Geology and Ground-Water Resources of the Lake Dakota Plain Area South Dakota

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1539-T

Prepared as part of the program of the Department of the Interior for the development of the Missouri River basin

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By WILLIAM B. HOPKINS *and* LESTER R. PETRI

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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GEOLOGY AND GROUND-WATER RESOURCES OF THE LAKE DAKOTA PLAIN AREA, SOUTH DAKOTA

By William B. Hopkins and Lester R. Petri

ABSTRACT

The Lake Dakota plain area is a nearly flat surface that includes parts of Spink, Brown, Marshall, and Day Counties in northeastern South Dakota. Agriculture is the principal occupation. Because precipitation often is insufficient for maximum crop production, the U.S. Bureau of Reclamation has developed a plan for irrigation of the area. Most of the irrigation water would be conveyed by canal from a reservoir on the Missouri River, about 100 miles to the west, but some would be obtained locally from the James River.

The surface of the Precambrian rocks, which underlie the area at a depth of 1,200 to 1,500 feet, is the lower limit to which water wells are drilled. Most of the producing wells in the area tap the Dakota sandstone, which has an average thickness of about 400 feet and rests on the Precambrian rocks. The Dakota is not recharged locally; water percolates into the Lake Dakota plain area principally from areas of recharge to the west. Because the aggregate discharge from wells tapping the Dakota exceeds the estimated rate of lateral percolation into the area, some of the discharged water probably is derived from storage. Although the artesian pressure is still sufficient to cause wells to flow, it is much less now than it was when the first wells were drilled in the 1880's. Water from the Dakota is highly mineralized; the specific conductance of water from 71 wells ranged from 2,590 to 4,380 micromhos per centimeter. Most of the water was of the sodium sulfate type and was soft. By recognized standards the water is chemically unsuitable for most uses, but for many years it has been the principal source of supply both on farms and in the municipalities. Use of the water for irrigation is reported to have made the soil unproductive.

The Dakota is overlain by younger Cretaceous rocks aggregating 700 to 800 feet in thickness. These rocks, which consist of shale and limestone, generally are too nearly impermeable to be a source of water supply.

Unconsolidated deposits of Quaternary age mantle the Cretaceous rocks. Although they consist mostly of material that is too fine grained to yield water freely to wells, the Quaternary deposits contain bodies of moderately to highly permeable material that yield water copiously. Such bodies may be located only by exploratory drilling or, possibly, geophysical methods. The water differs widely in amount of mineralization and in chemical composition; the specific

conductance of water from 322 wells ranged from 246 to 13,300 micromhos per centimeter. In most of the report area the water is of unsuitable quality for irrigation and domestic use. The principal source of recharge to the Quaternary deposits is infiltrating precipitation. Evapotranspiration accounts for nearly all the water discharged; the amount of water discharging into stream channels and withdrawn from wells is almost negligible by comparison. Irrigation of the area would increase the rate of recharge to the Quaternary deposits and would cause the water table to rise. Probably it would also cause an increase in the concentration of dissolved minerals in much of the ground water. Artificial drainage would be necessary to prevent waterlogging of cropland.

INTRODUCTION

PURPOSE OF INVESTIGATION

The Oahe unit, in eastern South Dakota, is one of several irrigation projects proposed under the program of the Department of the Interior for the development of the Missouri River basin. According to plans of the U.S. Bureau of Reclamation (1960), the Oahe unit consists of the Missouri slope area in Sully County (81,000 acres) and the Lake Plain area (445,000 acres) in Spink, Brown, Day, and Marshall Counties. (See fig. 1.) The Lake Plain area, which is in the James River lowland, lies on both sides of the southward-flowing James River. It is the area described in this report and is referred to as the Lake

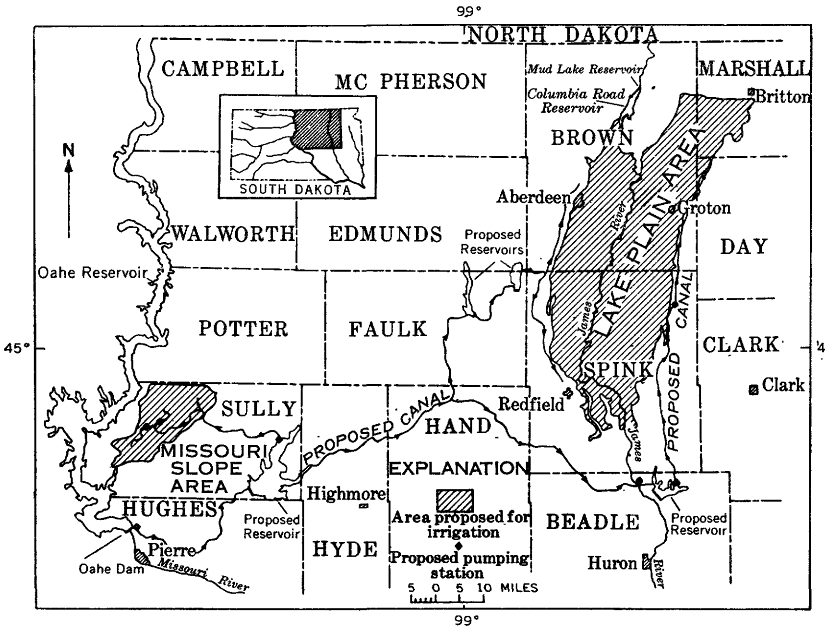

FIGURE 1.—Map of the Oahe unit in eastern South Dakota.

Dakota plain area. The principal source of water for irrigation would be the Oahe Reservoir, created by construction of the Oahe Dam on the Missouri River near Pierre, S. Dak. However, some of the water to be used in irrigating would be diverted from the James River. The original plan for the Oahe unit (U.S. Dept. Interior, 1944, p. 115–116) was to irrigate 750,000 acres, all in the James River lowland on the west side of the James River and generally west and south of the Lake Dakota plain area. However, detailed field investigations in that area raised serious doubts as to the feasibility of the plan and resulted in its abandonment.

The purposes of this investigation were (1) to determine the availability, under the present hydrologic regimen, of ground water for domestic, stock, irrigation, industrial, and municipal supply; (2) to ascertain whether irrigation would increase the amount of ground water available for utilization; (3) to obtain data on fluctuations of the water table under the present hydrologic regimen; (4) to relate the chemical composition of the ground water to the geology of the area; (5) to evaluate the quality of the ground water for irrigation and domestic use; and (6) to assess the probable effect that irrigation with water from the Missouri and James Rivers would have on the quality of the ground water.

PREVIOUS INVESTIGATIONS

Several publications contain much valuable information on the geology and hydrology of the Lake Dakota plain area. A report by Todd (1909) describes the subsurface rock units and the mineral resources of the Northville, Aberdeen, Redfield, and Byron quadrangles, South Dakota, and contains an areal geologic map and an artesian water map, both of which include the Lake Dakota plain area south of T. 124 N. Darton (1909) describes the geology and ground-water resources of the entire State and presents tabulated data on representative artesian wells, several of which were in the Lake Dakota plain area. Sayre (1935), in a report on the possibility of alleviating water shortages resulting from the drought of 1931–34, describes the municipal water supplies at Aberdeen and Redfield, both of which are in the area. Reports by Erickson (1954, 1955) describe artesian conditions in east-central and northeastern South Dakota; in addition to a discussion of the subsurface geology, these reports contain much tabulated information on artesian wells. In a report on ground-water reservoirs in the vicinity of Aberdeen, Rothrock (1955) describes buried water-bearing delta deposits that were laid down where the ancestral Elm River entered Lake Dakota and buried water-bearing alluvium in a preglacial valley that trends northeastward beneath Lords Lake. A

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treatise by Flint (1955) on the Pleistocene geology of eastern South Dakota contains detailed descriptions of the glacial deposits, a discussion of the drainage changes caused by glaciation, and an areal geologic map that includes all the Lake Dakota plain area. U.S. Geological Survey Water-Supply Paper 1425, prepared by Koopman (1957), describes the geology and ground-water resources of a part of Brown and Marshall Counties and contains many data on both shallow and deep wells in the northern part of the Lake Dakota plain area. Also, some geologic and hydrologic information collected by the Geological Survey in the Oahe unit as originally proposed is pertinent to the Lake Dakota plain area and was used in preparing this report. That information has been tabulated and reproduced as a series of open-file appendixes (U.S. Geol. Survey, 1957) to an interpretive report that has not yet been published. Copies of these appendixes (see list below) may be examined at the following offices: U.S. Geological Survey, Washington, D.C., and Denver, Colo.; South Dakota Geological Survey, Vermillion; South Dakota Water Resources Commission, Pierre; and at the city libraries, Pierre and Huron, S. Dak.

Appendix A. Records of wells, test holes, and springs in part of the James River valley in South Dakota.

Appendix B. Measurements of the water levels in wells in part of the James River valley in South Dakota.

Appendix C. Logs of wells and test holes in part of the James River valley in South Dakota.

Appendix D. Chemical analyses of water in part of the James River valley in South Dakota.

The relation of the Lake Dakota plain area to the area described by Koopman (1957) and to the Oahe unit as originally proposed is shown in figure 2.

SCOPE OF INVESTIGATION

This report is based partly on information contained in previous publications and partly on data collected during field investigations in the Oahe unit, both as originally proposed and as presently planned. Only the data for 1955, 1956, and 1957 were collected specifically for this report.

Data consisting of records and logs of wells and test holes, water-level measurements, altitudes of bedrock, and chemical analyses of ground water are not reproduced in this report but are presented in tables A–F of a separate report by Hopkins and Petri (1962), which has been published jointly by the South Dakota State Geological Survey and the South Dakota State Water Resources Commission. The references in this report to tables A–F are to tables in that publication, which are as follows:

Table A. Records of wells and test holes.
B. Water-level measurements.
C. Logs of wells and test holes.
D. Depth below land surface and altitude above mean sea level of the surface of the Pierre shale.
E. Chemical analyses of water from the Dakota sandstone.
F. Chemical analyses of water from deposits of Quaternary age.

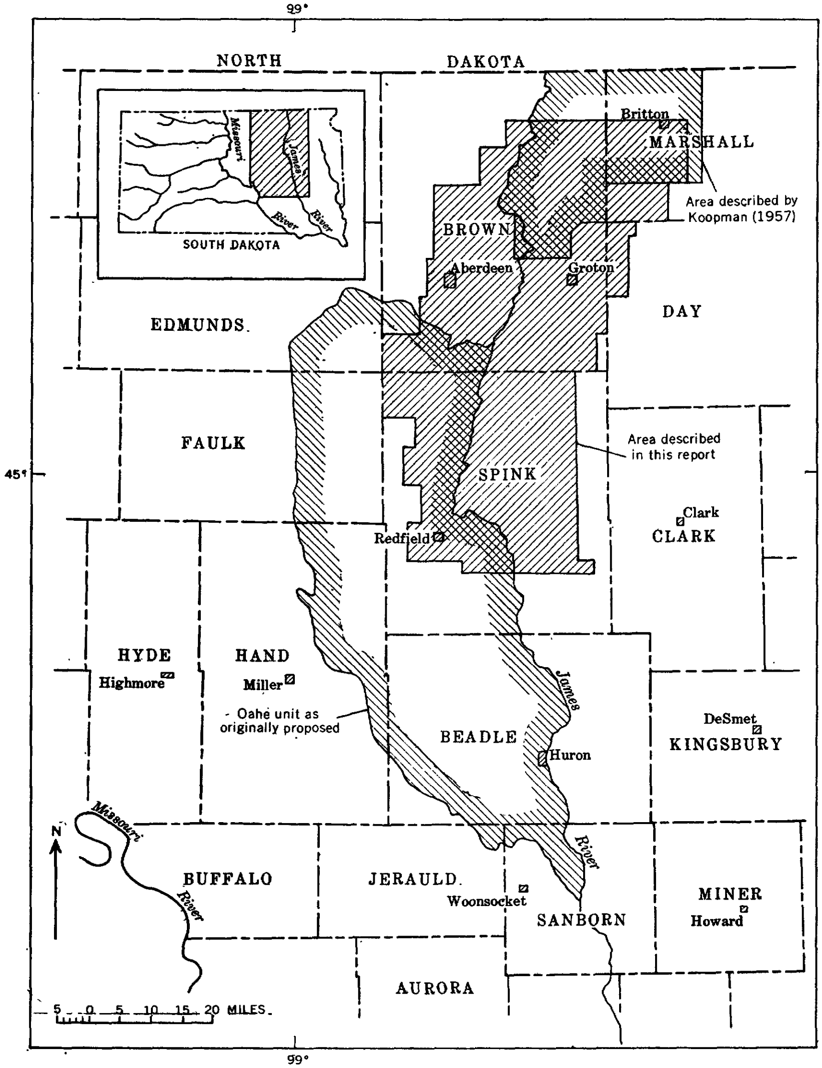

FIGURE 2.—Map of eastern South Dakota showing the area described in this report, the area described by Koopman (1957), and the Oahe unit as originally proposed.

Records of 1,412 wells and test holes and of 3 springs are presented in table A. Measurements of the diameter and depth of the wells and of the depth to water were made if convenient; the other information generally was obtained by interviewing the owners, operators, or drillers of the wells. The locations of the wells and springs for which data were obtained are shown on plate 1.

Of the 258 observation wells for which water-level measurements are given in table B, 67 were installed specifically for this investigation, 91 were installed for the study of the Oahe unit as originally proposed, 20 were installed for the study of the Crow Creek-Sand Lake area in Brown and Marshall Counties (Koopman, 1957), and 80 were privately owned. The Bureau of Reclamation drilled 43 of the wells that were installed specifically for this investigation, and the Geological Survey drilled the remaining 24 for use in making water-level measurements. Recording gages were used to obtain continuous measurements of water-level fluctuations in seven of the wells; noon readings at 5- or 6-day intervals are given for these wells. The intermittent measurements of the water level in all the other wells were made with a steel tape. During the 1956 growing season several nearly complete rounds of measurements were made, each within a span of 1 to 3 days. The locations of all 258 observation wells are shown on plate 1.

During the investigation, 60 test holes were drilled by the Bureau of Reclamation and 27 were jetted by the Geological Survey. The logs of these test holes are given in table C. Also in the same table are the logs of 77 test holes drilled for earlier studies (65 by the Bureau of Reclamation, 7 by the Corps of Engineers, U.S. Army, and 5 by the Geological Survey) and the logs, obtained from either the driller or the owner, of 90 commercially drilled wells.

During 1947–56, personnel of the Geological Survey and Bureau of Reclamation collected water samples for analysis from 322 wells tapping Quaternary deposits and from 71 wells tapping the Dakota sandstone. Many of the samples from the western and southern parts of the area were collected before 1956 for the study of the Oahe unit as originally proposed. Some wells were resampled after a lapse of several months or even several years, and a few of the wells were sampled several times during aquifer tests. The Missouri River at Pierre, S. Dak., was sampled daily by a local observer, and the James River and some of its tributaries were sampled by personnel of the Geological Survey. Most of the samples were analyzed in the laboratory of the Geological Survey in Lincoln, Nebr.; however, the specific conductance of some samples was determined in the field at the time of collection.

PERSONNEL AND ACKNOWLEDGMENTS

The geologic and ground-water studies in the Lake Dakota plain area were made by the Geological Survey as part of the program of the Department of the Interior for development of the Missouri River basin. The studies were under the general direction of G. H. Taylor, regional engineer, Ground Water Branch, and P. C. Benedict, regional engineer, Quality of Water Branch. The fieldwork was under the direct supervision of J. R. Jones, district geologist in charge of ground-water studies in South Dakota. E. A. Ackroyd, R. L. Barnell, R. W. Davis, D. C. Lewis, E. H. Lidstone, and R. S. Pocreva assisted in the collection, tabulation, and interpretation of the field data and in the writing of this report.

Appreciation is expressed to the several local well drillers who made available the logs of wells that they had installed, also to the many well owners who freely supplied information about their wells and permitted repeated access to them for water-level measurements and sampling of the water.

WELL-NUMBERING SYSTEM

Each well and test hole has been assigned a number according to its location within the Federal system of rectangular land surveys. The first segment of the number indicates the township north of the base line (in Arkansas), the second the range west of the fifth principal meridian, and the third the section and subdivision of the section. The first of the lowercase letters in the third segment denotes the 160-acre tract, the second the 40-acre tract, the third the 10-acre tract, and the fourth the 2½-acre tract. These letters are assigned in counterclockwise direction, beginning with the northeast quarter. Two or more wells within the smallest tract indicated by the letters are distinguished by consecutive numbers, beginning with 1, that follow the letters. This method of designation is shown in figure 3.

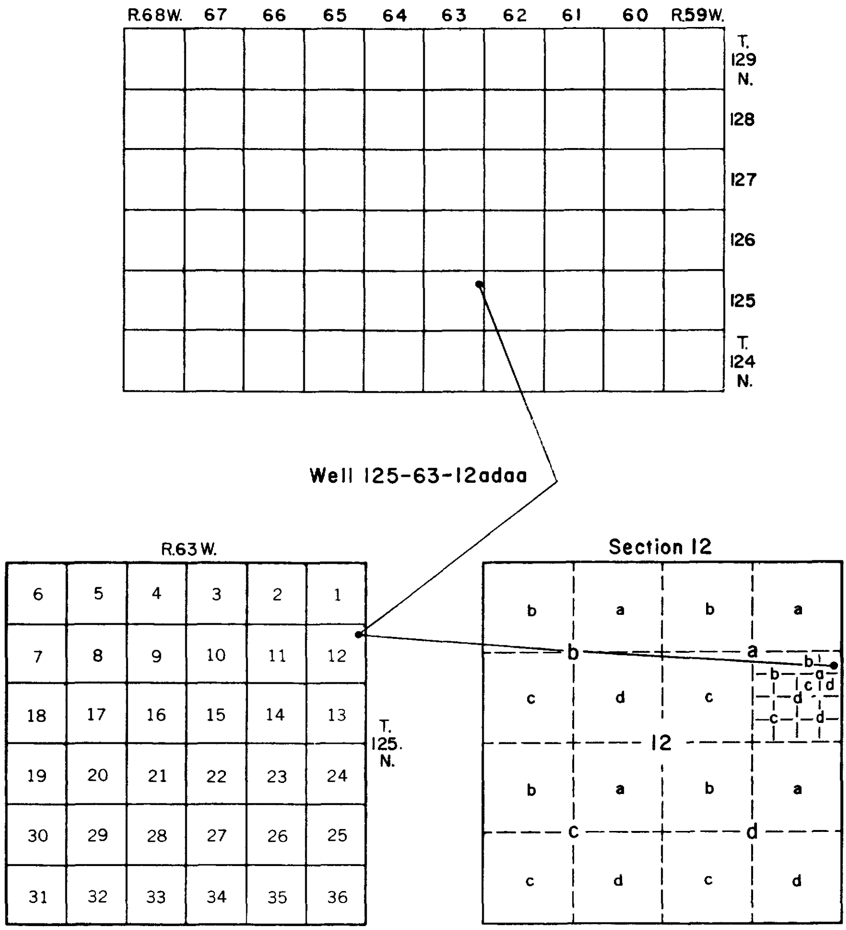

FIGURE 3.—Well-numbering system.

GEOGRAPHY

LOCATION AND EXTENT OF AREA

Many geologists believe that a shallow glacial lake—Lake Dakota—occupied the central part of the James River lowland during the waning phase of the last stage of glaciation in Pleistocene time. The lake extended from the vicinity of Redfield, S. Dak., to near Oakes, N. Dak., which is about 90 miles north-northeast of Redfield and about 14 miles north of the State line. The southern two-thirds of the lake floor and adjacent small tracts constitute the area described in this report. The area extends from a line 2 miles south of the north border of T. 115 N. to a line about 4 miles north of the south border of T. 127 N., and from the west border of R. 65 W. to the east border of R. 58 W.

Its north-south length is 72 miles, and its width ranges from 24 to 30 miles. Of the 2,139 square miles in the area, 1,082 is in Brown County, 845 in Spink County, 174 in Marshall County, and 38 in Day County. About two-thirds of the area is on the east side of the James River, which flows generally southward across the full length of the area.

POPULATION AND TRANSPORTATION

The population of the Lake Dakota plain area is estimated to be 37,500 (U.S. Dept. Commerce, 1951). About 25,000 live in cities and towns, and about 12,500 are rural residents. The density of the population in rural areas is about 6 persons per square mile.

Transportation facilities in the area include four railroad lines, one airline route, and a network of highways and section-line roads. The railroads are the Chicago and North Western, the Minneapolis & St. Louis, the Great Northern, and the Chicago, Milwaukee, St. Paul & Pacific. The Braniff International Airways connects Aberdeen with Huron to the south and with Bismarck, N. Dak., to the northwest. The area is served also by bus and truck lines. U.S. Highways 12, 212, and 281 and State Highways 10, 20, and 37 provide all-weather transportation, except for short periods when blocked by snow. Although not dependable from about the first of November to about the first of June, the section-line roads generally are passable during the warmer part of the year.

AGRICULTURE AND INDUSTRY

The main source of income in the Lake Dakota plain area is agriculture. Many dairy and beef cattle are raised. The principal crops include corn, wheat, oats, grain sorghum, flax, and several types of hay. According to the U.S. Bureau of Reclamation (1957, p. 4), the average size of the farms is 550 acres. Crops were irrigated on only 11 farms during 1956, but an increasing number of farmers are showing an interest in irrigating their land.

Most industries in the area are related to agriculture. Plants for processing milk, handling livestock, and manufacture of agricultural implements are in Redfield and Aberdeen. Grain elevators are situated in nearly every city and small town. Aberdeen and Redfield have sheet-metal works and manufacturers of concrete products. Aberdeen also has a machine-tool manufacturer, a "gray iron" foundry, and two manufacturers of agricultural chemicals.

WATER AND MINERAL RESOURCES

Most water for municipal and domestic use is obtained from deep wells that tap artesian aquifers. Such wells furnish water for Ashton, Brentford, Claremont, Conde, Doland, Ferney, Frankfort, Groton, Langford, Mansfield, Mellette, Northville, Redfield, and Stratford. Columbia obtains water from shallow wells and Aberdeen obtains water from a reservoir on the Elm River in sec. 4, T. 124 N., R. 63 W. Other towns in the area have no municipal supply, the residents depending on privately owned wells. Most farm wells tap the deep artesian aquifers, but a few tap shallow aquifers.

Irrigation with water from deep artesian wells was attempted in the 1890's, but the water was found to be chemically unsuitable for irrigation. The owner of one of these early wells, 117–62–32abaal, reports that the land has been relatively unproductive for more than 40 years because of the salts deposited in the soil from use of the water. Most of the water used for irrigation on the 11 farms irrigated in 1956 was obtained from streams. A demonstration irrigation well, 116–61–8dddd3, was installed in 1954 by the Bureau of Reclamation. It, like the few wells pumped for irrigating gardens, taps shallow aquifers.

Before diesel engines were used by the railroads, water from deep artesian wells was used in engine boilers.

Several pits have been opened into deposits of sand and gravel near Aberdeen and Redfield in the western part of the area and near Langford in the eastern part. No deposits of metallic minerals are known to be in the area.

CLIMATE

The Lake Dakota plain area is in a zone of subhumid continental climate. About three-fourths of the annual precipitation, which averages about 19 inches per year, is in the form of rain during the summer. The heavier rainfalls generally occur during thunderstorms, as much as 4 inches of water falling within a few hours on a relatively small area. The lighter rains commonly are more general in distribution. About a quarter of the annual precipitation is snow, which may cover the ground continuously from November through March during a not unusual winter. Precipitation in the Lake Dakota plain area during the period 1898–1956 ranged from about 12 to 36 inches per year. The annual precipitation and the monthly minimum, average, and maximum precipitation at Redfield, Aberdeen, and Britton are shown graphically in figures 4, 5, and 6.

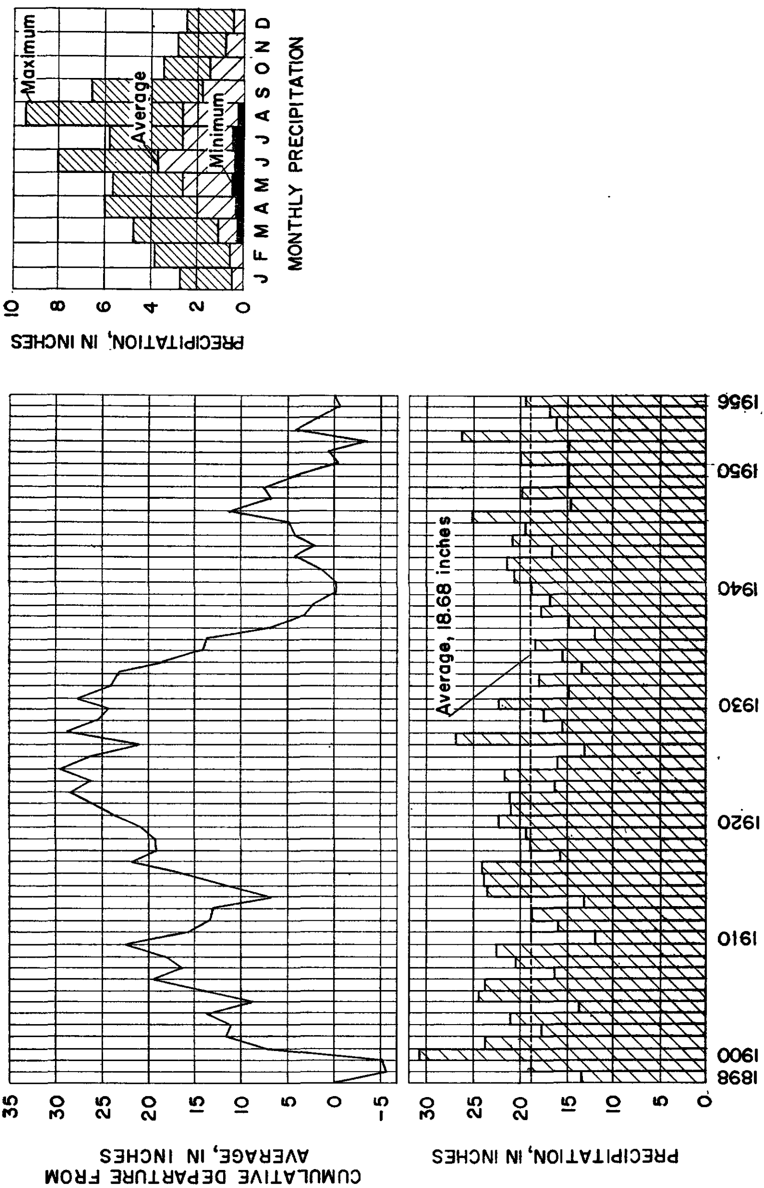

FIGURE 4.—Precipitation at Redfield, S. Dak., 1898–1956. From records of the U.S. Weather Bureau.

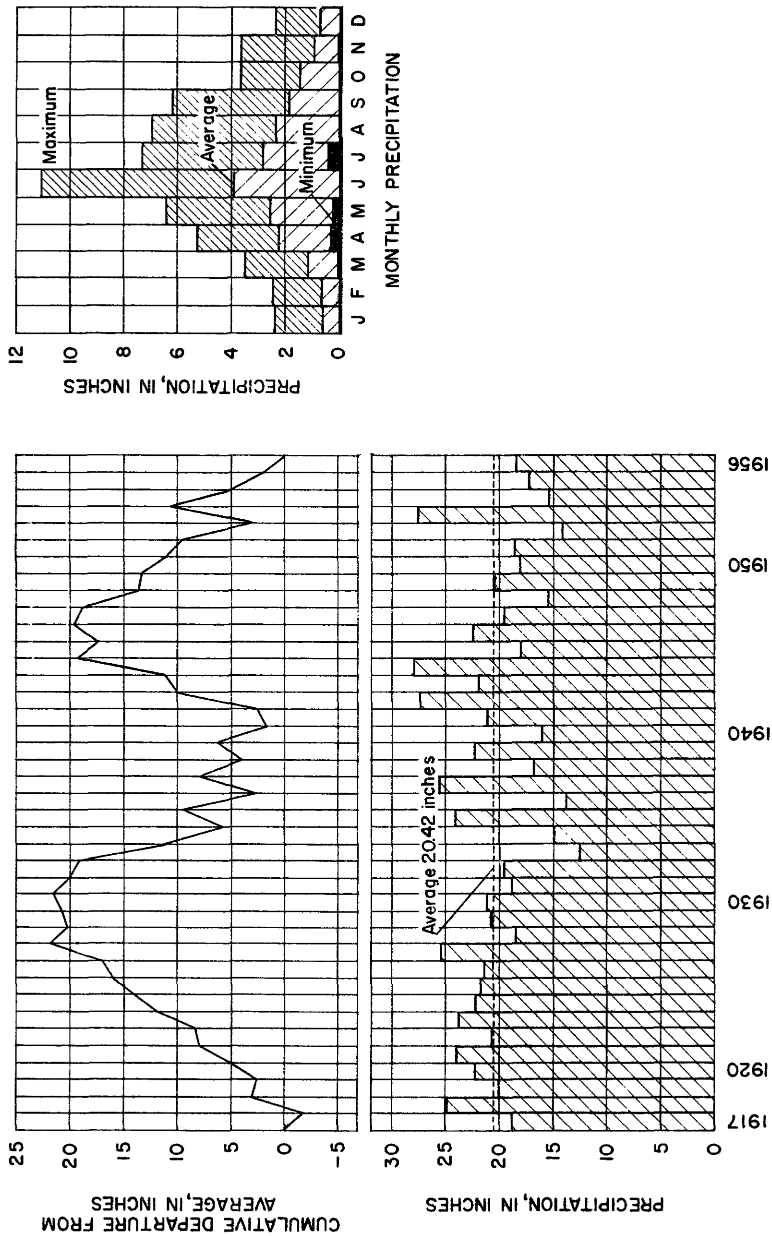

FIGURE 5.—Precipitation at Aberdeen, S. Dak., 1917–56. From records of the U.S. Weather Bureau.

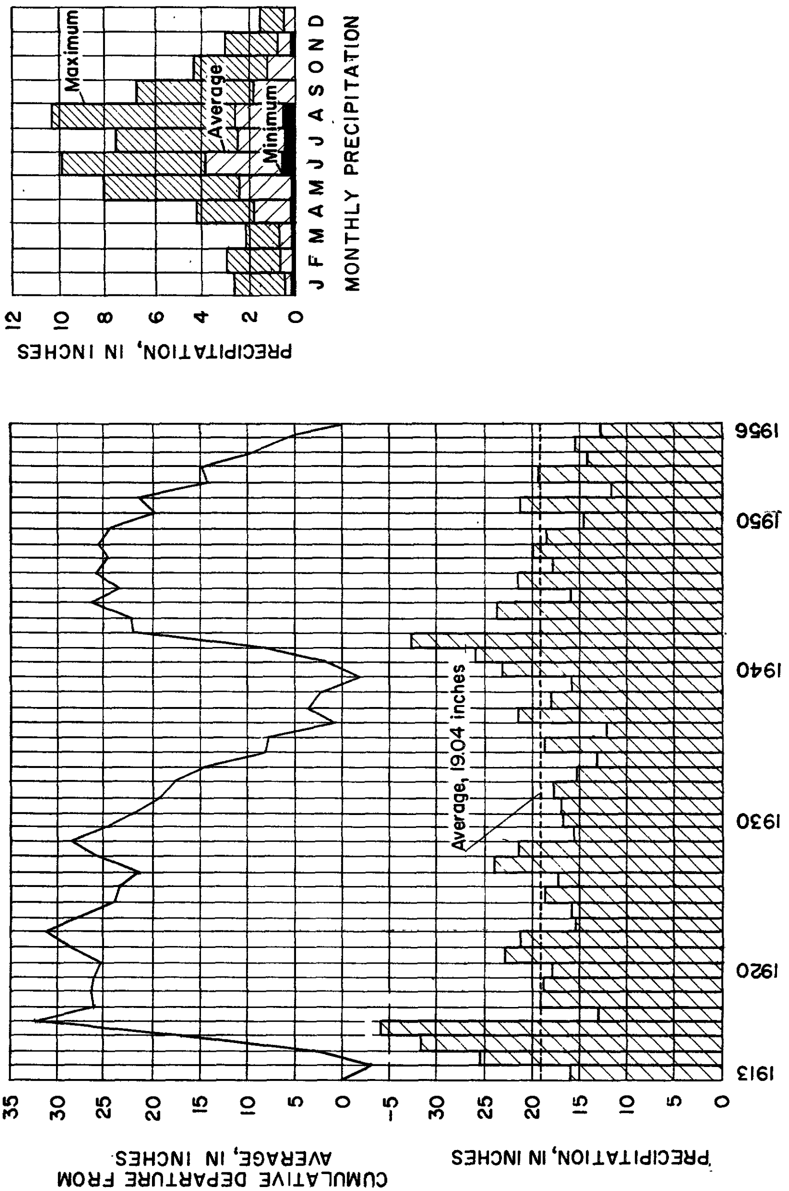

FIGURE 6.—Precipitation at Britton, S. Dak., 1913–56. From records of the U.S. Weather Bureau.

In the period 1898–1956, the lowest temperature recorded in the area was about −45°F and the highest about 117°F. Nearly every winter the temperature drops to below −20°F on a dozen or more days, and almost without fail the temperature climbs higher than 100°F several times each summer. The monthly minimum, average, and maximum temperature recorded at Aberdeen in the period 1917–56 is shown in figure 7.

Generally the relative humidity in the Lake Dakota plain area is low and tends to make the extremes of temperatures more endurable. Occasional days of both high temperature and high relative humidity are uncomfortable, but a week of these conditions is uncommon. Fog, associated with low temperatures and high relative humidity, is rare except along rivers and near ponds or flowing wells.

The evaporation potential in the area is two or three times as great as the normal annual precipitation. The average velocity of the wind is about 11 miles per hour, thereby aiding the evaporation of moisture from the soil zone. Since 1949, evaporation from the Weather Bureau's evaporation pan 6 miles east of Redfield has averaged 42.4 inches for the period April through September.

The growing season averages 134 days at Redfield, 133 at Aberdeen, and 125 at Britton (South Dakota State College, 1957). The length of the growing season is arbitrarily defined as the days between the

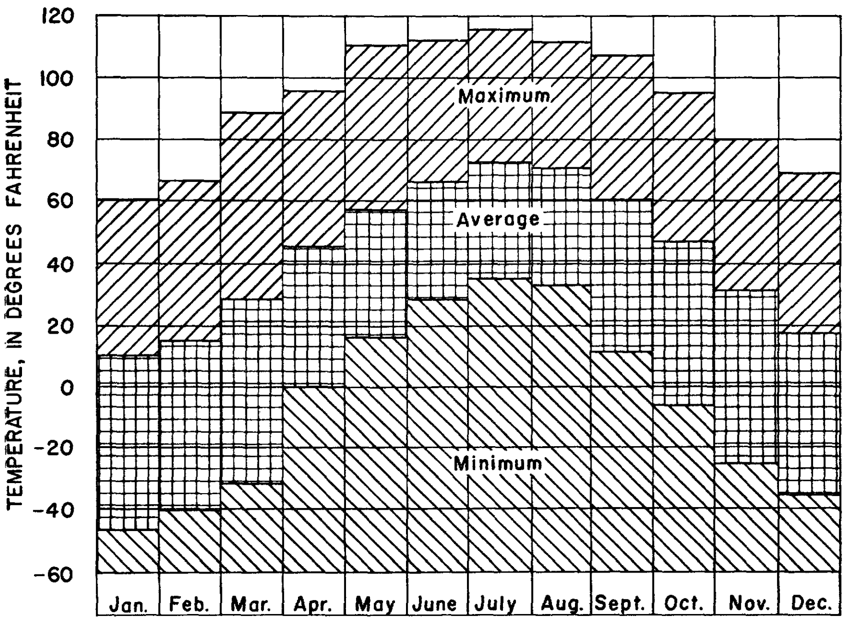

FIGURE 7.—Monthly minimum, average, and maximum temperature at Aberdeen, S. Dak., 1917–56. From records of the U.S. Weather Bureau.

last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall. Comparative data concerning the growing season in the area are presented in table 1.

TABLE 1.—*Comparative data on length of growing season*

[From records of the U.S. Weather Bureau]

Town	Length of record	Date of last freeze in spring		Date of first freeze in fall		Length of growing season				
						Shortest		Longest		Average number of days
		Earliest	Latest	Earliest	Latest	Number of days	Year of occurrence	Number of days	Year of occurrence	
Redfield	1898–1955	4-16-1948	6-21-1902	8-11-1902	10-11-1914	51	1902	176	1948	134
Aberdeen	1896–1955	4-17-1896	do	9- 4-1902	10-17-1911	75	1902	172	1922	133
Britton	1913–1955	4-29-1922 4-29-1936	6- 6-1924 6- 6-1935	8-25-1934	10-12-1948	95	1924 1934	155	1944	125

TOPOGRAPHY AND DRAINAGE

The Lake Dakota plain occupies the central part of the James River lowland—a valley, 50 to 60 miles wide and 200 miles long, between the Coteau des Prairies on the east and the Coteau du Missouri on the west. (See fig. 8.) The nearly flat surface of the Lake Dakota plain is topographically distinct from the smoothly rolling floor of the remainder of the James River lowland. It is a surface in the stage of earliest youth in the cycle of physiographic development, a well-integrated drainage system not yet having developed. The altitude of the plain is between 1,290 and 1,310 feet above sea level; in the parts of the report area that border the plain, the tops of the highest hills are about 1,380 feet above sea level.

The James River, which flows southward across the Lake Dakota plain area, has cut a relatively steep-sided valley ¼- to ¾-mile wide. The floor of this valley is 15 to 20 feet below the level of the plain at the north end of the area and 35 to 40 feet below at the south end. The river flows in an inner trench 125 to 200 feet wide, the bottom of which is less than 10 feet below the valley floor near the north end of the area and about 20 feet below at the south end. Streams tributary to the James River trend generally south-southwestward throughout the area. For much of their length, the valleys of the tributaries are little more than shallow depressions, but near their mouths the tributaries have cut to the level of the James River.

The James River is a slow-flowing stream, for its average gradient is only 0.26 foot per mile. The principal streams entering the James from the west are the Elm River and Moccasin, Snake, and Turtle Creeks and from the east are Mud Creek, Dry Run, and Timber Creek.

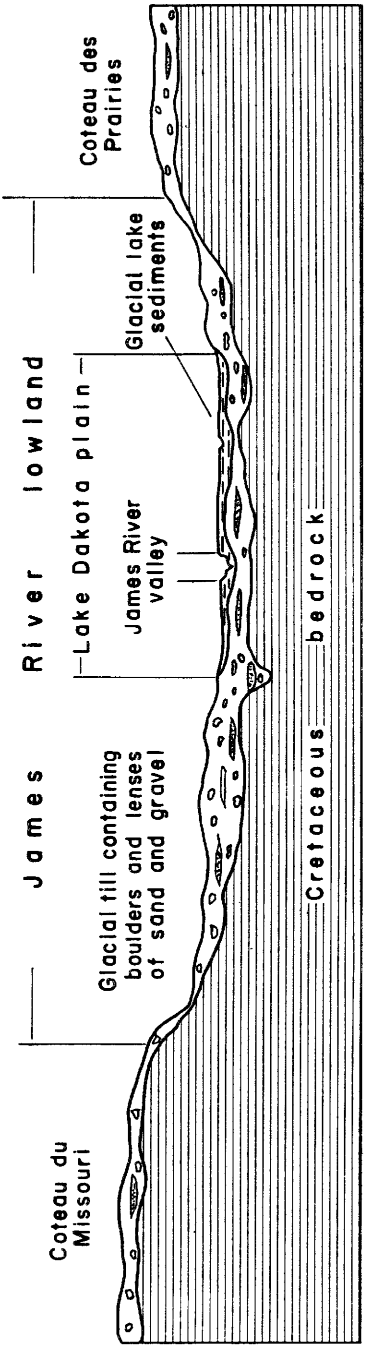

FIGURE 8.—Diagrammatic cross section of the James River lowland, South Dakota.

The Geological Survey stream-gaging stations in and near the area and the dates of their establishment are listed below.

Gaging station	*Established*
James River at Columbia	October 1945.
Elm River at Westport	October 1945.
James River near Stratford	March 1950.
Mud Creek near Stratford	September 1955.
James River at Ashton	October 1945.
West Branch Snake Creek near Athol	March 1950.
Snake Creek near Ashton	October 1955.
Turtle Creek at Redfield	October 1945.
James River near Redfield	March 1950.
Dry Run near Frankfort	September 1955.

Records of daily discharges at these stations are published annually by the Geological Survey in the series "Surface Water Supply of the United States."

If the drainage basin of the Elm River above the gaging station at Westport and the drainage basin of Turtle Creek above the gaging station at Redfield are excluded, the area drained by the reach of the James River between the gaging stations at Columbia and near Redfield is about 4,530 square miles and includes about two-thirds of the Lake Dakota plain area. An indication of the annual runoff to the James from this drainage area of 4,530 square miles is given by the difference in the height of columns A and D in each of the graphs in figure 9. For water years 1951–55 the annual increase in flow ranged from 3,420 to 79,020 acre-feet, or from 0.01 to 0.32 inch and averaged 0.11 inch. For the year ending September 30, 1956, evapotranspiration and seepage losses from the river channel exceeded the inflow so that less water passed the gaging station near Redfield than passed the gaging stations at Columbia and Westport.

Another indication of the runoff from the report area is given by the records of flow at the gaging stations on the Elm River, the West Branch of Snake Creek, and Turtle Creek. For 1950–56, the average annual runoff to these streams, which drain areas adjacent to the report area, ranged from 0.10 to 0.40 inch. The small amount of increase in the flow of the James River, despite the inflow of tributaries draining rolling lands adjacent to the Lake Dakota plain area, indicates that the average annual runoff from the nearly flat plain during the 6-year period 1950–56 was probably less than 0.10 inch. Even if that large, the runoff averaged only 0.5 percent of the precipitation.

At each gaging station on the James River, the discharge record for nearly every fall and winter is characterized by one or more periods of no flow.[1] Even in 1952, the year in which the maximum discharge of 6,100 cfs (cubic feet per second) was recorded (April 11) at the gaging station on the James River near Redfield, the discharge during the last 4 months of the year averaged only 0.5 cfs and the channel was dry for 2 days in September. In the 6-year period following establishment of the gaging station near Redfield, the month of greatest discharge has been as early as March and as late as August.

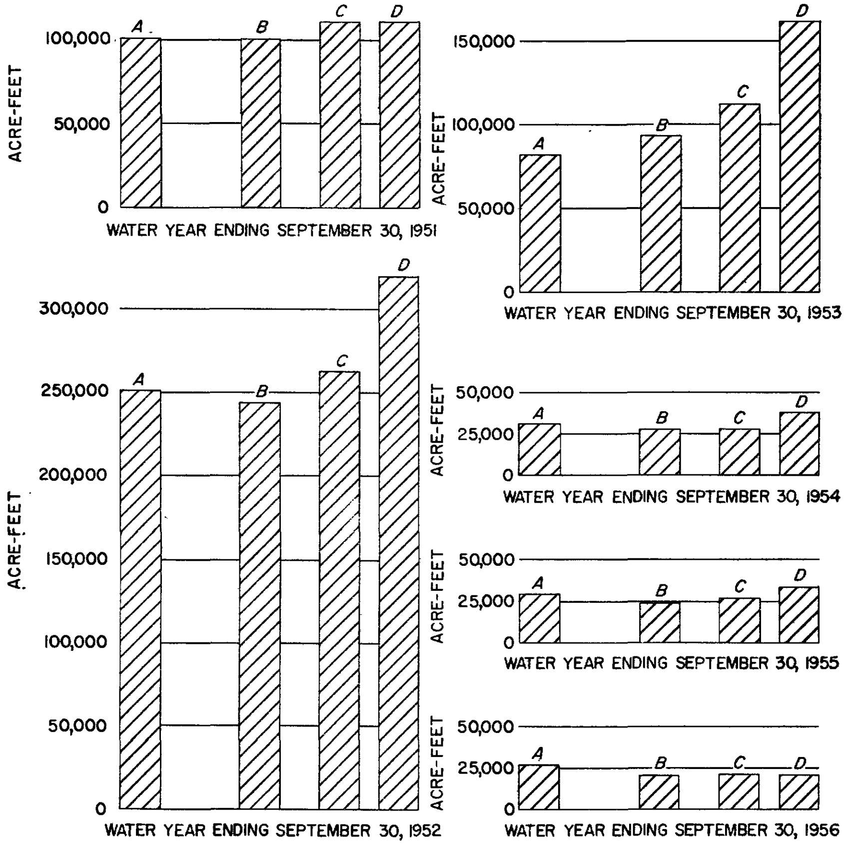

FIGURE 9.—Annual discharge of the James River, Columbia to Redfield, S. Dak., water years 1951 through 1956. The spaces between columns are roughly proportional to the distances between gaging stations. *A*, Discharge of James River at Columbia plus discharge of Elm River at Westport; drainage area 8,730 square miles. *B*, Discharge of James River near Stratford; drainage area 9,990 square miles. *C*, Discharge of James River at Ashton; drainage area 11,000 square miles. *D*, Discharge of James River near Redfield minus discharge of Turtle Creek at Redfield; drainage area 13,260 square miles.

[1] The Water Resources Review (U.S. Geol. Survey) for June 1959 stated that the James River had been dry above Huron, S. Dak., since the summer of 1958, except for a small release during March when repairs were made to a dam.

Tributary inflow sometimes causes reversals in the direction of flow in the James River. The Elm River causes reversals in the James at Columbia, and Snake and Turtle Creeks cause reversals in the James at Ashton. Until an earthen dike was constructed in sec. 24, T. 124 N., R. 62 W., water from the James River often would flood lowlands at the lower end of Putney Slough and back up into Crow Creek drain for several miles.

A comparison of the records of monthly discharge at gaging stations on the James River shows that losses in flow occur frequently in the reach between Columbia and Ashton. Also, if the inflow from Snake and Turtle Creeks is deducted, losses occur occasionally in the reach between Ashton and Redfield. The losses probably are due partly to seepage from the channel and partly to evapotranspiration.

GEOLOGY

At a depth ranging from about 1,200 to 1,500 feet is an erosional surface that 100 to 130 million years ago was the land surface. Rocks underlying that surface are of Precambrian age and generally are referred to as basement rocks. Consisting of granite and quartzite, the basement rocks are nearly impermeable and contain little or no water. The top of these rocks, therefore, is regarded as the lowest limit to which wells should be drilled when searching for a water supply.

Resting on the basement rocks is a succession of sedimentary rocks that were deposited in or along the shoreline of shallow seas that invaded the interior of the North American continent during Cretaceous time. These rocks, where they are exposed outside the Lake Dakota plain area, have been subdivided, in ascending order, into the Dakota sandstone, the Graneros shale, the Greenhorn limestone, the Carlile shale, the Niobrara formation, and the Pierre shale. Only the uppermost of these, the Pierre shale, crops out in the Lake Dakota plain area.

Except in a few small places, the erosional surface developed on the Cretaceous rocks is mantled by unconsolidated rock debris deposited in Pleistocene time by glacial ice when it melted, by streams flowing from the receding ice front, and by ponded melt water. Because these glacial deposits fill in the irregularities on a surface of moderate topographic relief, they differ in thickness from place to place; their maximum thickness, as determined by test drilling, is a little more than 250 feet.

The thickness, lithology, and water-bearing properties of the rocks underlying the Lake Dakota plain area are summarized in table 2. Each of the Cretaceous formations and the deposits of Quaternary age are described in greater detail below.

TABLE 2.—*Generalized section of stratigraphic units*

System	Series	Subdivision	Thickness (feet)	Physical characteristics	Water-supply characteristics
Quaternary	Recent	Soil	0–5	Reworked loess, dune sand, alluvium, lake deposits, and glacial till; contains much organic material.	Stores infiltrating precipitation to limit of moisture-holding capacity and transmits excess to underlying materials.
		Loess	0–5	Wind-deposited silt and very fine sand.	Do.
		Dune sand	0–10	Wind-deposited very fine to coarse sand.	Do.
		Stream alluvium	0–20	Stream-deposited clay, silt, sand, and gravel.	The part above zone of saturation stores infiltrating precipitation and seepage from streams to limit of moisture-holding capacity. The part in zone of saturation transmits water laterally toward pumped wells and areas of natural discharge. Helps to regulate stream discharge by temporarily storing part of flood flow and releasing water to streams after flood crest passes.
	Pleistocene	Lake sediments	0–135±	Lake-deposited clay, silt, and sand; locally grades into delta deposits.	Generally saturated. For the most part, transmit water very slowly toward pumped wells and areas of natural discharge. Delta deposits transmit water more freely.
		Glacial till	0–50±	Unsorted rock debris, principally silt and clay, left as residue by melting glacial ice. Locally contains irregular bodies of unstratified to poorly stratified sand and gravel.	Generally saturated. For the most part, transmits water exceedingly slowly toward pumped wells and areas of natural discharge.
		Outwash deposits	0–25±	Moderately well sorted sand and gravel deposited by melt water from glacial ice. Generally enclosed by till.	Generally saturated. Yield water freely to wells, but the enclosing till prevents free lateral movement to natural areas of discharge.
		Pierre shale	65–210	Predominantly shale, claystone, siltstone, and clay.	Nearly impermeable. Not considered to be an aquifer because it transmits water so slowly.
		Niobrara formation	70±	Calcareous shale.	Do.

Cretaceous	Upper Cretaceous	Carlile shale	240	Shale containing calcareous concretions and a few thin layers of sandstone.	Shale nearly impermeable. Sandstone layers formerly were tapped by a few wells, but no wells are known to tap it at present.
		Greenhorn limestone	15-50	Impure limestone.	Nearly impermeable. Not considered to be an aquifer because it transmits water so slowly.
		Graneros shale	200-325	Shale containing thin layers of sandstone near its base.	Shale nearly impermeable. Sandstone layers contain water under sufficient pressure to flow at the land surface. In places, water is muddy.
	? Lower Cretaceous	Dakota sandstone	200-650	Shale interbedded with sandstone.	Shale nearly impermeable. Sandstone layers contain water under sufficient pressure to flow at the land surface. Tapped by about 2,400 wells in Lake Dakota plain area.
Precambrian				Granite and quartzite.	Impermeable, or nearly so. Not considered to be an aquifer.

CRETACEOUS SYSTEM

DAKOTA SANDSTONE

The term Dakota sandstone is used in this report to include all the Cretaceous rocks older than the Graneros shale. Although it is reasonable to assume that at least the upper part of the Dakota sandstone in the Lake Dakota plain area is stratigraphically equivalent to the Dakota sandstone in its type area in northeastern Nebraska, it may include in its lower part the equivalents of two or more older formations that are exposed in the vicinity of the Black Hills. The Dakota sandstone of earlier geological reports on the Black Hills vicinity was subdivided by Darton (1901, p. 526–530) into four distinct formations—the Lakota sandstone, the Minnewaste limestone, the Fuson shale, and the Dakota sandstone. A later geologist, Russell (1927, 1928), determined that Darton's Dakota sandstone in the Black Hills vicinity is older than the Dakota in its type area, and he named it the Fall River sandstone. Recently, Waagé (1959) changed the name of the Fall River sandstone to Fall River formation and redefined the Lakota sandstone, changing the name to Lakota formation and including in it the Fuson and Minnewaste limestone members. How much, if any, of the redefined Fall River and Lakota is included in the Dakota sandstone as used in this report cannot be determined conclusively from present evidence. However, where the Dakota sandstone has been found to consist of an upper part of interbedded sandstone and shale, a middle part of shale, and a lower part of interbedded sandstone and shale, the South Dakota Geological Survey has designated the upper part Dakota sandstone, the middle part Fuson shale, and the lower part Lakota sandstone. (See logs of wells 117–61–13baa1 and 119–61–33ad1 in table C.)

The layers and lenses of sandstone in the Dakota probably constitute no more than one-fourth to one-fifth of the formation, the remainder being shale. Although drillers report a first flow, a second flow, and so on, as they deepen a hole through successive water-bearing sandstones, no evidence indicates that the sandstones producing the flows can be correlated from well to well over long distances. The sandstones differ in grain size, some being fine grained and others medium to coarse. Also, some of the sandstones are friable, whereas some are moderately to firmly cemented.

Because the Dakota sandstone was deposited on an irregular surface, its total thickness differs from place to place, ranging from not less than 180 feet to possibly as much as 650 feet. The greater thicknesses would be the more likely to include beds older than the type Dakota. No evidence of an erosional surface at the top of the Dakota has been reported.

The depth to the top of the Dakota sandstone is known with reasonable certainty for only three points in the area. The logs of wells 117-61-13bbaa1 and 123-60-7ccc1 indicate the top of the Dakota to be at depths of 867 feet and 790 feet, respectively (table C), and the log of a well drilled for the city of Aberdeen (Erickson, 1955, p. 22) indicates the top of the Dakota to be 830 feet below the land surface. Furthermore, the minimum depth of wells reported to tap the Dakota is 750 feet. From the available evidence it is concluded that the top of the Dakota is nowhere less than about 725 feet below the land surface and may be as much as 1,000 feet below the land surface.

The water-bearing sandstones in the Dakota constitute the most publicized artesian system in the United States. About 2,400 wells in the Lake Dakota plain area, or about 70 percent of the wells shown on plate 1, tap the Dakota and, of these, nearly all flow. Some wells tap only one water-bearing sandstone in the formation, whereas others tap two, three, or possibly more.

GRANEROS SHALE

The Graneros shale, which overlies the Dakota sandstone, is 200 to 325 feet thick. It consists mainly of dark-gray shale, but near its base contains thin beds of sandstone. Both Darton (1905, p. 62) and Todd (1909, p. 10) reported that a stratum, apparently near or at the base of the Graneros, contains muddy water under sufficient pressure to flow at the land surface; they referred to it as the "mud flow." According to drillers a well casing in contact with the "mud flow" is likely to corrode and allow salty and turbid water to enter the well. The turbidity of the water from well 117-62-32abaa1, 840 feet deep, suggests that this well taps the "mud flow" in the Graneros in addition to sandstones in the upper part of the Dakota. Wells 117-62-33aaaa1, 118-62-28cbcc1, and 125-63-26bbcc1, which are 800, 750, and 780 feet deep, respectively, probably tap water-bearing sandstones near the base of the Graneros. So far as is known, the water from these wells is clear.

GREENHORN LIMESTONE

The Greenhorn limestone, which overlies the Graneros shale, consists of hard thin-bedded layers of fossiliferous impure limestone. The formation, which in the report area is about 15 to 50 feet thick, is recognized readily by drillers as the caprock and is easily identified on electric logs. Although it is not an aquifer, the distinctive lithology, geophysical properties, and widespread distribution of the Greenhorn make it an excellent stratigraphic marker. A map showing the configuration of the top of the Greenhorn in northeastern South Dakota, prepared by Erickson (1955) from very few data, indicates that the average dip of the formation is about 1 foot per mile toward the southwest in the southern part of the Lake Dakota plain area and toward the west in the northern part.

CARLILE SHALE

The Carlile shale, which is about 240 feet thick, overlies the Greenhorn limestone. It consists chiefly of dark-gray to blue-gray shale and contains numerous calcareous concretions and a few thin layers of sandstone. A water-bearing sandstone, probably the Codell sandstone member, lies at or near the top of the formation. Years ago a few wells in the area obtained water from this sandstone, but at present no wells are known to tap it.

NIOBRARA FORMATION

The Niobrara formation overlies the Carlile shale and in the Lake Dakota plain area consists of calcareous shale which is not easily distinguishable from similar beds in the basal part of the overlying Pierre shale. Possibly the Niobrara is locally absent. Where the Niobrara is recognized, its average thickness is about 70 feet. The formation is not an aquifer in the area, although farther south in the James River lowland, where the Niobrara is a chalky limestone, it yields small quantities of water to wells. The water from the Niobrara generally is of poor quality.

PIERRE SHALE

Although the Pierre shale contains some thin beds of limestone, shaly chalk, and sandstone, it consists predominantly of dark shale, claystone, siltstone, and clay. The descriptions of the lithology of the Pierre shale in several of the logs in table C show the range in composition of the formation.

The Pierre shale is exposed at a few places along the lower end of Turtle Creek, along the James River northeast of Redfield, and in a draw west of Doland. Thin layers of cream-colored chalk interbedded with shale in a road cut 1½ miles southeast of Redfield are considered by Searight and Moxon (1945, p. 6) to be part of the Pierre shale.

The Cretaceous rocks were exposed to subaerial erosion throughout most, if not all, of Tertiary time. How much of the Pierre shale in the Lake Dakota plain area was carried away by the streams that drained its surface is not known, but it probably was at least 500 feet. From the little information available, the thickness of the Pierre shale that remains in the area is estimated to range from about 65 to 210 feet, but according to Flint (1955, fig. 5), the thickness of the Pierre is as much as 600 feet beneath the Coteau des Prairies and as much as 800 feet beneath the Coteau du Missouri. The logs of wells and test holes drilled to the Pierre shale indicate that the top of the Pierre lies between 1,150 and 1,300 feet above sea level throughout nearly all the area. (See table D.) The lowest known points are a few miles southwest of Aberdeen, where the surface of the Pierre is 1,087 feet above sea level in test hole 122–64–30baaa1 and below 1,081 feet above sea level in test hole 121–65–1aaaa1. These two points are near the south end of the Lords Lake buried channel, which was described by Rothrock (1955, p. 20–22, illus. 2–4).

The Pierre shale is so nearly impermeable that drilling for shallow supplies of ground water rarely is continued below the top of the formation. Well 117–61–35bbbb2 is the only well in the area that may be tapping the Pierre shale. The water from this well is highly mineralized.

QUATERNARY SYSTEM

The unconsolidated rock debris that mantles the Cretaceous bedrock consists principally of materials that were deposited during the Pleistocene epoch, or ice age. Although the materials close below the land surface in the Lake Dakota plain area were deposited during and following the melting of the last, or Wisconsin, ice sheet, evidence in areas nearer to the periphery of glaciation indicate that at least three earlier ice sheets had advanced over the area. The glacial deposits in the area are assumed, therefore, to consist of materials associated with each of the four glaciations.

When the glacial ice advanced, it picked up and incorporated within itself soil and rock fragments derived from the surfaces it overrode. Where that surface was deeply weathered, the rock fragments picked up were mostly fine grained; but where the surface consisted of coarsely disintegrated rock or bedrock still in place, the rock fragments picked up were of many sizes, some as large as immense boulders. Because the glaciers overrode differing terranes, they acquired rock fragments of various sizes and lithology; many of the fragments were pulverized into rock flour by the grinding action of the ice.

Streams of melt water from the glacier transported rock fragments away from the ice margin. As the carrying power of the streams lessened, the coarsest rock fragments were dropped first and the finest last. The resultant deposits, termed "outwash," are horizontally stratified and consist of interbedded lenses of fine- and coarse-grained materials. Where saturated, several feet thick, and areally extensive, these deposits are capable of yielding moderately large to large quantities of water to wells.

The rock debris in the glacial ice that was not carried off by the melt-water streams was left as a residue at the farthest point to which it had been transported. Such deposits, called till, show little or no evidence of sorting. Till underlies much of the Lake Dakota plain area, but it is exposed only outside the area of lake beds. Because the till consists largely of silt and clay, it is nearly impermeable and yields very little water to wells.

According to Todd (1909, p. 8), when the margin of the last great ice sheet had melted back into North Dakota, melt water flowing from it accumulated in a shallow depression in what is now referred to as the James River lowland. Todd, who gave the name of Lake Dakota to this glacial lake, referred to the deposits on its floor as Lake Dakota silts. However, Rothrock (1943, p. 32) points out that some geologists have doubted the existence of the lake because beaches, wave-cut cliffs, and other shoreline phenomena are lacking. Be that as it may, the area is a distinct topographic unit that is widely known as the Lake Dakota plain, which name was adopted for use in this report.

The types of material comprising the glacial deposits have been revealed by drilling test holes. (See table C.) In the test holes drilled by the Bureau of Reclamation clay, silt, and fine sand—described as lake deposits—constituted about 50 percent of the materials penetrated. These materials were finely laminated, or varved, and generally were present just beneath the soil. In a few test holes they extended all the way to bedrock; however, except for those holes drilled outside the Lake Dakota plain proper, the so-called lake deposits were underlain by materials identified as till or outwash deposits. Till, which is a direct deposit of glacial ice and is characterized by a wide range in grain size and a lack of obvious arrangement of component grains, constitutes about 38 percent of the material penetrated in the drilling of the test holes. Typically it is a silty clay in which fragments ranging in size from sand to boulders are embedded. Also enclosed within the till are small bodies of unstratified to poorly stratified sandy gravel, sand, and silt. The outwash deposits, which constitute about 8 percent of the total, consist of coarse sand, sandy gravel, or cobbles intermixed with gravel. Included with the outwash deposits are the delta deposits that underlie an area of about 35 square miles, principally in T. 124 N., R. 63 W. (Rothrock, 1955, p. 19–21). The delta was formed in glacial Lake Dakota at the mouth of the ancestral Elm River. The remaining 4 percent was identified as wind-deposited or stream-laid material and generally was interlayered with the lake deposits. Considered as a whole, the glacial deposits in the Lake Dakota plain area are mostly fine grained; about 42 percent is predominantly clay, about 39 percent silt, 18 percent sand, and 1 percent gravel.

The alluvium in the stream valleys, the sand dunes in the northern part of the area, and the veneer of loess and soil throughout nearly the entire area are of Recent age, but, in general, are composed of weathered and reworked Pleistocene deposits. Their total volume probably is no more than one one-hundredth as great as that of the glacial deposits.

The thickness of the unconsolidated Quaternary deposits ranges from a featheredge around the periphery of bedrock exposures to more than 256 feet in the Lords Lake buried channel a few miles southwest of Aberdeen. Available logs of holes drilled to bedrock indicate that the average thickness of the deposits is 76 feet.

About 30 percent of the wells shown on plate 1 tap the Quaternary deposits. However, not all these wells are sources of water supply, many being used only for observation of water-level fluctuations or not used at all. Unlike the wells tapping the Dakota sandstone, these wells do not flow.

GROUND WATER

Except for the very few wells that tap Cretaceous rocks other than the Dakota sandstone, all wells in the Lake Dakota plain area either tap the Dakota or the glacial deposits. Because the two aquifers differ in so many respects, they are discussed separately in this report.

WATER IN THE DAKOTA SANDSTONE

The presence of an artesian aquifer beneath the James River lowland was known at least 10 years before South Dakota became a State. A well at Aberdeen, 1,066 feet deep and drilled in 1881, was among the first in South Dakota to tap this aquifer. Hundreds of deep wells had been drilled by 1920, and while still new most of them had a strong flow. The availability of such an ample supply of ground water without the need for pumping equipment prompted early writers to describe the James River lowland as a "Garden of Eden."

RECHARGE

Because the Dakota sandstone in this area is overlain by a thick succession of beds that are practically impervious to water, the places where water enters the formation obviously are outside the area. Also, because water in the Dakota in this area is under sufficient pressure to flow from wells, the places where water enters the formation must be at a higher altitude. Hydrologists long have recognized that the water in the formation throughout the James River lowland is not of local origin and generally have agreed that the formation is recharged principally where it crops out in the vicinity of the Black Hills in western South Dakota. However, G. A. LaRocque and J. R. Jones, of the Geological Survey, who made a hydrologic study of the Oahe unit as originally proposed, believe that only a small part of

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the recharge enters the Dakota where it is exposed and much, if not most, of the recharge is from formations that underlie the Dakota in the western part of the State but crop out at a higher altitude. These underlying formations, notably the Pahasapa limestone and Minnelusa sandstone, receive much greater recharge than does the Dakota from streams crossing their outcrop in the Black Hills region (Brown, 1944, p. 1), and, because they thin eastward to a knife edge west of the James River lowland, the water in them percolates under pressure into the overlying Dakota. LaRocque and Jones believe also that the Dakota may be recharged by downward movement of water in the large area where the hydrostatic pressure in the Dakota is less than enough to raise the water in wells to the top of the zone of saturation in overlying rocks.

MOVEMENT

According to Darton (1909, p. 60–61), the hydraulic gradient (and, therefore, the direction of percolation) of water in the Dakota is generally eastward throughout South Dakota. The rate of eastward percolation toward the James River lowland in T. 129 N. (the southernmost east-west row of townships in North Dakota) was estimated by Meinzer and Hard (1925, p. 90) to be 400 to 500 gpm (gallons per minute), and this estimate probably is equally applicable to each east-west row of townships in the Lake Dakota plain area. The average rate of discharge from the Dakota that could be maintained indefinitely without a regional diminution of hydrostatic pressure would be equal to the rate of eastward percolation across the west boundary of the area of withdrawal.

If the casing of a flowing well tapping the Dakota were to be extended upward to a level that flow no longer occurred, the water level in the casing would coincide approximately with the piezometric, or pressure-indicating, surface of the water in the Dakota at that point. Because some wells tap only one water-bearing stratum and some tap two, three, or possibly more, the water level in the extended casing of one well would not necessarily represent precisely the same piezometric surface as the water level in another well. However, they probably would differ in such a small amount, all other factors being equal, that in this report the water in the Dakota is considered to have only one piezometric surface. This imaginary surface is continuous with the water level in nonflowing wells that tap the Dakota outside the report area, provided the failure to flow is not due to plugging of the well screen or escape of water from the well into rocks overlying the Dakota. Because maps showing the configuration of the piezometric surface, prepared by Erickson (1954, 1955), show that a trough in that surface coincides with the James River lowland and that the trough was created by the release of hydrostatic pressure which has attended the drilling of wells into the formation, it must be assumed also that the reversal of the hydraulic gradient along the east side of the James River lowland indicates that water now percolates into the Lake Dakota plain area from the east as well as from the west. Possibly, therefore, the present rate of percolation into the report area should be regarded as somewhat greater than Meinzer's estimate, which was based on the assumption that percolation was eastward only. If there is no recharge to the Dakota east of the James River lowland, westward percolation of water within the formation constitutes a loss in storage beneath the western part of the Coteau des Prairies.

DISCHARGE AND DECLINE IN ARTESIAN PRESSURE

The total amount of water being discharged from wells tapping the Dakota sandstone in the James River lowland from T. 116 N. through T. 126 N., is estimated to be at least 7,000 gpm, or an average of 635 gpm for each east-west row of townships. This estimate is based on the sum of the reported, estimated, and measured discharges from individual wells that were inventoried during the Geological Survey's investigations of the Crow Creek-Sand Lake area (Koopman, 1957), the Oahe unit as originally proposed, and that part of the Lake Dakota plain area not included in either of the other investigations. Even though the yields of many wells were not measured and so are not included in the total, the average for each east-west row of townships exceeds by about 25 percent Meinzer's estimate of eastward percolation in each east-west row of townships. Because the discharge rate from the Dakota probably was greatest in the first two decades of the century and has declined progressively since that time, it is reasonable to assume that the aggregate discharge from the Dakota since 1900 has greatly exceeded the rate of eastward percolation.

As an explanation for the ability of the Dakota to discharge for so long a time at a rate greater than the rate of eastward percolation from the area of recharge, Meinzer and Hard (1925, p. 90–93) theorized that the water-bearing sandstones in the Dakota are compressible and that their interstitial space has been reduced by a volume equal to the difference between the volume of percolation and the volume of discharge. If the theory of compressibility is correct, water discharged in excess of the rate of percolation has been and is derived from storage in the sandstone. It is interesting to speculate whether the withdrawal of so much water from the Dakota and the resultant compression of the aquifer has resulted in subsidence of the land surface and, in turn, has been a factor contributing to poor drainage of parts of the James River lowland. Although topographic maps made in the 1950's show a much smaller part of the area to be above 1,300 feet than do the topographic maps made in the 1890's and thus would seem to indicate that the land surface has subsided in the meanwhile, it must be recognized that the two surveys were not equally precise and so are not comparable in detail.

The amount of reduction in artesian pressure and attendant lowering of the piezometric surface in the Lake Dakota plain area since the first wells were drilled into the Dakota cannot be determined precisely because the original artesian pressure was recorded for so few wells drilled before 1900. Of the 12 such wells, all south of T. 124 N., for which Todd (1909, p. 11) reported information, the artesian pressure ranged from 80 to 177 psi (pounds per square inch)[2] and averaged 140 psi. The artesian pressure in 57 representative wells that were measured by Todd (1909, p. 11) during 1903–05 in the same part of the Lake Dakota plain area ranged from 42 to 240 psi and averaged 109. In 1954, Erickson (1954, 1955) recorded the pressure in 61 wells south of T. 124 N., but in none was it greater than 55 psi. As the average of Erickson's measurements was only 12.5 psi, the average decline in the altitude of the piezometric surface since Todd made measurements is about 225 feet. Erickson also measured the pressure in 37 wells in T. 124–127 N. and obtained an average of 9 psi. Compared to the average pressure in 8 wells measured by Darton (1909, p. 73, 123) in the same part of the area, the average reduction in pressure is the same as that south of T. 124 N. The decline from the original pressure is estimated to have lowered the piezometric surface about 300 to 350 feet in the Lake Dakota plain area. Although a few deep wells in the area do not flow, the wide distribution of flowing wells indicates that in no part of the area has the artesian pressure in the Dakota sandstone been reduced so much that a flowing well cannot be obtained.

Before wells were drilled into the Dakota, water was discharged from the formation by leakage into overlying rocks and by seepage along the outcrop. The movement of but very small quantities through each unit area of the vast interface between the Dakota and the overlying formations would amount to a large total discharge. Now that the piezometric surface has been lowered and the hydraulic gradient along the east side of the James River lowland has been reversed, percolation out of the Lake Dakota plain area to the areas of natural discharge from the formation presumably has ceased.

Nearly all the wells tapping the Dakota in the Lake Dakota plain area are less than 3 inches in diameter. About one-third are 1¼

[2] 1 psi is equivalent to a head of 2.3 ft.

inches in diameter, and most of the others are ¾, 1, 1½, or 2 inches. The largest reported diameter, that of the municipal-supply well for Groton, is 10 inches. The reported depths range from 750 to 1,500 feet and average about 1,000 feet. In general, the average depth of the wells is less than 1,000 feet southeast of a line extending from T. 118 N., R. 65 W., to T. 121 N., R. 60 W., and north of T. 124 N. and east of R. 62 W.; elsewhere in the area it is more than 1,000 feet.

The maximum rate of flow from a well is governed partly by which and how many water-producing zones are tapped. Both the capacity to transmit water and the hydrostatic pressure probably differ from place to place in the same zone and from zone to zone. Only four of the available logs of deep wells (table C) contain information as to the thickness of and depth to different zones. One, the log for well 116–64–4ad1 near Redfield, indicates a zone 22 feet thick at a depth of 898 feet, a 6-foot zone at 967 feet, and a 38-foot zone at 982 feet. Another, for well 116–62–8ad1 at Frankfort, indicates a 122-foot zone at 803 feet, a 40-foot zone at 945 feet, and an 8-foot zone at 1,000 feet. Both of the other two, for wells 123–61–31cbbb1 and 123–62–32 in Brown County, show only two water-producing zones. The log for 123–61–31cbbb1 indicates a 35-foot zone at 925 feet and a 40-foot zone at 1,108 feet, and that for 123–62–32 indicates two 30-foot zones, one at 960 feet and the other at 1,022 feet. Only the log for well 116–64–4ad1 indicates that drilling was continued to granite. If the other wells had been drilled to granite, possibly additional water-productive zones would have been penetrated. Hard (1929, p. 49) stated that as many as seven successive zones in the Dakota have been penetrated in the drilling of wells in Dickey and La Moure Counties, N. Dak.

The rate of flow from a well also may be governed partly by the condition of the casing. The openings through which water enters the well may become clogged, and corrosion may produce holes in the casing that allow water to escape into permeable rocks younger than the Dakota. By recasing wells whose casings have deteriorated, the flow sometimes is increased appreciably. Many wells in the area have been recased at least once, and some have been recased two or three times.

Escape of gas from the water and changes in atmospheric pressure cause temporary changes in the clearness of the water and the rate of flow from wells tapping the Dakota. Many owners report that the water from their wells becomes roily, milky, dark colored, silty, or sandy during storms or "when the wind comes from the south"—a time commonly coincident with the approach of an area of low atmospheric pressure.

Most wells tapping the Dakota are allowed to flow continuously. However, because the flow from most wells either is reduced by use of a small-diameter discharge pipe or a "pinhole choke" or is controlled by the opening and closing of valves, relatively few wells were flowing at their maximum rate when visited. Of the wells visited in 1955, the maximum rate of flow was 50 gpm from well 117–61–7ddcd1 in Spink County. Drilled in 1948, this well was recased in 1955. The flow from most wells ranged from a trickle to about 5 gpm, and averaged about 2.8 gpm. Some wells are pumped to increase their rate of discharge. In the early part of the century, according to Todd (1909, p. 10), the average rate of flow was about 25 gpm from wells 1¼ inches in diameter and as much as 200 to 300 gpm from wells 3 inches in diameter.

A well, especially one that was poorly constructed or inadequately developed, is likely to flow for a longer time if it is allowed to flow continuously at a slow rate. An abrupt decrease in the velocity of water rising in a well that is closed suddenly may cause particles in suspension to settle and pack at the bottom of the casing, thereby closing the openings from the aquifer to the well. If a well is closed slowly, the coarser particles will settle first and will not necessarily close the openings into the well. Sudden closure of an old well may also cause a weakened casing to rupture; this would result in loss of water and necessitate repairs or the construction of a new well. In cold weather, a flow of about 1 gpm prevents the freezing of water above the frostline in the well.

TEMPERATURE

In only those wells where the water rises fairly rapidly to the surface is the temperature of the water when discharged approximately the same as it was while still in the aquifer. The velocity of flow through a 1¼-inch pipe that is discharging 1 gpm is about 15.7 feet per minute; consequently, the time required for water to rise from a depth of 800 feet in a well of that diameter is nearly 50 minutes. During that time the water cools, possibly several degrees, as the water rises through progressively cooler layers of rock. The average temperature of the water flowing from 323 wells was 57.5°F, or about 14° warmer than the average annual air temperature at Aberdeen. The highest temperature recorded was 64°F.

WATER IN THE QUATERNARY DEPOSITS

Below the water table, the Quaternary deposits in the Lake Dakota plain area are saturated with water under hydrostatic pressure. The water table may be less than 1 foot below the land surface in swampy areas and may be as much as 35 feet or a little more beneath the surface of topographic rises. Unlike water in the Dakota sandstone, the water in the Quaternary deposits is not artesian; the water surface in these wells stands at or near the level of the water table.

Some or all of the interstitial space in the basal part of the material immediately above the water table is saturated with water held by capillary attraction. This water is referred to as the capillary fringe. When the water table rises, the capillary fringe also rises, and when the water table declines, the capillary fringe declines with it. The thickness of the capillary fringe depends on the texture of the material; it may be as much as 8 feet or even more in fine-grained materials, but in coarse materials may be as little as a fraction of an inch.

RECHARGE

The principal source of recharge to the Quaternary deposits is the rain and snow that falls on the area. Measurements of the depth to water in wells scattered throughout the area indicate that the water table generally is highest in late spring or early summer and, therefore, suggest that the recharge rate is greatest at that time of the year. However, the amounts of water-table rise in different years are highly unequal. For example, the measurements of water level in well 121–64–3baab1 (fig. 10) show that recharge in the spring caused a water-level rise of about 4 feet in 1952, 10 in 1953, 3 in 1954, 2 in 1955, and 2 in 1956. During the 5-year period of record for this well, the highest water level was 5.33 feet below land surface and the lowest was 16.56 feet. Comparison of the hydrographs in figure 10 reveals that the amount of recharge not only varies from year to year, but varies from place to place within the same year.

Under differing combinations of conditions, equal amounts of precipitation can result in widely differing amounts of recharge. The more important factors governing the amount of recharge to the Quaternary deposits are discussed in the following paragraphs.

Because saturated or nearly saturated soil that is frozen cannot be penetrated by moisture, precipitation in winter generally accumulates as a mantle of snow and ice that is dissipated through evaporation and melting. However, slowly melting snow and ice on unfrozen ground may be a source of much recharge. Probably the greatest amounts of recharge to the Quaternary deposits are derived from snow melt and rain at the time of the spring thaw and from rain that falls before vegetation leafs out.

Fine-textured soil, especially when cultivated, has the capacity to store large amounts of water. Thus, if the amount of water entering the soil does not exceed the soil's capacity to store moisture, little or none of the water is transmitted downward to the zone of saturation.

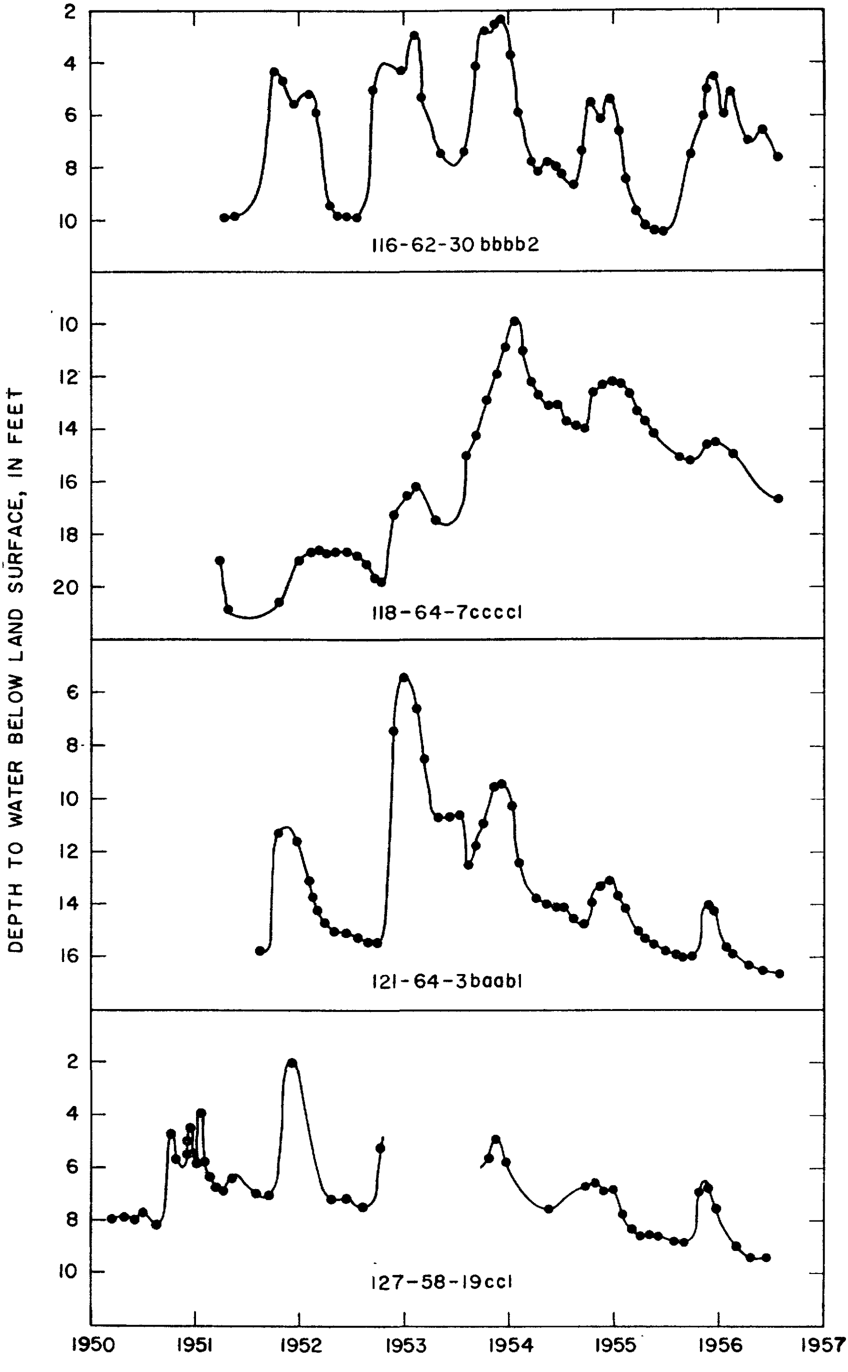

FIGURE 10.—Graphs of water-level fluctuations in four wells tapping Quaternary deposits.

However, if its moisture-holding capacity is exceeded, the soil transmits the excess water downward at a rate largely governed by the minimum permeability of the materials above the water table. The capacity of the soil to store and transmit water may be compared to the similar capacity of a surface reservoir. No water spills over the dam if the reservoir is empty or only partly filled, and only when water enters a full reservoir does spillage occur.

Recharge to the zone of saturation causes a rise of the water table and, consequently, a rise in the water level in wells tapping the water-table aquifer. If, for example, the material that becomes saturated as a result of the recharge has an effective porosity of 25 percent, 3 inches of recharge to the zone of saturation would cause a 1-foot rise of the water level in wells. The amount of water-level rise in a well is a measure of the amount of recharge only if discharge has been negligible during the period of recharge. If discharge has been significant, the actual water-level rise plus an amount equal to the additional water-level rise that would have occurred if there had been no discharge would be a measure of the amount of recharge.

Studies made by Schneider (1958) in Minnesota show that the first recharge in the spring may be due largely to the melting of the frost layer in the soil, the lower part of which was formed from water that moved upward by capillarity from the water table to the frozen soil. Schneider's findings may be equally applicable to the Lake Dakota plain area, the water level in wells sometimes continuing to decline during the early winter even though the ground is frozen and natural ground-water discharge is minimal.

Rain in the summer and fall rarely seems to be a source of substantial recharge because the soil, its moisture having been depleted through evaporation and plant intake, is capable of storing all the moisture that enters it. Unless a summer rain is followed by cool weather and overcast skies, much of the rainwater evaporates before it can infiltrate the soil. Vegetal withdrawal of water from the soil during the growing season generally exceeds the rate of replenishment, and by fall the supply of moisture has been so nearly depleted that for a time the soil usually is capable of storing all the infiltrating moisture.

When the James River is at high stage, it is a source of recharge to the immediately adjacent ground-water reservoir. Although large quantities of river water may go into bank storage at times, they are stored so temporarily that they do not constitute a significant source of recharge to the ground-water supply of the area as a whole. Other sources of recharge that may be important locally are the overland runoff and subsurface inflow from both the west and east sides of the area, subsurface leakage from artesian wells, unused discharge from the flowing wells, seepage from closed depressions that contain water, and seepage along drainageways when they carry runoff.

According to the plan developed by the Bureau of Reclamation for irrigation of the Lake Dakota plain area, an average of 991,000[3] acre-feet of river water would be available for distribution to 445,000 acres of cropland (U.S. Bur. Reclamation, 1960). Most of the water would be consumed by the growing crops, but some would be evaporated in the process of distribution and some would seep to the water table. The water added to the zone of saturation would be an increment to the supply of ground water in the area. Although no appreciable recharge would occur if water sufficient only for crop needs were to be applied, the annual recharge from irrigation might be as much as 175,000 acre-feet if enough water is applied to leach from the soil the undesirable salts that would accumulate as a result of irrigation. The ratio of the potential recharge from irrigation to the present natural recharge rate cannot be estimated from available data; just as the present natural rate differs from place to place and from time to time, so, too, would the recharge from irrigation. If leakage from the canals and laterals proved to be a source of excess recharge and threatened to cause waterlogging, it could be controlled by lining the canals and laterals.

MOVEMENT

Unlike the level water surface of an open reservoir, the water table is similar to a topographic surface of low relief, and if the configuration of the water table is depicted by contour lines, certain generalizations can be made as to the direction and rate of ground-water movement and the hydrologic properties of the material containing the water. The contour lines shown on plate 1 are based on the position of the water level in wells that were measured in October 1956. However, because the control points are so widely scattered and because it was not feasible to determine whether the water level in all the wells coincided with the position of the water table surrounding the wells, caution must be used in interpreting the contour lines.

As drawn, the contour lines indicate that the water table slopes and, therefore, that ground water moves toward either the James River or one of the several drainageways tributary to the James. Because the James River and its tributaries flow southward throughout most of their length in this area, the direction of ground-water movement throughout the largest part of the area is either westward or eastward. The fact that the water table slopes toward drainageways whose

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[3] Net amount after an estimated annual loss of 116,500 acre-feet by evaporation and seepage from reservoirs and canals and an estimated annual diversion of 99,900 acre-feet for irrigation on the Missouri slope. (See fig. 1.)

streams are intermittent indicates that the rate of movement must be exceedingly slow, because, if movement were at a significant rate, the discharge of ground water would maintain a perennial flow in the streams. Furthermore, the steep slope of the water table along the James River (as steep as 40 ft in half a mile) at the southern end of the area indicates that the water-bearing materials, at least in that part of the area, have a very low capacity to transmit water. Although these generalizations pertain to the Quaternary deposits as a unit, they should not be considered applicable to each type of material comprising the whole. As indicated by the test drilling, the Quaternary deposits consist of a variety of materials, some of which are highly permeable and others of which are nearly impermeable. The nearly impermeable materials through which the water must move to reach a stream govern the rate of movement in the aquifer as a whole.

DISCHARGE

In the Lake Dakota plain area ground water is discharged through natural processes such as evaporation, vegetal intake, seepage into streams and closed topographic depressions, and flow from springs. It is discharged artificially when wells are pumped.

Unlike recharge, which is an intermittent process, natural discharge from the ground-water reservoir rarely ceases completely. In the intervals between periods of recharge, lateral percolation of the ground water lowers the water table toward the level at which the hydraulic gradient equals that necessary to overcome the friction of lateral percolation. Discharge through evaporation and vegetal intake and the pumping of water from wells not only hastens the rate of lowering, but it can depress the water table to a level lower than that which could be reached through lateral percolation alone.

In the Lake Dakota plain area, most ground-water discharge occurs through the processes of evaporation and vegetal withdrawals. In large parts of the area, especially along the surface drainageways, the capillary fringe is in contact with the zone of soil moisture and the water lost from the soil by evaporation and plant intake is replenished by upward capillary migration from the water table. In such places the annual discharge of ground water probably exceeds the annual direct recharge from precipitation; part of the discharge consists of water that has percolated laterally from adjoining areas where a zone of aeration intervenes between the capillary fringe and the zone of soil moisture. Direct evaporation of ground water is negligible in the parts of the area where the capillary fringe is not in contact with the zone of soil moisture but is within the reach of plant roots; in those places the only significant natural ground-water discharge, other than by lateral percolation to depressions where the capillary fringe is in contact with the zone of soil moisture, is by plant absorption and consequent loss to the atmosphere through the process of transpiration. The roots of some nonwoody plants, such as alfalfa, and the roots of many trees extend below the zone of soil moisture and obtain water from the capillary fringe, even where it is as much as 30 feet below the land surface. According to studies made at Redfield and Huron by the South Dakota State College (1954, p. 30–31), water use by alfalfa averaged 22.2 inches per year during the period 1950–53. As the amount is several inches more than the average annual precipitation during the same period, the alfalfa must have consumed ground water in addition to precipitation. The same studies showed that corn and wheat, which are relatively shallow-rooted plants, consumed an average of 16.6 and 16.3 inches per year, respectively.

At present, pumpage from wells constitutes only a minute fraction of the total quantity of water discharged from the Quaternary deposits. Not only are the wells that are a source of supply relatively few in number, but their yield is small. Most of them were dug, although some were bored. The dug wells are 24 to 72 inches in diameter and extend only a few feet below the water table, whereas the bored wells are 3 to 36 inches in diameter and many extend to the base of the Quaternary deposits. The pumped water is used principally for domestic and livestock supplies. Withdrawal of water from the Quaternary deposits constitutes, in effect, a salvaging of ground water that would otherwise be discharged by evapotranspiration.

Some of the numerous ponds, or "dugouts," constructed for livestock use extend below the water table and so are maintained by ground water. Evaporation from the surface of such ponds constitutes another minor fraction of the total discharge of ground water from the Quaternary deposits. The average pond is about 150 feet long, 50 feet wide, and 12 feet deep, and was constructed by use of a dragline.

Test drilling has revealed that the Quaternary deposits contain bodies of moderately to highly permeable material capable of yielding large supplies of water to favorably situated and properly constructed wells. A body of stratified sand 84 feet thick and tapped by well 116–61–8dddd2 was found by the pumping-test method to have a coefficient of transmissibility (T) = 286,000 gpd per ft (gallons per day per foot) and a coefficient of storage (S) = 0.028. The well discharges about 1,000 gpm with a drawdown of about 12 feet. A 50-foot thickness of stratified sand tapped by well 117–62–13badal was found to have T = 69,500 gpd per ft and S = 0.043. In many places, however, the Quaternary deposits consist almost wholly of material that has a low capacity to transmit water and thus will yield water to wells at only a low rate. For example, a test made by pumping from well 122–64–

36ccdd1, which extends 19 feet into water-bearing stratified clay, silt, and fine-grained sand, gave $T=39$ gpd per ft and $S=0.001$. As the presence of permeable water-bearing material cannot be detected from surface observations, the location for a well from which a large yield is desired can be determined only by exploratory test drilling or, possibly, by geophysical methods.

Even though the water-table contour lines on plate 1 indicate a hydraulic gradient toward the surface drainageways, very little ground water discharges into the stream channels. A stream into which ground water discharges is termed an "effluent stream." Under natural conditions such a stream continues to flow during periods of no overland runoff; the flow then is maintained by the ground water that is discharging into the channel. Streamflow consisting wholly of ground-water discharge is referred to as base flow. Examination of the available records of discharge at the gaging stations on the James River shows that the James has no base flow, and the river channel is dry at each station for a period of a few days to several months nearly every year. Apparently, therefore, the ground water percolating toward the James or its tributaries is discharged en route by evapotranspiration, and little or none remains to be discharged as surface flow.

Possibly the flow in the James is maintained beyond the period of overland runoff by the return to the river of water that has been stored in its banks during high stages. That large quantities of river water either go into bank storage or are evaporated is indicated by the losses in streamflow that frequently are recorded between successive downstream gaging stations. Although, strictly speaking, the James River may be considered influent at high stages and effluent during periods immediately following high stages, it is a significant agent of ground-water recharge and discharge only within its narrow valley. It is not a significant agent of recharge and discharge for the Lake Dakota plain area as a whole.

The Bureau of Reclamation's plan for irrigating the Lake Dakota plain area proposes to augment ground-water discharge by installing tile subsurface drains, collector drains, and main outlet drains that will discharge into the James River. The drains, which are to be placed about 330 feet apart and 9 feet below the land surface, will be designed to remove all noncapillary water from the root zone in 48 hours (U.S. Bur. Reclamation, 1957, p. 91). Drains probably would not be needed in those parts of the irrigated area that are underlain by layers of moderately to highly permeable material if the position of the water table were controlled by pumping water from strategically placed wells. The pumped water, if not needed locally or of too poor quality for use, could be conveyed by ditch or pipe to the nearest surface drainageway.

TEMPERATURE

The average temperature of the water yielded by 151 wells tapping the Quaternary deposits was 48.6° F. Because most of the measurements were made in the summer, the water may have had an opportunity to become slightly warmed between the time it left the aquifer and the time the temperature was measured. Probably, therefore, the average temperature of the water while still in the aquifer is a little cooler. The lowest water temperature recorded was 44° F, which is 1° warmer than the average annual air temperature at Aberdeen.

Seasonal variations in the temperature of shallow ground water, perhaps as much as 3° to 5°, are to be expected as the sediments are warmed and cooled in response to changes in air temperature. The extremes in water temperature probably lag as much as 2 to 3 months behind the extremes of air temperature.

CHEMICAL QUALITY OF THE WATER

Water from natural sources always contains some chemical constituents in addition to the oxygen and hydrogen of which water itself is composed. Even rainwater, the purest water of natural origin, contains such impurities as dissolved atmospheric gases. In addition to such impurities, ground water contains chemical constituents dissolved from organic and mineral material composing the earth's crust. For this investigation, the concentrations of the principal chemical constituents were determined, certain properties of the water dependent on the concentrations of the chemical constituents were measured, and the ratios of the concentrations of certain constituents to each other were calculated for the water in the report area.

All the sampling sites except for the Missouri River are shown on plate 2, and the results of the analyses of the dissolved mineral constituents are shown in parts per million in tables 3, 4, E, and F. A part per million (ppm) is a unit weight of a constituent in a million unit weights of sample. In some of the illustrations and in parts of the text the concentrations of the chemical constituents are given in equivalents per million. An equivalent per million (epm) is a unit chemical-combining weight of a constituent in a million unit weights of sample. Analytical results in parts per million are converted to equivalents per million by multiplying parts per million by the following factors.

Cation	Conversion factor	Anion	Conversion factor
Calcium (Ca^{++})	0.04990	Carbonate (CO_3^{--})	0.03333
Magnesium (Mg^{++})	.08224	Bicarbonate (HCO_3^-)	.01639
Sodium (Na^+)	.04350	Sulfate (SO_4^{--})	.02082
Potassium (K^+)	.02558	Chloride (Cl^-)	.02820
		Fluoride (F^-)	.05263
		Nitrate (NO_3^-)	.01613

The pH is a measure of the acidity or alkalinity of the water: a pH of less than 7 is acidic, a pH of 7 is neutral, and a pH of more than 7 is alkaline.

Specific conductance is a measure of the ability of a water to conduct electricity and is expressed in micromhos per centimeter at 25°C. (The basic unit of conductance is the mho, but the unit is so large that for convenience the micromho, which is one-millionth of a mho, is used.) For brevity, specific conductance is expressed in this report as "micromhos per centimeter." The specific conductance depends on the amount of dissolved minerals in the water; and the larger the amount of dissolved minerals, the higher the specific conductance. Specific conductance, therefore, provides a convenient method for roughly estimating the amount of dissolved minerals in the water. Care must be taken in the estimation, however, because the specific conductance depends also on the types of ions in the water.

Percent sodium is the ratio of the concentration of sodium to the total concentration of cations in equivalents per million. Sodium-adsorption-ratio (SAR) is closely related to percent sodium. Both ratios are useful in evaluating the suitability of water for irrigation.

MINERAL COMPOSITION OF WATER FROM THE DAKOTA SANDSTONE

Water from the Dakota sandstone is highly mineralized; the specific conductance of 71 samples ranged from 2,590 to 4,380 micromhos per centimeter. (See table E.) Most of the water sampled is of the sodium sulfate type and is soft, some is of the sodium sulfate type and is hard, and a small part is of the sodium chloride type and is soft.

Because the Dakota sandstone is composed of sandstone beds separated by shale layers, several investigators of the quality of water from the Dakota in the State of North Dakota have attempted to relate water types to the rock layers, or "zones," from which the water flows. Wenzel and Sand (1942, p. 22) observed that, in general, water from the upper part of the Dakota sandstone is soft and water from the lower part is hard. In the report area, most of the water used is from the first or second zone penetrated in drilling; water from the first zone is soft, whereas water from the second zone is hard.

MINERAL COMPOSITION OF WATER FROM THE QUATERNARY DEPOSITS

The water from the Quaternary deposits is heterogeneous in specific conductance and in the relative amounts of the various dissolved minerals (percentage composition). The specific conductances of the water from 322 wells ranged from 246 to 13,300 micromhos per centimeter. (See table F.) They differed widely not only from place to place, but also within the same locality (pl. 3). They even differed widely in water from closely spaced wells that have about the same depth (for example, wells 123–62–17bd1 and –17bd3). Water having a specific conductance of less than about 1,600 micromhos per centimeter apparently is most abundant in the extreme southern, the west-central, and the northwestern parts of the report area. Water having a specific conductance of more than 5,000 micromhos per centimeter (not represented separately on pl. 3) was found principally in areas outside or near the periphery of the old lake bed.

The specific conductances of water from many wells changed noticeably from year to year and probably from season to season (for example, wells 123–63–6ad1 and 118–64–7cccc1, table F). They also changed during aquifer tests, ordinarily by increasing (for example, wells 116–61–8dddd2 and 117–64–4cbdd2).

The concentrations of the principal chemical constituents in water from the Quaternary deposits are plotted against specific conductances in figures 11 and 12. Certain ions react similarly when in water solution and can be combined in the evaluation of water-quality data; therefore, calcium was plotted with magnesium, and sodium was plotted with potassium. The concentrations vary widely from the averages, which are represented in the figures by curves.

The average concentration of calcium plus magnesium exceeds the average concentration of sodium plus potassium in water in which the specific conductance is less than about 8,000 micromhos per centimeter (fig. 11). The averages show only the quality characteristics of the water in the report area as a whole and do not necessarily indicate the quality characteristics of water from individual wells.

In water having a specific conductance of less than about 1,600 micromhos per centimeter, the average concentration of bicarbonate exceeds the average concentration of sulfate or chloride. In water having a specific conductance of more than about 1,600 micromhos per centimeter, the average concentration of bicarbonate remains fairly uniform, whereas the concentration of sulfate or chloride increases significantly (fig. 12). Sulfate is the predominant anion in most water having a specific conductance of more than 1,600 micromhos per centimeter; chloride is the predominant anion in water from only a few places and only in water having specific conductance of more than 3,000 micromhos per centimeter.

The concentrations of nitrate shown in table F were generally less than about 20 ppm; however, a few were much higher (1,240 ppm in water from well 117–61–14bbbc2). Most water that had concentrations in excess of about 20 ppm was from wells less than about 30 feet deep; many of these shallow wells were stock wells in or near corrals. The high nitrate concentrations probably are caused by contamination from surface sources.

RELATION OF WATER QUALITY TO USE

Interest in the quality of the water in the report area centers around domestic, stock, and irrigation uses. Little is known about the quality requirements of water for stock use, but generally water of suitable quality for domestic use is also of suitable quality for

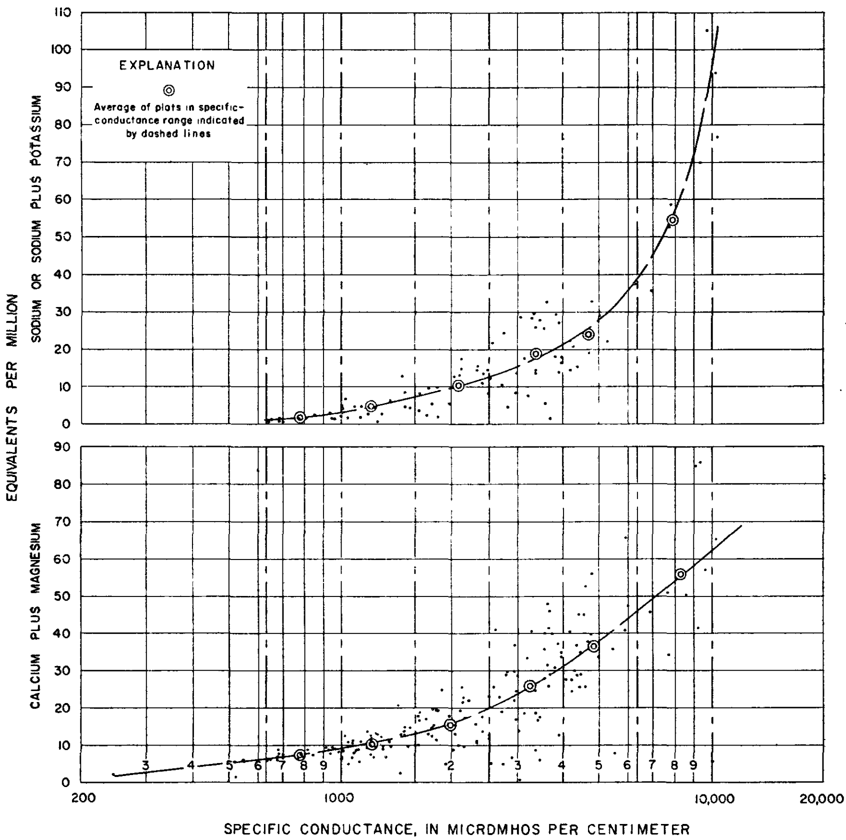

FIGURE 11.—Relation of concentrations of cations to specific conductance of water from Quaternary deposits.

stock use. The following discussion is limited, therefore, to the quality of water for domestic use and for irrigation.

DOMESTIC USE

Ground water is a complex solution and contains many dissolved substances; even a very comprehensive chemical analysis cannot disclose the concentrations of all the constituents. The constituents of most importance to domestic users are calcium and magnesium, iron and manganese, fluoride, sulfate, chloride, and nitrate. The presence of high concentrations of these constituents may make the water unfit for domestic use because of their physiological effects on human beings or because of esthetic or economic reasons.

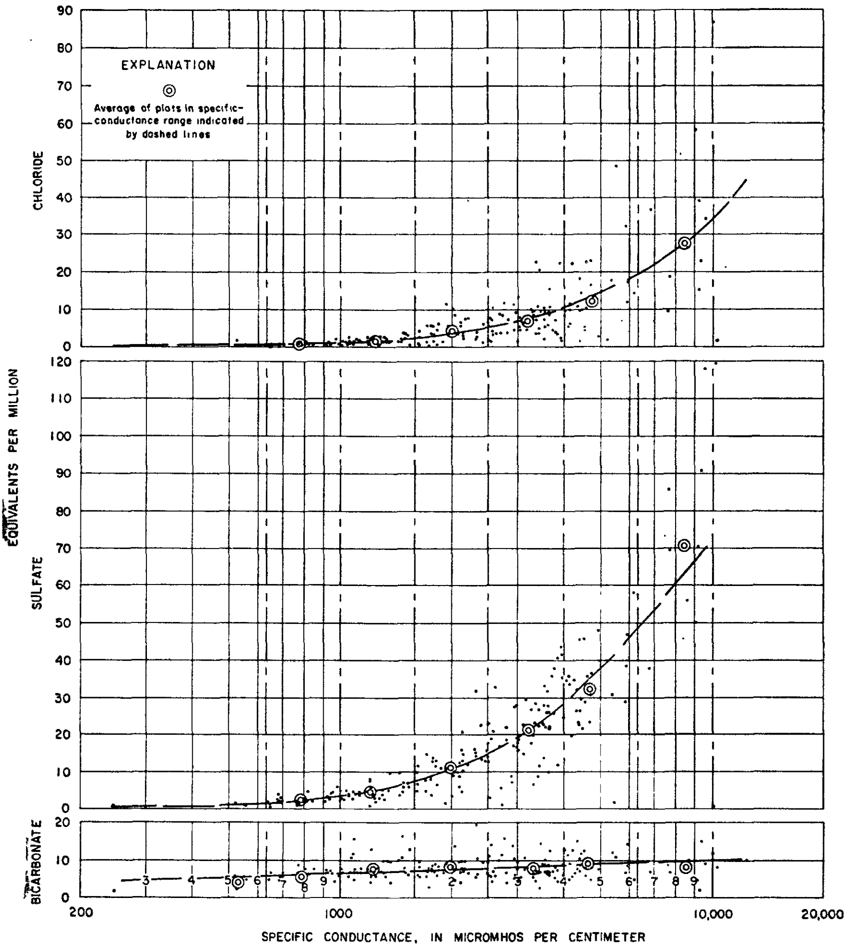

FIGURE 12.—Relation of concentrations of anions to specific conductance of water from Quaternary deposits.

The U.S. Public Health Service in 1914 established standards for the quality of water used in interstate traffic under its jurisdiction. The standards tend to be conservative because they are designed for the protection of people who are easily affected by changes in water and who have no opportunity to become accustomed to the water. The standards were revised in 1946 and were adopted by the American Water Works Association for all public supplies. The standards pertaining to some of the chemical constituents are as follows:

Constituent	*Concentrations not to be exceeded (ppm)*
Iron plus manganese (Fe+Mn)	0.3
Magnesium (Mg)	125
Sulfate (SO_4)	250
Chloride (Cl)	250
Fluoride (F)	1.5
Nitrate (NO_3)	[1] 44
Dissolved solids	[2] 500

[1] Maxcy (1950, p. 265). Not a Public Health Service recommendation.
[2] 1,000 ppm permitted if water of better quality is not available.

Iron and manganese stain laundry and porcelain fixtures, and they can be tasted in concentrations higher than 0.5 to 1.0 ppm (California Inst. Tech., 1957, p. 276). Also, iron may promote the growth of so-called iron bacteria, which, in turn, may make the water unpalatable.

High concentrations of chloride cause water to taste salty and may cause physiological injury to people suffering from certain heart or kidney ailments.

Fluoride in high concentrations in drinking water used during the calcification of the teeth may cause the enamel to be mottled (Dean, 1936). The mottling becomes noticeable if the concentrations exceed about 1.5 ppm and becomes pronounced if the concentrations exceed about 3.0 ppm. However, small amounts of fluoride aid in sound tooth development and lessen the incidence of dental caries. The presence of 0.6 to 1.5 ppm in water probably satisfies the requirement for sound tooth development (Am. Water Works Assoc., 1950, p. 56–57).

High concentrations of sulfates in drinking water may cause a laxative effect; however, many persons develop a tolerance to sulfates through continued use of the water. A cathartic dose of sulfate is 1.0 to 2.0 grams, which is equivalent to a liter of water containing 1,000 to 2,000 ppm of sulfate (California Inst. Tech., 1957, p. 378).

Nitrate is the end product in the oxidation of organic nitrogen compounds; therefore, high concentrations of nitrate may indicate pollution from organic wastes. Also, high concentrations of nitrate may cause cyanosis in infants who are given the water in feeding formulas.

Calcium and magnesium in water cause hardness, which impairs the quality of the water because of curd that forms when soap is added and because of scale that is deposited in pipes and in water heaters and boilers. No specific standards for hardness have been established, but the following gradations are generally recognized.

Hardness as $CaCO_3$ (ppm)	Rating of water	Suitability of water
<60	Soft	Suitable for many uses without further softening.
60–120	Moderately hard.	Usable except in some industrial applications.
121–180	Hard	Softening required by laundries and some other industries.
>181	Very hard	Requires softening for most uses.

Magnesium in high concentrations, especially when associated with sulfate, may act as a laxative.

WATER FROM THE DAKOTA SANDSTONE

The water from the Dakota sandstone generally is of unsuitable quality for domestic use, according to the standards for public supplies. The concentrations determined exceeded the suggested maximums for iron in nearly all the samples, for chloride in about a third of the samples, and for fluoride in nine-tenths of the samples. The concentrations of sulfate and of dissolved solids for all the samples exceeded by several times the suggested maximums. The water ranges in hardness from soft to very hard.

Although of poor quality for domestic needs, the water is used because no better water in sufficient quantity is available in much of the area. People accustomed to drinking the water claim that they suffer no ill effects and that less mineralized water tastes flat.

WATER FROM THE QUATERNARY DEPOSITS

Water from the Quaternary deposits also is generally of poor quality for domestic use. The concentrations of iron, or iron plus manganese, exceed the suggested maximum concentrations in about 60 percent of the samples analyzed. The dissolved-solids content, shown by analysis or estimated from the specific conductance, exceeded 1,000 ppm in most of the samples. Water from nearly all the wells is very hard.

The percentages of the samples in which the concentrations of magnesium, sulfate, chloride, and nitrate equaled or exceeded given concentrations are shown in figure 13. The suggested maximum concentrations were exceeded by sulfate in 66 percent of the samples, by chloride in 33 percent, by magnesium in 28 percent, and by nitrate in 20 percent. The concentrations of fluoride in all samples analyzed were low.

IRRIGATION

Water for irrigation is used under many different conditions of climate, soil structure and drainage, type of crop, and farm-management practices. Water that is of satisfactory quality for irrigation under one set of conditions may not be satisfactory under another set of conditions. The conditions may be as important as the quality of the water in determining the suitability of the water for use and must be given careful attention.

Generally, water for irrigation should be of such quality that it will not adversely affect the productivity of the land to which it is applied. Investigators have suggested methods for classifying irrigation water so that its long-term effect on soil productivity can be predicted (Wilcox, 1948; Scofield, 1936; Eaton, 1950; U.S. Salinity Laboratory Staff, 1954). All methods of classifying water are arbitrary to a certain degree. The method of classification used in this report was proposed by the U.S. Salinity Laboratory Staff (1954).

Certain properties are of principal importance in determining the quality of water for irrigation. These properties are the total concentration of the dissolved salts, the relative proportion of sodium to calcium and magnesium, the concentration of boron or other elements that may be toxic, and, for some water, the concentration of bicarbonate as compared with the concentrations of calcium and magnesium.

High concentrations of dissolved salts in irrigation water tend to cause an accumulation of salts in the soils and to make them saline. Because plants take in water by osmosis, a favorable balance must be maintained between salts within a plant and salts in the soil solution. When the total concentration of salts in the soil solution becomes too high for plants to take in an adequate amount of water or when the concentration of certain salts in the soil solution becomes so high as to be toxic, the growth of the plants is adversely affected. The tendency of irrigation water to cause an accumulation of salts in the soil is called the salinity hazard of the water. The specific conductance of the water is used as an index of the salinity hazard.

High concentrations of sodium relative to the concentrations of calcium and magnesium in irrigation water can adversely affect soil structure. Cations in the soil solution become fixed on the surface of fine soil particles; calcium and magnesium tend to flocculate the particles, whereas sodium tends to deflocculate them. Flocculation gives the soil looseness, provides good penetration by water and air, and generally gives the soil good tillage properties. Deflocculation promotes packing and prevents free movement of air and water. The adverse effect on soil structure caused by high sodium concentrations in the irrigation water is called the sodium hazard of the water.

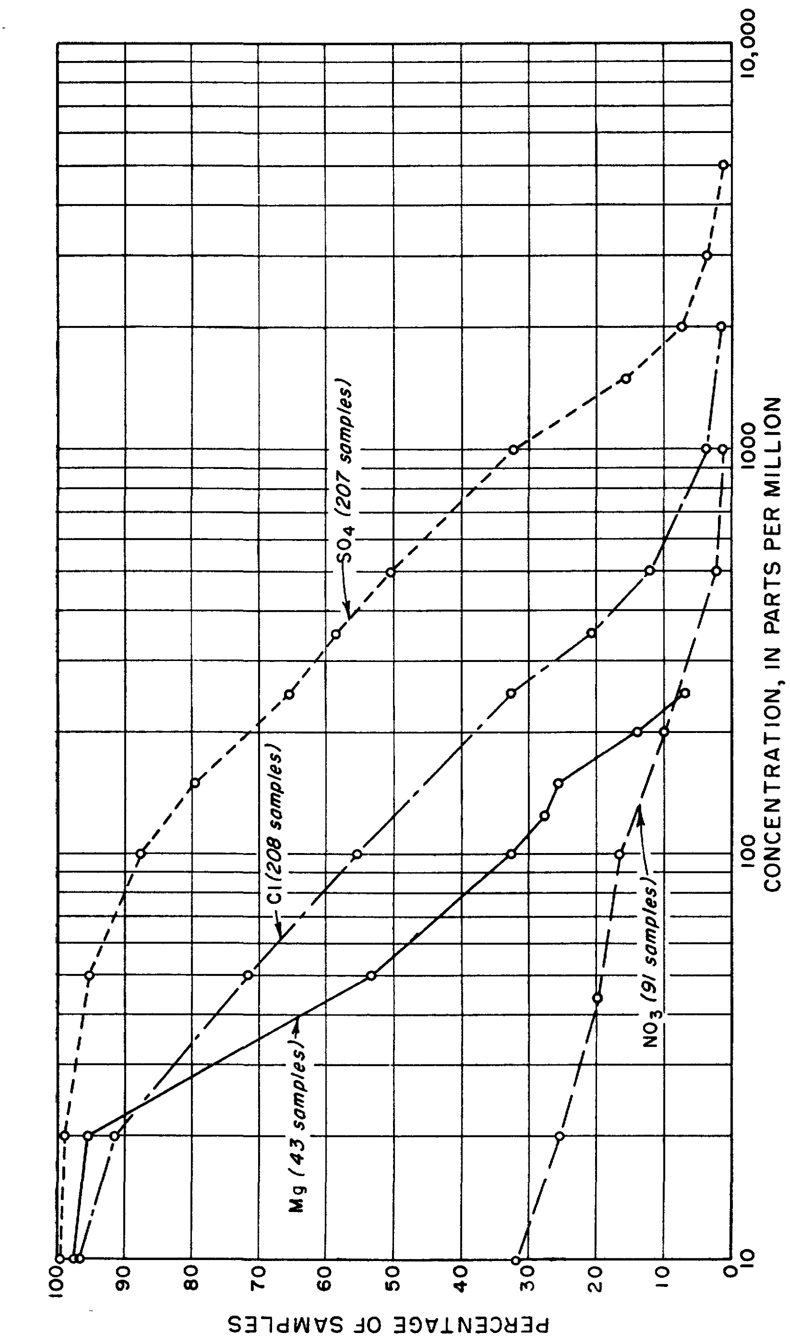

FIGURE 13.—Percentage of samples in which concentrations equaled or exceeded given concentrations.

An index used for predicting the sodium hazard of a water is the sodium-adsorption-ratio (SAR), which is defined by the U.S. Salinity Laboratory Staff (1954) as follows:

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

where, Na^{+}, Ca^{++}, and Mg^{++} are expressed in milliequivalents per liter (nearly identical to equivalents per million).

The salinity hazard and the sodium hazard of the water may be evaluated by use of a diagram by the U.S. Salinity Laboratory Staff (1954). Interpretation of the diagram (fig. 14) is as follows:

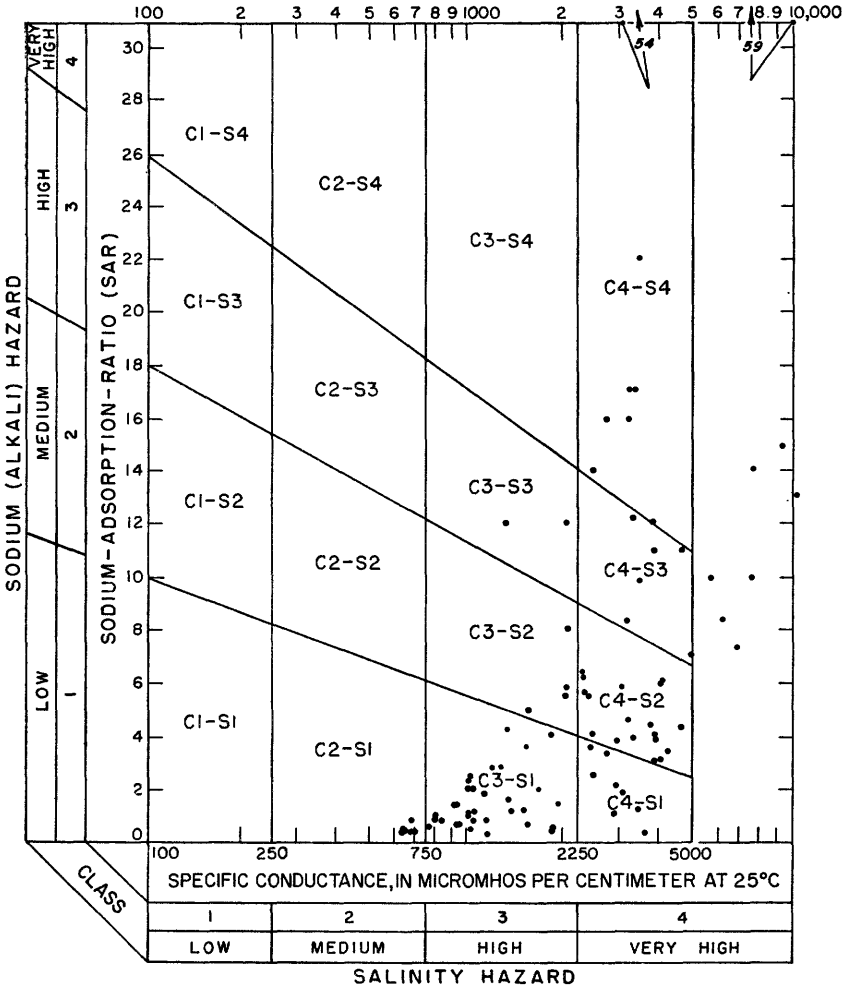

FIGURE 14.—Classification for irrigation of water from Quaternary deposits. Diagram after U.S. Salinity Laboratory Staff (1954).

Low-salinity water (C1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-salinity water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

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, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical condition of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues when exchangeable sodium values are lower than those effective in causing deterioration of the physical condition of the soil.

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. However, sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

Medium-sodium water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange-capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-sodium water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very high sodium water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

Boron is essential to the normal growth of all plants; however, if present in excessive concentrations, it may be highly toxic to some species of plants. Scofield (1936) proposed the limits shown in the following table.

Permissible limits for concentration of boron, in parts per million, in several classes of water for irrigation

Boron class	Sensitive crops	Semitolerant crops	Tolerant crops
1	<0. 33	<0. 67	<1. 00
2	. 33-. 67	. 67-1. 33	1. 00-2. 00
3	. 67-1. 00	1. 33-2. 00	2. 00-3. 00
4	1. 00-1. 25	2. 00-2. 50	3. 00-3. 75
5	>1. 25	>2. 50	>3. 75

High concentrations of bicarbonate in irrigation water may cause calcium and magnesium to precipitate in the soil as carbonate salts. Precipitation of calcium and magnesium results in an increase in the proportionate amount of sodium in the water; the effect on the soil is the same as if the sodium hazard of the irrigation water had been high. High bicarbonate concentrations may also cause an increase in the pH of the soil and may lead eventually to a soil condition known as "black alkali."

The effect of the bicarbonate concentration of irrigation water on the exchangeable sodium percentage of the soil has been studied by Wilcox, Blair, and Bower (1954). Their study indicated that if the concentrations of bicarbonate do not exceed those of calcium and magnesium by more than about 1.25 epm, the water is probably safe for use.

WATER FROM THE DAKOTA SANDSTONE

The water from deposits of the Dakota sandstone is of unsuitable quality for irrigation. It has a high salinity hazard, generally a high sodium hazard, and relatively high concentrations of boron.

WATER FROM THE QUATERNARY DEPOSITS

The specific conductance and SAR of samples for which the values could be calculated are plotted on figure 14. The water generally has a salinity hazard that is high (C3) or very high (C4) and a sodium hazard that ranges from low (S1) to very high (S4). The salinity hazard and sodium hazard of some of the samples are so high that plotted points representing the samples lie outside the diagram.

The concentrations of boron are as high as 3.4 ppm. Water from many wells probably is toxic to crops, at least to those that are boron sensitive. However, high concentrations of boron seem to be associated only with water that is otherwise unsuitable for irrigation because of very high salinity hazard.

The concentration of bicarbonate was less than the concentration of calcium plus magnesium or was in excess by less than 1.25 epm in all but 12 samples. The amounts of excess, in equivalents per million, in the 12 samples were as follows:

Well	$HCO_3-(Ca+Mg)$
116-64-15aa1	3.29
116-64-15ba1	1.44
118-63-36aad1	6.41
119-61-9ab1	8.09
121-60-27cc1	4.40
121-65-20ad2	6.87
122-64-14ab1	2.37
123-61-18caaa1	11.21
123-63-17cd1	4.13
123-63-20dc1	3.81
123-64-23dd1	3.55
125-62-36ab1	9.12

In general, water from Quaternary deposits is of poor quality for irrigation. The water of good or fair quality, as indicated by a low specific conductance (pl. 3), probably is present in quantities too small for irrigation development.

LEACHING REQUIREMENTS OF THE WATER

Salts in water that has been applied to the soil gradually become more concentrated because of the loss of water by evaporation and plant use. The accumulation of large amounts of salt in the root zone of the soil profile in irrigated areas causes the soil to become saline unless sufficient water is applied to leach the salts through the root zone.

Eaton (1954, p. 6) gives the following equation for estimating the percentage of the applied water necessary to provide adequate leaching:

$$\frac{Sw \times 100}{(2 \times Mss) - Sw} = d\%,$$

in which

Sw is salinity of irrigation water in equivalents per million of Cl plus $\frac{1}{2}SO_4$;

$d\%$ is percentage of applied water that should be passed through the root zone (leaching requirement);

Mss is salinity of mean soil solution in equivalents per million of Cl plus $\frac{1}{2}SO_4$.

The deleterious effects on plant growth of high salinity in the root zone are caused principally by sulfate and chloride. The effects of salinity from sulfate are about half as much as the effects of salinity from chloride when the two are present in equivalent concentrations.

The amount of salinity in the mean soil solution that will cause a significant reduction in crop yields varies with soil structure, climatic conditions, and salt tolerance of crops grown. Eaton assumes that for average conditions the *Mss* should not exceed about 40 epm if reasonable yields (about 70 to 80 percent of the yield that normally would be expected from nonsaline soils) are to be produced. The assumption is based on observations of crops of intermediate salt tolerance grown in the semiarid climate of Riverside, Calif., and probably is valid for much of the irrigated regions of Western United States.

The leaching requirements of the water from most of the wells in Quaternary deposits have been calculated. Ranges in leaching requirements for long-term use of the water and the number of wells in which the water has leaching requirements in each range are as follows:

Range in leaching requirements (d%)	*Number of wells*
0–5	58
6–10	18
11–20	35
21–30	21
31–50	34
51–100	14
$>$ 100	15
Total	195

The water from 84 of the 195 wells has leaching requirements of more than 20 percent. A leaching requirement of more than 100 percent indicates that the salinity of the water to be applied is higher than the desired salinity for the mean soil solution.

The relation of leaching requirements of the water to specific conductance is shown in figure 15. The probable leaching requirements of water from individual wells can be estimated by use of the figure. Water having a specific conductance of 1,000 micromhos per centimeter requires about 4 percent leaching; 2,000 micromhos per centimeter, about 12 percent; and 5,500 micromhos per centimeter, about 100 percent. Samples having a specific conductance of more than about 6,000 micromhos per centimeter are not plotted because the leaching requirements exceed 100 percent.

Determining the feasibility of long-term irrigation with water of a given chemical quality requires an intimate knowledge of the drainage capabilities of the soil and of the area to be irrigated. The drainage capabilities should be adequate at least for the removal of the leaching water required for the maintenance of proper salinity levels in the root zone. For example, if an average of 18 inches of water is to be applied during a season and the required leaching is 30 percent, the soil must be capable of transmitting at least an average of 5.4 inches of water through the root zone during the season.

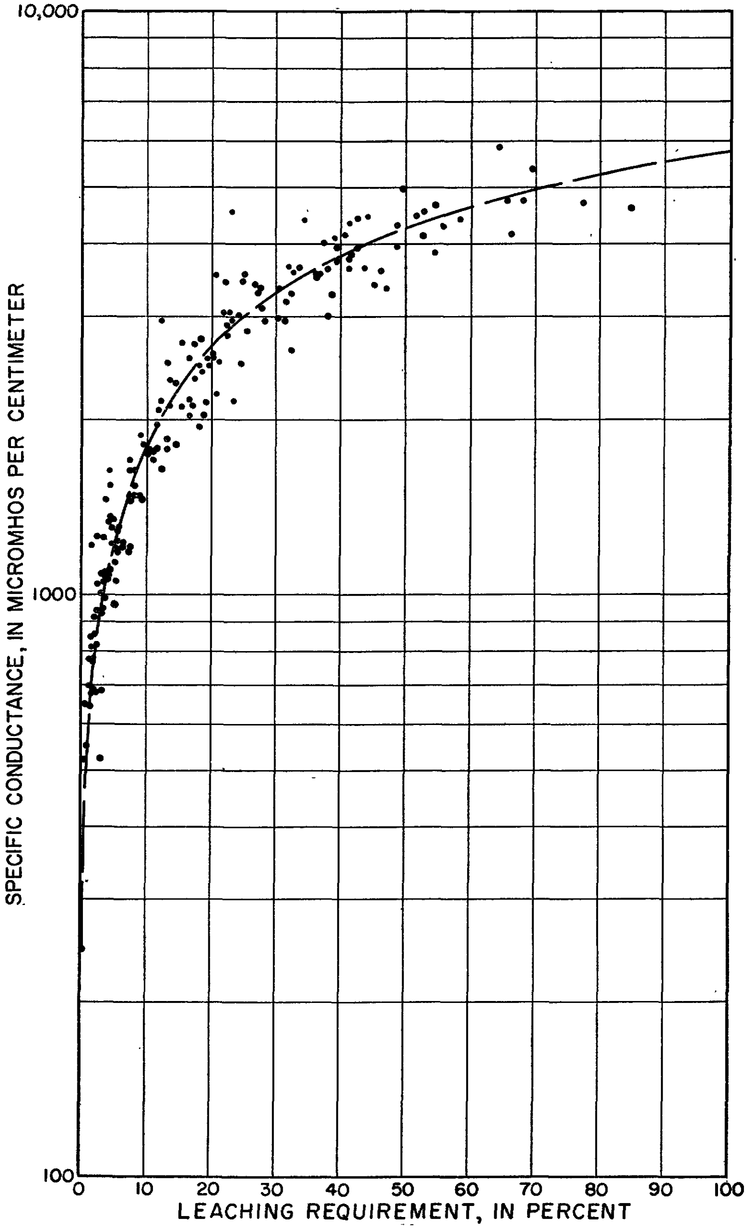

FIGURE 15.—Relation of leaching requirements to specific conductance.

PROBABLE EFFECT OF PROPOSED IRRIGATION ON THE QUALITY OF GROUND WATER IN THE QUATERNARY DEPOSITS

The application of surface water for irrigation generally affects the quality of the ground water. Experience has shown that in most places where irrigation is practiced, the total concentration of dissolved minerals in the ground water has increased. Whether it will increase or decrease can be estimated by determining if the concentration of dissolved minerals in the recharge to the Quaternary deposits will be higher or lower than that in the water already in these deposits.

The concentration of dissolved minerals in the recharge depends on many factors. Because the concentration in irrigation water is higher than that in natural precipitation, irrigation will tend to increase the concentration in the recharge. As the water percolates to the water table, its volume is decreased by evaporation and transpiration and it dissolves some of the minerals with which it comes into contact. Both the volume decrease and the dissolving of minerals tend to increase the concentration in the recharge. The precipitation of calcium and magnesium carbonates, caused by volume decrease in the water, and the intake of salts by plants tend to decrease the concentration in the recharge. The decrease by plant intake, however, is relatively small.

According to proposals for the development of irrigation in the Lake Dakota plain area, water from the Missouri and James Rivers is to be used. A summary of the annual averages, weighted with water discharge, for the Missouri River at Pierre, S. Dak., is given in table 3; and chemical analyses of water from the James River and some of its tributaries are given in table 4. More complete quality-of-water data for the streams are given in the regular series of U.S. Geological Survey water-supply papers entitled "Quality of Surface Water of the United States." Data for the Missouri River at Pierre are representative of the quality of the water impounded by Oahe Dam and of most of the water to be used for irrigation.

Water from the Missouri River is of suitable quality for irrigation. It has a medium salinity hazard (C2) and a low sodium hazard (S1). Concentrations of boron are low, and the concentrations of bicarbonate, in equivalents per million, are less than those of calcium plus magnesium. Water from the James River is suitable for irrigation much of the time. The water has a medium (C2) to high (C3) salinity hazard and a low (S1) sodium hazard. The concentrations of boron vary but are not high; and the concentrations of bicarbonate, in equivalents per million, generally do not exceed those of calcium plus magnesium.

TABLE 3.—*Yearly averages, weighted with discharge, of chemical analyses, Missouri River at Pierre, S. Dak.*

[Results in parts per million, except as indicated]

Water year	Mean discharge (cfs)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids: Residue on evaporation at 180°C	Dissolved solids: Tons per acre-foot	Dissolved solids: Tons per day	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio	Specific conductance (micromhos per cm)
1951	[1]31,860	14	0.02	48	16	53	3.8	167	149	7.3	0.4	2.1	0.13	389	0.53	33,460	186	49	38	1.7	581
1952	36,490	------	------	51	16	52	------	170	152	6.9	------	2.1	.10	385	.52	37,930	193	54	37	1.6	583
1953	25,710	------	------	58	18	68	------	188	201	8.6	------	2.3	.17	473	.64	32,830	219	65	39	2.0	706
1954	23,600	------	------	------	------	64	------	183	184	------	------	------	------	450	.61	28,670	213	63	37	1.9	675
1955	20,140	------	------	------	------	68	------	192	209	------	------	------	------	481	.65	26,160	226	69	39	2.0	723

[1] Represents 72 percent of runoff for water year.

TABLE 4.—*Chemical analyses of water from the James River and some of its tributaries*

[Results in parts per million, except as indicated]

Date of collection	Water discharge (cfs)	Silica (SiO_2)	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: Residue on evaporation at 180° C	Dissolved solids: Tons per acre-foot	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio	Specific conductance (micromhos per cm)	pH
James River at Columbia																						
June 1, 1949	116	17	0.04	48	25	60		285	0	91	17	0.3	0.8	1.5	410	0.56	223	0	37		642	7.3
Aug. 9	6.9	14	.04	37	31	67		258	0	110	24	.3	6.4	.54	448	.61	220	8	40		647	8.2
May 2, 1950	2,590	14	.20	26	11	24		134	0	38	8.0	.3	.6	.20	200	.27	110	0	32		304	7.4
June 15	1,480	15	.04	38	16	28		180	0	60	7.0	.2	2.6	.20	274	.37	161	13	28		420	7.6
July 12	501	22	.02	52	24	47		300	0	78	1.0	.2	.4		394	.54	228	0	31		578	7.9
July 26	142	20	.02	58	29	58		328	0	82	19	.2	10		472	.64	264	0	32		619	7.3
Aug. 2	31	21	.34	51	29	63		318	0	92	19	.2	.6	.10	458	.62	247	0	36		679	7.3
Aug. 16	31	28	.16	60	30	63		334	0	103	20	.2	.9		522	.71	273	0	33		765	8.1
Sept. 8	.1	23	.02	68	44	99		394	0	170	46		.6		660	.90	351	28	38		1.010	8.1
Mar. 17, 1951	14	40	.10	258	50	230		906	0	444	97	.5	8.0	.74	[1] 1.570	2.27	848	105	37		2.230	7.8
Apr. 12	494	16	.02	88	46	115		436	0	213	53	.2	5.8	.24	762	1.04	409	51	38		1.180	7.2
June 14	228							329	0								267	0			747	7.6
Apr. 30, 1952	1,540			26	9.7	27		125	0	43	11			.05			105	2	36	1.1	323	7.3
June 12	28			71	31	89		375	0	103	29			.19			306	18	33	1.7	815	7.5
July 10	.8			50	11	50		149	0	136	11						171	49	39	1.7	533	8.2
Mar. 19, 1953	[2]—47			40	20	61		182	0	98	46			.18			184	34	42	2.0	641	7.1
Apr. 1	6.8			67	24	65		167	0	207	39			.20			266	129	35	1.7	763	6.9
Apr. 9	2.4			130	55	135		245	0	510	79			.12			550	349	35	2.5	1.480	7.2
Apr. 23	.2			160	90	285		371	0	856	138			.26			770	466	45	4.5	2.070	7.4
May 9	7.7			70	48	133		314	0	306	59			.34			370	113	44	3.0	1.180	7.4
May 28	52			72	45	132		338	0	287	55			.27			366	89	44	3.0	1.150	8.1
June 19	[2]—45			46	27	85		227	0	161	41			.18			227	41	45	2.5	770	7.2
June 24	196			44	17	66		186	0	120	32			.17			178	25	45	2.2	611	7.2
Aug. 30, 1954	2.4			47	42	146		364	0	218	67				764	1.04	292	0	51	3.7	1.160	7.4
Nov. 4	50			66	50	141		397	0	259	68				848	1.15	369	43	44	3.2	1.280	7.5

See footnotes at end of table.

TABLE 4.—*Chemical analyses of water from the James River and some of its tributaries*—Continued

Date of collection	Water discharge (cfs)	Silica (SiO_2)	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: Residue on evaporation at 180° C	Dissolved solids: Tons per acre-foot	Hardness as $CaCO_3$	Noncarbonate hardness as $CaCO_3$	Percent sodium	Sodium adsorption ratio	Specific conductance (micromhos per cm)	pH
James River at Columbia—Continued																						
Mar. 10, 1955	17	----	----	114	89	244	----	652	0	493	114	----	----	----	1.490	2.03	652	117	44	4.2	2.100	7.5
Mar. 15	32	----	----	67	44	117	----	340	0	241	61	----	----	----	773	1.05	349	70	41	2.7	1.160	7.2
Mar. 21	5	26	0.04	123	107	269	----	791	0	515	124	0.6	0.8	0.66	1.650	2.24	747	98	43	4.3	2.300	7.5
Apr. 6	49	----	----	39	36	95	----	270	0	165	43	----	----	----	553	.75	247	26	46	2.6	874	8.0
Apr. 13	106	----	----	56	46	128	----	359	0	225	55	----	----	----	734	1.00	330	36	46	3.1	1.130	7.3
Apr. 21	98	----	----	----	----	125	----	344	0	220	55	----	----	----	----	----	322	40	46	3.0	1.120	7.2
June 3	12	----	----	55	42	121	----	332	0	238	51	----	----	----	735	1.00	311	39	44	3.0	1.110	8.0
June 22	24	----	----	----	----	126	----	323	0	248	56	----	----	----	----	----	313	48	46	3.1	1.120	7.8
Aug. 4	1.5	----	----	55	42	133	----	359	0	253	61	----	----	----	768	1.04	310	16	45	3.3	1.160	7.7
Apr. 25, 1956	[3] 3.0	----	----	45	34	100	----	300	0	160	52	----	----	----	596	.81	253	7	45	2.7	918	7.8
May 16, 11:00 a.m.	166	----	----	45	41	118	----	330	0	193	57	----	----	----	670	.91	282	11	46	3.1	1,040	7.9
May 16, 12:30 p.m.	166	----	----	52	41	119	----	340	0	203	60	----	----	----	715	.97	298	19	45	3.0	1,070	7.6
June 7	4.1	17	.20	59	50	132	14	412	0	238	67	.3	.3	.48	818	1.11	354	16	44	3.0	1,230	7.7
June 27	226	19	.09	52	44	118	13	376	0	200	57	.3	.6	.40	714	.97	310	2	44	2.9	1,090	7.7
July 20	82	26	.10	53	45	120	14	403	0	185	58	.0	.7	.42	725	.99	316	0	44	2.9	1,100	7.7
Aug. 8	1.3	26	.10	63	49	126	15	480	0	155	70	.1	1.0	.41	784	1.07	358	0	42	2.9	1,180	7.9
Elm River at Westport																						
Aug. 9, 1949	3.3	19	0.04	37	21	123		268	0	98	87	0.2	2.5	0.46	552	0.75	179	0	60	----	851	7.6
Aug. 2, 1950	4.1	6.0	.04	49	35	116		251	0	172	93	.3	1.6	.26	636	.86	267	61	49	----	994	7.4

Elm River near Ordway																					
Aug. 9, 1956	[3] 8	------	------	----	--------	106	272	0	120	71	------	2.0	------	564	0.77	219	0	51	3.1	906	7.6
James River 3 miles north of Stratford																					
Aug. 9, 1949	21.1	22	0.04	55	27	81	318	0	109	33	0.2	4.5	0.43	500	0.68	249	0	41	------	732	7.9
James River 6¾ miles southwest of Stratford																					
Aug. 3, 1950	453	16	0.04	56	26	47	299	0	71	19	0.2	4.1	0.03	414	0.56	248	3	29	------	627	7.0
James River near Mellette																					
Aug. 9, 1949	19.6	16	0.04	54	26	75	298	0	114	27	0.2	6.4	0.27	488	0.66	242	0	40	------	697	7.8
James River at Ashton																					
Aug. 10, 1949	28.2	19	0.04	52	22	75	240	14	115	26	0.2	8.1	0.52	478	0.65	221	1	42	------	663	8.4
Aug. 3, 1950	714	18	.06	57	27	46	303	0	73	17	.2	3.7	.05	420	.57	253	5	28	------	633	7.1
Turtle Creek at Redfield																					
Aug. 10, 1949	0.17	15	0.10	55	19	792	402	0	1,240	216	1.4	10	0.79	[1] 2,550	3.47	215	0	89	------	3,510	8.2
Mar. 30, 1950	1,430	8.3	.30	20	2.6	12	71	0	18	2.8	.1	8.1	.30	138	.19	61	3	31	------	180	7.4
James River east of Redfield																					
Aug. 10, 1949	34.2	20	0.10	51	23	75	270	0	106	32	0.3	8.3	0.76	466	0.63	222	1	42	------	671	7.9

[1] Sum of the determined constituents.
[2] Negative figures indicate reverse flow caused by backwater from Elm River.
[3] Daily mean discharge.

Only data for the Missouri River water have been used to estimate the probable concentration of the recharge because the yearly average concentrations in water from the James River are not known. The natural flow of the James will contribute less than 6 percent of the total annual quantity of water to be used. According to plans (U.S. Bur. Reclamation, 1960), 796,300 acre-feet of water from the Missouri River and 411,100 acre-feet from the James River will be diverted annually for irrigation in the Lake Dakota plain area. Of the amount from the James River, 345,900 acre-feet will be return flow from irrigation of the Lake Dakota plain and 65,200 acre-feet will be natural flow of the James River.

The average quality of Missouri River water is represented best by the average concentrations for the 1952 and 1953 water years, because data for 1951 are for only part of the year and data for 1954 and 1955 do not show the concentrations of all the major ions. The data in table 3 were converted to equivalents per million, and the results are shown in the following table.

Averages of mineral constituents, weighted with water discharge, Missouri River at Pierre, S. Dak.

	Water year		
	1952	1953	1952-53
Mean water discharge cfs	36, 490	25, 710	31, 100
Calcium (Ca) epm	2. 54	2. 89	2. 68
Magnesium (Mg) epm	1. 32	1. 48	1. 39
Sodium (Na) epm	2. 26	2. 96	2. 55
Bicarbonate (HCO_3) epm	2. 79	3. 08	2. 91
Sulfate (SO_4) epm	3. 16	4. 18	3. 58
Chloride (Cl) epm	. 19	. 24	. 21
Nitrate (NO_3) epm	. 03	. 04	. 03
Total epm	12. 29	14. 87	13. 35

The concentration of the dissolved minerals in the recharge can be estimated with the following equation based on Eaton's concepts (1954):

$$C_r = \frac{C_i - 2HCO_3\,(1-d)}{d} + Q_s,$$

in which

C_r is the concentration in the recharge, in equivalents per million of anions plus cations;

C_i is the concentration in the irrigation water, in equivalents per million of anions plus cations;

HCO_3 is the concentration, in equivalents per million, of bicarbonate plus carbonate in the irrigation water and is equal to or less than the concentrations of calcium plus magnesium;

d is the ratio of the volume of irrigation water reaching the ground-water reservoir to the volume of irrigation water applied;

Q_s is the amount of mineral material dissolved between the soil surface and the water table per unit volume of recharge water.

If 13.35 epm and 2.91 epm are substituted for C_i and HCO_3, respectively, in the equation and if d is assumed to be 0.2, then

$$C_r = \frac{13.35 - 2\,[2.91\,(1-0.2)\,]}{0.2} + Q_s.$$

$$= 44 + Q_s$$

Probably d will be less than 0.2, and C_r, therefore, will be more than 44 epm plus Q_s. The Q_s cannot be evaluated, but obviously would make the final answer larger.

Where the concentrations of dissolved minerals in the ground water are less than about 44 epm, irrigation probably will cause the concentrations in the ground water to increase. Where the concentrations of dissolved minerals in the ground water are more than 44 epm, irrigation may or may not cause the concentrations of salts in the ground water to decrease; the possibility of a decrease depends, to a great extent, on the hydrologic changes that may result from irrigation development.

After the first year or two of irrigation, mixing of the more highly mineralized irrigation return water with the water of the Missouri and James Rivers will cause the concentration in the applied water to increase and will, therefore, cause the concentration in the recharge to increase.

The relation of specific conductance to total concentration of cations and anions, in equivalents per million, is shown in figure 16. The figure shows that the water having a concentration of less than about 44 epm has a specific conductance of less than about 2,000 micromhos per centimeter. In the parts of the report area where the specific conductance is less than 2,000 micromhos per centimeter, the concentration of dissolved minerals in the ground water probably will increase as a result of irrigation.

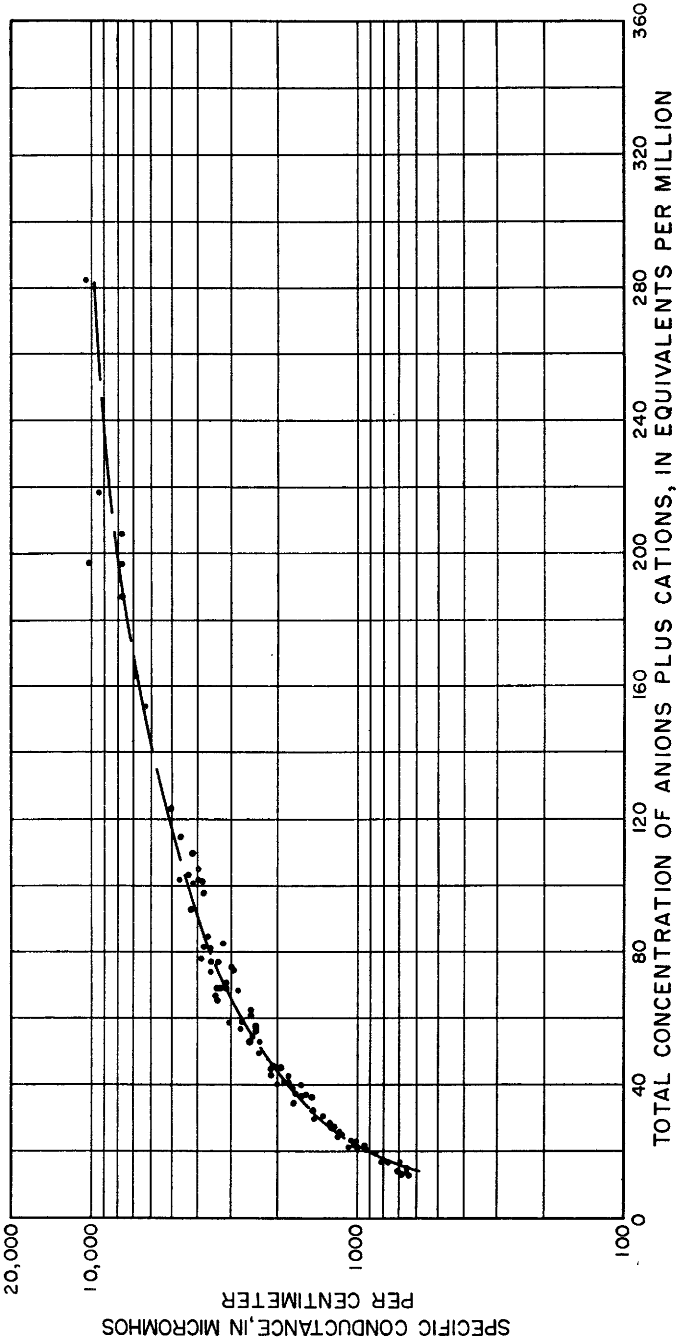

FIGURE 16.—Relation of specific conductance to total concentration of dissolved minerals for water from Quaternary deposits.

SUMMARY AND CONCLUSIONS

Since the turn of the century most of the ground water used in the Lake Dakota plain area for domestic and stock supplies has been obtained from the Dakota sandstone of Cretaceous age. The Dakota is buried beneath about 700 to 800 feet of younger Cretaceous rocks, which are, in turn, mantled by about 75 feet of unconsolidated deposits of Quaternary age. Because withdrawals have exceeded the rate of lateral percolation from areas of recharge, the artesian pressure has declined materially and the rate of flow from wells has diminished correspondingly. However, wells that would flow still can be drilled in all parts of the Lake Dakota plain. Most of the water from the Dakota is of the sodium sulfate type and is soft; some is of the sodium sulfate type and is hard; and a small part is of the sodium chloride type and is soft. The water from the Dakota is unsuitable for irrigation and is of poor quality for domestic use. The specific conductance of 71 samples ranged from 2,590 to 4,380 micromhos per centimeter.

The Quaternary deposits are an important source of ground water in only a relatively small part of the area. Although much more water could be obtained from these deposits by pumping from wells, extensive use for irrigation is unlikely because large supplies of chemically suitable water cannot be obtained in many places. At present evapotranspiration accounts for almost all the water removed from the Quaternary deposits.

Water from the Quaternary deposits is heterogeneous in amount of mineralization and in chemical composition. Specific conductance ranged from 246 to 13,300 micromhos per centimeter. The water is unsuitable for domestic use in most parts of the report area and generally is unsuitable for irrigation. Use of surface water for irrigation probably will cause the concentration of dissolved minerals in much of the ground water to increase.

If the area is developed for irrigation according to the present plans of the Bureau of Reclamation, the average annual recharge to the zone of saturation in the Quaternary deposits underlying the irrigated areas probably will be doubled owing to the infiltration of irrigation water. Because the capacity of the Quaternary deposits to drain by lateral percolation toward the natural surface drainageways is so small, the added recharge will cause the water table to rise and artificial drainage probably will be necessary to prevent waterlogging. Although a general rise of the water table would mean that more water is in storage, the increase in storage probably would be advantageous only in years of drought. During years of normal or above-normal precipitation even a small rise of the water table would necessitate artificial drainage in large parts of the area if maximum crop production were to be maintained. The effect of irrigation on the position of the water table should be watched closely so that remedial measures can be taken promptly if waterlogging threatens in any part of the area.

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