because of its small areal extent and probable thinness.

*Location and extent.*--As interpreted in plate 4, the Oberon aquifer underlies about 200 acres in sec. 3, T. 150 N., R. 67 W.; however, parts of the outwash in secs 2, 4, 5, and 6 may also have sufficient saturated thickness to be included in the aquifer.

*Thickness and lithology.*--The aquifer's thickness in Eddy County is unknown, but about 7 miles north, immediately in front of the Viking moraine, test holes penetrated 10 to 40 feet of surficial outwash averaging about 24 feet (Aronow and others, 1953, p. 100-101). The saturated thickness may be about 12 feet. The outwash probably thins southward from the end moraine, and the water table slopes southward toward the river; these effects limit the southern extent of the aquifer.

Paulson and Akin (1964, p. 27) described the Oberon outwash as somewhat clayey sand and gravel. Aronow and others (1953, p. 100 - 101) described it as sand, medium to coarse, and gravel, medium to coarse. The grain size probably decreases southward to Eddy County.

## Cherry Lake aquifer

Bluemle (1965, pl. 1) showed that Cherry Lake (148-63-11) is in a surficial outwash channel. Test hole 148-63-11ccb penetrated two layers of outwash separated by 14 feet of till. It is assumed that the two layers of outwash are interconnected and form one aquifer, but further drilling would be required to prove this.

*Location and extent.*--The aquifer is not yet well defined. As interpreted in plate 4, it underlies about 3 square miles in Tps. 148 and 149 N., R. 63 W. This area is less than the mapped extent of the surficial outwash.

*Thickness and lithology.*--Test hole 148-63-11ccb penetrated 7 feet of surficial outwash, 14 feet of till and 25 feet of coarse to very coarse sand overlying 24 feet of till. Approximately 5 feet of the surficial sand and gravel is saturated.

*Storage.*--Assuming an average thickness of 30 feet and an average porosity of 30 percent, the aquifer should hold about 17,000 acre-feet of water in storage.

*Water-level fluctuations.*--Water levels in observation well 148-63-11ccb varied from 3.08 feet below land surface on August 10, 1964, to a high point (questionable--ice in casing) of 1.30 on December 21, 1964 (fig. 20). The well freezes in winter. The water level was rising in the fall of 1965.

Rainfall in both 1964 and 1965 was above average and continued above average into September 1965. Considering the unusual conditions, the record is too short to show that the water level in the aquifer rises each winter, but ground water probably moves toward Cherry Lake from the surrounding area with a resulting rise in water levels possibly continuing into early winter.

*Quality of water.*--A water sample from 148-63-11ccb had a dissolved solids concentration of 419 ppm, and was calcium bicarbonate type (table 3). Concentrations of the dissolved constituents fell within the limits recommended by the U.S. Public Health Service for drinking water. The water would be classed as very hard, but it was softer than many North Dakota ground waters.

The irrigation classification of the water was C2-S1 (medium salinity, low sodium hazard).

### Russell Lake aquifer

Bluemle (1965, p. 27, pl. 1) mapped and described an esker running southeast from sec. 13, T. 145 N., R. 67 W., Foster County, into Stutsman County. Two test holes at 145-66-32baa and 145-67-13dcc penetrated saturated sand and gravel overlain by till.

Several rural homes obtain water from wells constructed in the esker deposits.

*Location and extent.*--The Russell Lake aquifer is interpreted as being coextensive with the esker mapped by Bluemle. Inventory and test-hole data indicate a thin glacial drift cover and low well yields within a short distance on either side of the esker. According to the present interpretation, the aquifer underlies about 3 square miles in Foster County and extends into Stutsman County.

*Thickness and lithology.*--Test hole 145-66-32baa penetrated 23 feet of sand, of which about 9 feet is water-saturated, underlain by 40 feet of gravel. Test hole 145-67-13dcc penetrated 63 feet of sand and gravel, of which about 48 feet is water saturated.

*Storage.*--Assuming an area of 3 square miles, an average thickness of 48 feet, and an average porosity of 30 percent, the aquifer should hold about 28,000 acre-feet of water in Foster County.

*Water-level fluctuations.*--Hydrographs of observation wells 145-66-32baa and 145-67-13dcc show a similar pattern from 1963 to 1965, but with greater water-level fluctuations in 145-67-13dcc (fig. 22). The greater range in water levels may indicate a lower storage coefficient in the aquifer around this well. The record high water level for 145-67-13dcc is 19.38 feet below land surface on August 13, 1965, and the low is 23.93 feet on April 22, 1964. The record high for 145-66-32baa is 22.57 feet below land surface on July 14, 1965; the low is 24.64 feet on April 22, 1964.

The well hydrographs may be compared with the hydrographs of other observation wells in the project area and to precipitation at Carrington. High water levels in the aquifer occurred 1 or 2 months after high levels in well 145-67-16ccb in the Pipestem Creek aquifer, and lagged periods of high precipitation. Although the esker is a surface feature, and the water level stands below its top, the water levels behave more like the levels in buried aquifers than in surficial aquifers. The explanation seems to be that the Russell Lake aquifer does not receive most of its recharge in the form of precipitation falling directly on the esker, much of which must run off, nor from the adjacent till, which is thin, has low permeability, and contains water with high concentrations of dissolved solids. Instead, the aquifer probably receives recharge from Russell Lake and from ephemeral ponds along the sides of the esker. The esker has a covering of till, which may retard recharge sufficiently to explain the lagging response of the water level to precipitation.

*Quality of water.*--A water sample from 145-66-32baa had a dissolved solids concentration of 654 ppm and was sodium calcium bicarbonate type (table 3). The dissolved solids and iron concentrations exceeded the limits recommended for drinking water by the U.S. Public Health Service (1962a, p. 7-8). The water would be classed as very hard, but it was softer than many North Dakota ground waters.

The irrigation classification of the water was C3-S1 (high salinity, low sodium hazard). The boron concentration for the sample from well 145-66-32baa was 1.00 ppm.

## Glacial till

The greater part of Eddy and Foster Counties is covered by glacial till. Many rural domestic and stock wells yield water from the till. These wells are generally shallow, and their yields are generally less then 10 gpm. Although the till probably comprises many aquifers, to subdivide it would be beyond the scope of the present report.

*Location and extent.*--The glacial till extends throughout all of Eddy and Foster Counties, except where:

1. The Pierre Shale bedrock outcrops or is above the water table. These

areas are the areas of zero saturated drift thickness (pl. 2).

2. Water-saturated till is present, but is so low in permeability that it does not yield useful quantities of water to wells. Some of the areas shown on plate 3 as having transmissibilities of less than 1,000 gpd per foot in the glacial drift fall in this category. Glacial till may be locally absent in areas of high transmissibility (pl. 4). In these areas, outwash may be present with little or no till.

*Thickness and lithology.*--The maximum known water-saturated thickness of till in Eddy and Foster Counties is about 282 feet (146-63-10bbb), which included several thin layers of sand and gravel. The test hole was drilled near the axis of the New Rockford channel, at a site where the New Rockford aquifer is thin or absent (pl. 5).

Glacial till consists of clay, silt, sand, gravel, and boulders, mixed in varying proportions. Locally, till may contain stringers and pockets of sand and gravel that are too small or ill-defined to map separately as outwash or ice-contact deposits. Some of these will yield ground water. Till also may have a high proportion of disseminated sand or gravel, and thus may have sufficient transmissibility as a unit to yield moderate amounts of water.

The till may be jointed or fractured. The joints or fractures may be water bearing, and if a well intersects one or more of these, it may yield an adequate supply of water although other wells nearby are inadequate. Ordinarily, water-bearing fractures may be expected to be less numerous at depth, so that shallow wells are most likely to derive water from them.

*Water supplies from glacial till.*--Because of incomplete records, it usually is not known whether a well is getting water from sand and gravel stringers within the till, from sandy or gravelly till, from fractures and joints, or from unmapped buried outwash. Also, because of the variability of the till, favorable conditions usually cannot be predicted when constructing a well in the till. Test-drilling data are likely to be significant only for the test site. Rotary test drilling is likely to pass up fractured till or till containing a high proportion of disseminated sand. Hand-dug or bored holes often may not penetrate far enough below the water table to assure a supply in dry years.

*Water-level fluctuations.*--Because the till varies from place to place in its lithology, thickness, and position relative to areas of recharge and discharge, water levels in till wells in various parts of the area differ considerably in the range of fluctuations (figs. 7, 146-67-19aba; 14, 147-67-25ddd; 21, 147-62-22ccd; and 22, 145-66-31bbb).

The maximum and minimum ranges of water levels observed during the period of record were 8.38 feet for 147-67-22ccd and 3.42 feet for 147-67-25ddd. In general, the wells have large fluctuations because of the low coefficient of storage of the till.

During 1964, the water level in one well (146-67-19aba) declined to the annual low in February-March, two (147-67-25ddd and 147-62-22ccd) in March, and one (145-66-31bbb) in April. Two (146-67-19aba and 147-62-22ccd) reached highs in June and one (147-67-25ddd) in December.

During 1965, the water level in well 147-62-22ccd declined to an annual low in February, 145-66-31bbb and 146-67-19aba in March, and 147-67-25ddd in April. The annual high was in September for well 146-67-19aba, in October for 147-62-22ccd, in November for 145-66-31bbb, and in December for 147-67-25ddd.

Of the four wells, 147-62-22ccd and 146-67-19aba are most typical of shallow water-table wells in glacial drift. They show wide annual ranges in water levels, with lows occurring just before the ground thaws and highs (in 1964) in late spring before evapotranspiration demands reach their peak. In 1965, water levels kept rising into the fall because of the cool, rainy late summer-early fall weather, which combined reduced evapotranspiration with increased precipitation.

The water levels in 147-67-25ddd are affected by changes in artesian head in the underlying Carrington aquifer, which recovers in late fall and early winter from pumping during the preceding irrigation season at the nearby Carrington Irrigation Branch Station. The water-level fluctuations in 145-66-31bbb are similar to those in the Russell Lake aquifer wells, 145-67-13dcc and 145-66-32baa. The hydrographs of these wells show a delayed response to precipitation. The till in the vicinity of well 145-66-31bbb evidently is hydrologically connected to the Russell Lake aquifer, or both have a common source of recharge.

*Quality of water.*--Wells in glacial till in Eddy and Foster Counties yield water with a wide range in quality, illustrated by two examples (148-65-35bbd and 150-67-21cab1) in table 3. The former sample had a dissolved-solids concentration of 1,060 ppm and was magnesium calcium sulfate type; the second had 5,200 ppm dissolved solids and was magnesium sodium sulfate type.

Dissolved solids concentrations in most of the samples from glacial till wells in Eddy and Foster Counties were higher than in most samples of water from outwash wells. They generally exceeded the limit of 500 ppm recommended by the U.S. Public Health Service (1962a, p. 7-8) for drinking water, and most would be classed as slightly saline (Robinove and others, 1958, p. 3). Concentrations of sulfate and iron also commonly exceeded the recommended limits for drinking water, and all the samples were very hard. Four samples contained excessive nitrate concentrations (Trapp, 1966, table 4). Local residents frequently describe till waters as having an "alkali" taste. The examination of analyses suggests that the reported taste is often associated with high concentrations of dissolved solids and sulfate.

The mineral content of the till waters probably depends largely on the time of residence of the water in the till. The time of residence depends on the permeability of the till, depth, and hydraulic gradient. Poorly drained areas with high concentrations of salts in the soil are likely to have highly mineralized ground water at shallow depths. The presence of nitrate in water cannot always be explained, but it often appears in shallow ground waters subject to contamination by animal waste.

The irrigation classification of glacial till waters varies from place to place. The classification of the samples collected for this study ranged from C3-S1 (high salinity, low sodium hazard) to such high salinity that the sodium hazard classification could not be determined. Irrigation with water from the glacial till is not usually practical, except for small-scale lawn and garden watering, because of the low yields of till wells.

# UTILIZATION OF GROUND WATER

The population of Eddy and Foster Counties is almost entirely dependent on ground water for domestic and stock needs. The three municipalities that have public water systems all use wells for their sources of supply. Most farms have wells for domestic use; springs also are used, particularly for stock watering, where available. Ground water is used to irrigate about 900 acres in the western portion of the area. Irrigation on a larger scale, using surface water, may be expected upon completion of the Garrison Diversion Unit.

## Domestic and stock use

Most wells supplying domestic and stock needs in Foster County are 4 to 6 inches in diameter, and 50 to 250 feet deep. Most of these were drilled by cable tool rigs, but hydraulic-rotary rigs are also used. The percentage of drilled wells has increased in recent years, although wells also are being dug, bored, or driven.

In Eddy County, dug wells outnumber drilled wells, and driven wells are numerous. The explanation for this is that adequate shallow water supplies are more widespread than in Foster County due to a greater area of surficial outwash.

Dug wells may be satisfactory where an adequate supply of water can be obtained near the surface, but they have certain disadvantages. Wells cannot be dug by hand very far below the water table; consequently, if the water table is lowered substantially, the wells must be deepened or they will go dry. Because they penetrate only a few feet of the upper part of the aquifer, they commonly have low yields. Dug wells tap shallow aquifers, which are often subject to surface sources of contamination. Furthermore, it is difficult to seal a dug well properly and still provide access for repairs. Because of low yields, possible contamination, and a shortage of labor willing and able to work on dug wells, drilled wells have been replacing dug wells for domestic supplies wherever deeper aquifers yield water of satisfactory quality.

Bored wells are similar to dug wells, except that they may penetrate farther below the water table, and would then be less likely to go dry when the water table falls. A typical boring machine, as used in this area, has a cylindrical bucket with cutting blades at the bottom on the end of a rotating shaft. It can bore wells as large as 36 inches in diameter and as deep as 100 feet. In past years, some wells were constructed in Eddy and Foster Counties with boring machines powered by horses. Boring is most satisfactory where the material does not contain too many boulders. Contamination problems with bored wells are similar to those associated with dug wells.

In surficial outwash aquifers, driven wells are the cheapest to construct and are satisfactory sources of domestic and stock supplies. These wells are often installed by the landowner. Frequently, several are used around a farmstead, since it is easier to drive a well wherever water is needed than to pipe it from a central source. Driven wells are usually 10 to 20 feet deep. If driven far enough below the water table, they are not likely to go dry. Although they may be sealed against contamination more readily than dug wells, the highly permeable surficial aquifers in which they are constructed may carry contamination to them. Therefore, special care should be taken to locate driven wells used for domestic supply away from septic tanks and barnyards, and to test the water periodically for the presence of coliform bacteria and nitrates.

Persons wishing to install or improve water systems for domestic and stock use may consult with their county agricultural agent for advice on proper construction methods, disinfection, and chemical and biological testing of the water. In addition to the booklets published by the State that are available through county agents, a useful manual for individual water-supply systems has been published by the U.S. Public Health Service (1962b).

## Public supply

Carrington, New Rockford, and Sheyenne have public water systems. The village of Glenfield has a public well from which local residents haul water. The communities of Hamar, Brantford, McHenry, Glenfield, Grace City, Juanita, and Barlow are each within 2 miles of aquifers that may be adequate for public supply.

### CARRINGTON

The city of Carrington is supplied by two wells (146-66-18ada2) in the Carrington aquifer. The water is treated by aeration, softened with lime and sodium aluminate, filtered, recarbonated, chlorinated, and fluoridated. The capacity of the system is 1,000,000 gpd, and storage is 870,000 gallons at the plant and 300,000 gallons elevated. Average daily consumption in 1963 was about 200,000 gallons, or about 82 gpd per capita. There were 665 metered taps.

The original public supply at Carrington was from a Dakota Sandstone well near the center of town. This was unsatisfactory because the water was highly mineralized and the well tended to become plugged with sand. Later, a well (146-66-6aad) was dug into the outcrop of the Carrington aquifer in Scotts Slough north of the city (Simpson, 1929, p. 131-132). In 1957 and 1959, the U.S. Geological Survey, in cooperation with the North Dakota State Water Commission, drilled test holes to partially delineate the Carrington aquifer (unpublished study). The sites for the present Carrington municipal wells in sec. 18, T. 146 N., R. 66 W., were located on the basis of this test drilling. These wells seem adequate for the foreseeable future, but if larger supplies are required, more wells could be constructed in the Carrington aquifer.

## NEW ROCKFORD

The city of New Rockford is supplied by one well (148-66-6bcc) in the New Rockford aquifer, with six older wells available for standby purposes. The water is softened with lime and sodium aluminate, recarbonated, filtered, chlorinated, and fluoridated. The treatment capacity of the system is about 300 gpm; storage capacity is 150,000 gallons elevated and 250,000 gallons in the plant. Average daily use in 1963 was about 150,000 gallons through 556 metered taps, or about 69 gpd per capita. Peak daily use reached 300,000 gallons.

The present well at New Rockford should be adequate for the immediate future. If water requirements increase substantially, additional wells could be drilled in the New Rockford aquifer. For maximum yield, completely penetrating wells should be drilled near the center of the aquifer where it has the maximum transmissibility. If quality of the water is the main consideration, water samples should be collected from test holes at various depths and locations and the chemical composition compared.

## SHEYENNE

The village of Sheyenne is supplied by one well (150-66-9cab1) in the Sheyenne Village aquifer. The well, which can be pumped at 150 gpm for a short period, functions as a reservoir because of its large diameter. It has been pumped for 24 hours at 60 gpm with 4 feet of drawdown.

The water is chlorinated. Elevated storage capacity of the system is about

50,000 gallons. Average daily use in 1965 was 20,000 gallons, or about 47 gpd per capita. The peak use was 35,000 gallons. There were 105 metered taps.

The water supply at Sheyenne is adequate during normal and wet years, but shortages have developed in dry years. The village has dealt with this temporarily by pumping water from the Sheyenne River to an infiltration pond near the well. Froelich (1964, p. 26-27) has made alternative recommendations:

1. Use water from Warsing Reservoir to recharge the well.
2. Drill a new well at 150-66-8aaa, also in the Sheyenne Village aquifer. (This was done, but the well failed to produce 30 gpm and was abandoned, although a test hole a few feet away yielded more than 30 gpm.)
3. Put in a line of driven wells just south of the bluffs of the Sheyenne River at 150-66-5d. These should be placed so as to intercept water now being lost from the Sheyenne Village aquifer through springs in the river bluffs.
4. For larger supplies, the outwash in the Sheyenne River valley (Sheyenne channel aquifer) should be explored further.

Dealing with a water shortage in the drought of the early 1930's when Sheyenne residents were supplied by individual wells, A. N. Sayre (1935, p. 118) recommended:

1. Deepen wells to below the water table. (This would not help the present village well, which bottoms in Pierre Shale.)
2. Dam the slough south of the town (150-66-16b) so that recharge to the aquifer would be augmented by impounded runoff.

Any of the above recommendations, except the one for developing the Sheyenne channel aquifer, would at best only moderately increase the supply. The Sheyenne channel aquifer apparently has the potential for large yields.

## HAMAR

There are two aquifers that might serve the community of Hamar as sources of water for a public supply. One is the surficial Warwick aquifer, which presently supplies individual residences. The other is the Hamar aquifer.

The maximum aquifer thickness in the vicinity of the community should be located by test drilling before attempting to construct a large-capacity well in the Warwick aquifer. The unused Great Northern Railway station well (150-62-3aba), which taps the Hamar aquifer, has been pumped at a rate of 10 gpm with 21 feet of drawdown. The well is partially penetrating; a fully-penetrating well could be expected to yield somewhat more.

## BRANTFORD

Brantford lies on the northeast edge of the New Rockford aquifer, which can supply large quantities of water. Test hole 148-65-35cbb, within half a mile south of the center of town, penetrated 36 feet of gravel in the interval between 168 and 219 feet. Chemical analyses of water from private test holes at 148-65-35cdb, 147-65-3a, and 147-65-3d (Trapp, 1966, table 4) showed the water to contain from 700 to 1,200 ppm dissolved solids, which were principally sodium, calcium, bicarbonate, and sulfate in varying amounts.

## McHENRY

Most of the residents of McHenry have individual wells that tap the Pierre Shale. The water generally is high in chloride, although the salty taste is barely perceptible in water from some of the wells. Formerly, shallow drift wells were used, but these went dry at times and the water was reported to be of poor quality.

Two test holes penetrated water-saturated sand and gravel near McHenry that might be of sufficient extent and thickness to be suitable sources for a public supply. Test hole 147-62-10abb, southeast of town, penetrated medium to coarse sand and fine gravel from 34 to 52 feet. The extent of this deposit is now known, and it is not shown as an aquifer on plate 4. A water sample from the test hole was sodium bicarbonate sulfate type, with a dissolved-solids concentration of 910 ppm. The dissolved solids, sulfate, and iron concentrations (Trapp, 1966, table 4) exceeded the limits recommended for drinking water by the U.S. Public Health Service (1962a, p. 7-8). Water levels from July 1964 to November 1965 ranged from 13.85 feet below land surface on March 30, 1965, to 9.10 feet on November 23, 1965 (Trapp, 1966, table 2).

Test hole 148-62-29daa penetrated surficial sand and gravel to a depth of 40 feet and buried sand and gravel from 85 to 106 feet. Bluemle (1965, pl. 1) mapped the surficial outwash penetrated by this hole as covering about 1,000 acres, but the extent to which it may be an effective aquifer is not known, nor is the extent of the buried sand and gravel. A water sample from the lower zone was calcium bicarbonate type, with a dissolved-solids concentration of 278 ppm (Trapp, 1966, table 4). The analyzed constituents fell within the limits recommended by the U.S. Public Health Service for drinking water, except for iron, which was slightly above the recommended limit. Water levels in the buried sand and gravel were measured monthly from July 1964 to November 1965 (Trapp, 1966, table 2). They varied from 25.06 feet below land surface on March 30, 1965 to 23.87 feet on November 23, 1965. The possibility of two aquifers and water with lower concentrations of dissolved solids and sulfate makes prospecting for water around this site appear more favorable than around 147-62-10abb.

## GLENFIELD

Glenfield is underlain by the New Rockford aquifer (pls. 4, 5). This should be a suitable source for a large water supply.

The village's present public well (146-62-21aac) is constructed in the aquifer. A water sample from this well was sodium bicarbonate chloride type, with a dissolved-solids concentration of 613 ppm. Its analyzed constituents fell within the limits recommended by the U.S. Public Health Service for drinking water, except for dissolved solids. The water was very hard.

### GRACE CITY

Grace City is served by individual wells. It is about 2 miles northeast of the New Rockford channel (pl. 2), but present data are insufficient to define the channel and to show that the New Rockford aquifer is continuous through this area. Test holes to delineate the channel and to determine the nature of the channel fill would be required before plans for a public supply from the aquifer could be made. Test holes drilled at 147-64-29aaa and 147-64-29ccc would probably find the channel; more detailed drilling might be required later.

Another possible source of water for Grace City is the Lake Juanita aquifer to the southeast (pl. 4). This aquifer, in the valley of the James River and the Lake Juanita channel, is also inadequately defined by test drilling to date, and additional drilling would be required. Favorable areas would be sec. 25, T. 147 N., R. 64 W., or sec. 19, T. 147 N., R. 63 W.

### JUANITA

Juanita is near the north edge of the New Rockford channel (pl. 2), which ordinarily would be regarded as a favorable location for a large supply of water. However, the New Rockford aquifer is thin through much of the channel here. At the southwest edge of the community, test hole 146-63-4aaa penetrated 44 feet of poorly sorted, partly clayey gravel from 94 to 144 feet, which would probably be adequate for a small public supply. Detailed test drilling might disclose a more favorable site for a well.

### BARLOW

Barlow, in Foster County, is less than 2 miles north of the Carrington aquifer, which should yield an abundant water supply. Test holes drilled at 147-67-12ccc and south or west from this point should penetrate the aquifer.

## Irrigation

Three farms are irrigated from ground-water sources in Eddy and Foster

Counties. Two use water from the buried Carrington aquifer in Foster County, and one taps the surficial Northwest Eddy aquifer. Reported withdrawals for irrigation from the Carrington aquifer totaled 940 acre-feet for 1966; irrigation use varies with wet and dry years and present water rights are not fully exercised. Irrigation withdrawal from the Northwest Eddy aquifer was 55 acre-feet in 1966. None of the developments have thus far depleted the aquifers appreciably. The Carrington aquifer probably could supply further irrigation development. The Northwest Eddy aquifer probably also could support more irrigation, but more intensive test drilling would be required to localize areas of sufficient water-saturated thickness.

The surficial Central Eddy aquifer is similar to the Northwest Eddy aquifer, but of greater extent. Detailed test drilling is needed to localize areas of water-saturated thickness sufficient to sustain irrigation wells.

On the basis of present knowledge, the New Rockford aquifer has the greatest potential yield in the area, but much of the water in it is of marginal quality for irrigation. Water should be sampled and analyzed from various levels in test holes at a proposed irrigation site. Consideration should be given to soil type, drainage, and crops to be raised before irrigation with the water is attempted.

Most of the other glacial drift aquifers, except those in till, have the potential of yielding sufficient water for irrigation, but require more intensive exploration. The suitability of the soil for irrigation in the vicinity of the aquifers must be considered, along with the availability and quality of water.

The construction of the Garrison Diversion Unit, which will supply surface water for irrigation, and the need for water management will have an impact on the future use of ground water for irrigation in Eddy and Foster Counties. The evaluation of this impact involves economic and legal considerations beyond the scope of this report.

## SUMMARY AND CONCLUSIONS

The nature and distribution of rock material, together with topography and drainage, control the distribution of ground-water supplies in Eddy and Foster Counties. There are two types of aquifers in the area: those in consolidated rocks and those in glacial drift.

Although the distribution, thicknesses, and lithologies of formations below the Dakota Sandstone are fairly well known through records of exploratory oil tests, little is known of their water-bearing potential. The water they contain is probably saline, but perhaps only slightly to moderately saline. Because of their depth, their questionable water-bearing characteristics, and the availability of other sources of supply, they have not yet been explored for water.

Dakota Sandstone wells in western Foster County have artesian heads within a few feet of land surface. The Dakota has not been extensively explored as an aquifer because it is at least 1,300 feet below land surface and the water is slightly to moderately saline. It is a potential source of supply for stock water and domestic uses other than drinking.

The Pierre Shale forms the bedrock surface below the glacial drift and outcrops locally in Eddy and Foster Counties. Most shale wells have small to moderate yields of water that is slightly to moderately saline. The water is used for livestock, and, in some localities, for drinking. It is usually softer than glacial drift water and therefore some shale wells supply water for washing.

Glacial drift aquifers include (1) buried sand and gravel deposits, (2) surficial sand and gravel deposits, and (3) glacial till. The buried aquifers include outwash-channel fill, outwash-plain deposits, and ice-contact deposits. These are generally semiconfined aquifers. The surficial sand and gravel aquifers include outwash plains, exposed outwash channel deposits, terrace deposits, and at least one esker. The water-bearing characteristics of glacial till are controlled by the presence of sand and gravel lenses, disseminated sand and gravel, and fractures. The surficial aquifers and some aquifers in the glacial till are unconfined.

Two of the largest and most productive of the buried aquifers are the New Rockford aquifer, which consists of outwash in a buried channel, and the Carrington aquifer, a buried outwash-plain deposit. The New Rockford channel extends southeastward across Eddy and Foster Counties, a distance of about 43 miles. The water-saturated drift filling the channel generally ranges from 260 to 320 feet in thickness, of which as much as 161 feet is sand and gravel. The aquifer supplies the city of New Rockford, plus numerous domestic and stock wells. Where boundary effects are not too great, properly constructed wells should be capable of yielding 1,000 gpm or more of water from the aquifer. Some of the water sampled from the New Rockford aquifer was sodium bicarbonate type and had dissolved-solids concentrations exceeding 1,000 ppm. Much of the water is unsuitable or of marginal quality for irrigation.

The Carrington aquifer, in Foster County, has an average thickness of about 44 feet, and, in most places, is covered by about 40 feet of till. Wells in this aquifer supply the city of Carrington and the Carrington Irrigation Branch Station and are capable of producing more than 1,000 gpm. The water is generally calcium bicarbonate type, with dissolved-solids concentrations ranging from 400 to 1,200 ppm. Other buried aquifers are less well defined by test drilling and none appear to have as great a potential for development of ground water within the area as do the New Rockford and Carrington aquifers.

Surficial aquifers include the Northwest Eddy, Central Eddy, James River, and Sheyenne Village aquifers. The first two are outwash-plain deposits, the Sheyenne Village aquifer consists of terrace deposits, and the James River aquifer consists of valley-train deposits. An irrigation well in the Northwest Eddy aquifer is capable of yielding more than 750 gpm, and the Central Eddy aquifer probably could supply water at a similar rate locally. The Sheyenne Village aquifer is of small extent and is thin, but is important to the community, which uses it for its public supply. The water from surficial aquifers (other than glacial till) is generally bicarbonate type, with dissolved-solids concentrations ranging from 118 to 1,350 ppm. The James River aquifer and other surficial aquifers have been delineated only partially, and no large capacity wells have been constructed in them.

New Rockford, Sheyenne, and Carrington presently use ground water for municipal water systems. Potential ground-water sources for public water supplies are available within a few miles of Hamar, Brantford, McHenry, Glenfield, Grace City, Juanita, and Barlow.

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