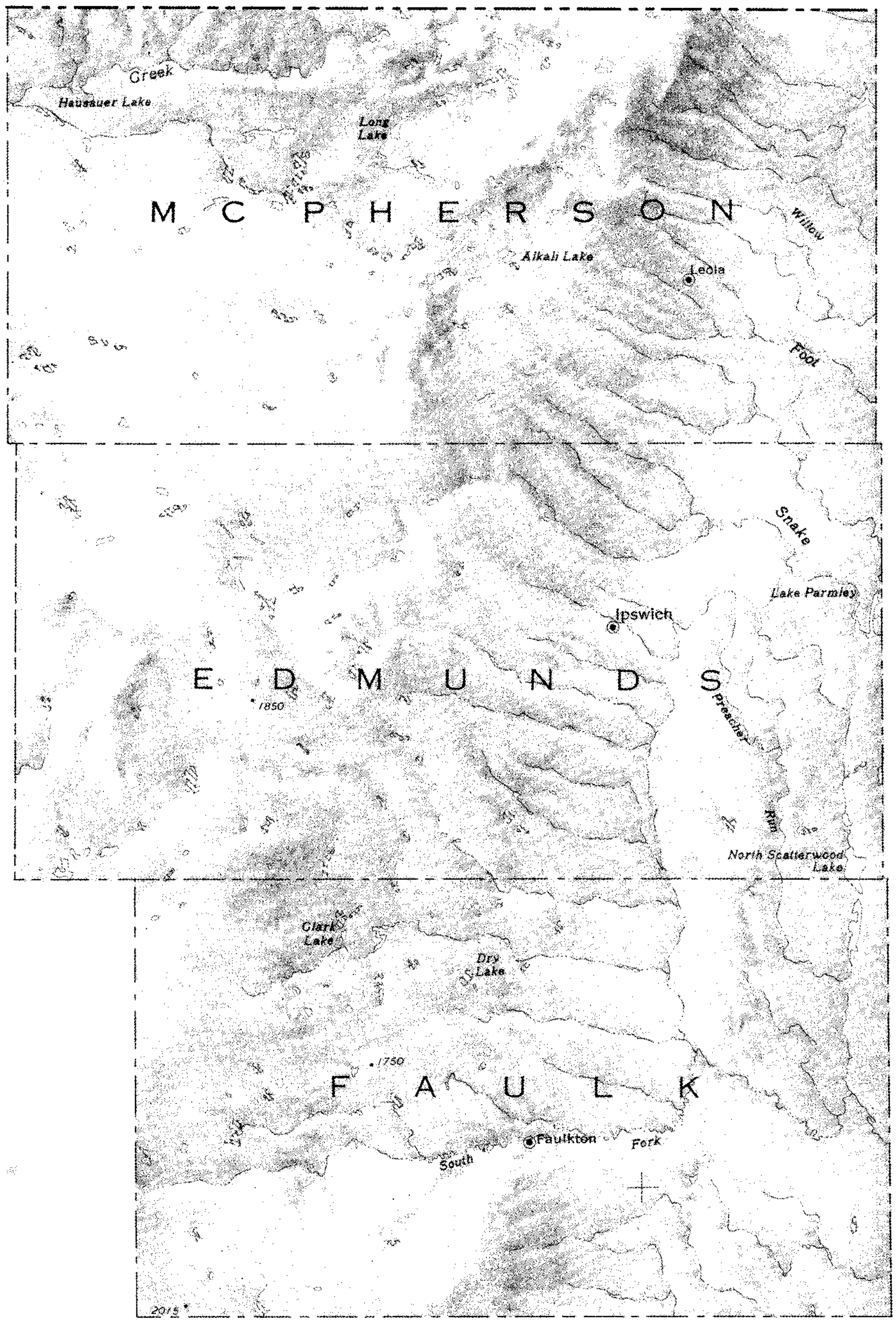
Bulletin 26

GEOLOGY AND WATER RESOURCES OF McPHERSON, EDMUNDS, AND FAULK COUNTIES, SOUTH DAKOTA

Part II: WATER RESOURCES



by Louis J. Hamilton

Prepared in cooperation with the Oahe Conservancy Sub-District, McPherson, Edmunds, and Faulk Counties, and the South Dakota Geological Survey - 1982

DEPARTMENT OF WATER AND NATURAL RESOURCES - GEOLOGICAL SURVEY - 1982

STATE OF SOUTH DAKOTA
William Janklow, Governor

DEPARTMENT OF WATER AND NATURAL RESOURCES
Warren R. Neufeld, Secretary

GEOLOGICAL SURVEY
Merlin J. Tipton, State Geologist

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Part II: Water Resources

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the South Dakota Geological Survey

Science Center
University of South Dakota
Vermillion, South Dakota
1982

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DEFINITIONS OF TERMS

AQUIFER - A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. For this report a major aquifer is one that can supply large-capacity wells.

ARTESIAN WATER - Ground water confined under hydrostatic pressure.

BEDROCK AQUIFER - A water-bearing geologic formation composed of consolidated rock.

DEGREES C - Degrees celsius. There are 100 degrees of temperature between the freezing and boiling points of water under laboratory conditions. Degrees celsius may be converted to degrees fahrenheit by the following formula: degrees fahrenheit = 9/5 (degrees celsius) + 32.

DIP - The downward inclination of a stratum with reference to a horizontal plane.

DISCHARGE - The volume of water (or more broadly, total fluids) that passes a given point within a given period of time.

DRAINAGE LAKE - A lake that loses water through a surface outlet.

DRAWDOWN - The amount of lowering of the water table or potentiometric surface by pumping or artesian flow.

DUGOUT - A pit excavated in the ground to provide water for livestock.

ELECTRIC LOG - An electrical recording obtained by lowering electrodes in a borehole and measuring various electrical properties of the geologic formations transversed.

EVAPOTRANSPIRATION - Water withdrawn from a land area by evaporation from the water surface and moist soil and by plant transpiration.

GAGING STATION - A particular site on a stream, canal, lake or reservoir where systematic observations of hydrologic data are obtained.

GLACIAL AQUIFER - A water-bearing formation composed of materials transported and deposited by glacial action. In this report it is mainly unconsolidated sand and gravel deposited as outwash from a glacier.

GROUND-WATER DIVIDE - A broad mound or ridge in the water table or other potentiometric surface from which the ground water represented by that surface moves away in many directions.

HARDNESS - Hardness of water is a physical-chemical characteristic attributable to the presence of alkaline earths (principally calcium and magnesium) and is expressed as equivalent calcium carbonate ($CaCO_3$). It has been classified in some reports of the U.S. Geological Survey as follows (Durfor and Becker, 1964, p. 27):

	Milligrams per liter	Grains per gallon
Soft	0- 60	0- 3.4
Moderately hard	61-120	3.5- 7.0
Hard	121-180	7.1-10.5
Very hard	More than 180	More than 10.5

HEAD (STATIC HEAD) - The height above a standard datum of a vertical column of water that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

HYDRAULIC CONDUCTIVITY - The volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

LARGE-CAPACITY WELL - Defined by South Dakota Law as a well capable of yielding at least 18 gallons per minute.

MILLIEQUIVALENT PER LITER (meq/L) - One milliequivalent of solute in a liter of solution. The concentration of an ion, in milligrams per liter can be converted to milliequivalents per liter by dividing by its combining weight. The value can be used to compare the concentrations of ions on the basis of their chemical equivalence.

MILLIGRAMS PER LITER (mg/L) - A unit for expressing the concentration of chemical constitutents in solution. Milligrams per liter represents the weight of solute per unit volume of water.

OUTWASH - A stratified deposit of sand and gravel that has been washed, sorted, and deposited by meltwater from a glacier.

PERCENTAGE COMPOSITIONS - Concentrations of ions expressed as percentages of the total concentrations, in milliequivalents per liter, of either cations or anions.

PERMEABILITY - The capacity of a material to transmit a fluid under a potential gradient.

POTENTIOMETRIC SURFACE - An imaginary surface that represents the static head in an aquifer as represented by the level to which water will rise in tightly cased wells.

PROPERLY-CONSTRUCTED WELL - One constructed to admit a maximum amount of water from an aquifer without excessive loss of head at the well. This generally requires installing a well screen or perforating the casing opposite the aquifer. It also requires pumping the well in such a manner as to remove drilling mud and other fine-grained material from the aquifer adjacent to the well.

RECHARGE - Addition of water to the zone of saturation by infiltration of precipitation, seepage from streams or other bodies of surface water, or subsurface inflow.

RUNOFF - That part of precipitation that constitutes surface streams. It is the same as streamflow unaffected by artificial diversions, storage, or other works of man.

SALINE WATER - As used in this report it is water containing more than 1,000 milligrams per liter of dissolved solids.

SEEPAGE LAKE - A lake that loses water by seepage through the walls and floor of its basin.

SHUT-IN PRESSURE - The hydrostatic pressure or static head measured at the land surface when the flow of an artesian well is stopped.

SPECIFIC CAPACITY - The rate of discharge of water from a well divided by the drawdown of water level within the well. It varies with the duration of discharge.

SPECIFIC CONDUCTANCE - The ability of water to conduct an electrical current, expressed in micromhos per centimeter at 25 degrees C. Because the specific conductance is related to the number and specific chemical types of ions in solution, it can be used for approximating the dissolved-solids content in the water. The following general relation is applicable: Specific conductance, in micromhos per centimeter x 0.65 = Dissolved solids, in milligrams per liter.

SPECIFIC YIELD - The ratio of (1) the volume of water which the rock or soil, after being saturated, will yield by gravity to (2) the volume of the rock or soil.

STORAGE COEFFICIENT - The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

TILL - An unsorted, unstratified mixture of clay, silt, sand, gravel, and boulders deposited by a glacier.

TRANSMISSIVITY - The volume of water at the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit width of an aquifer.

WATER TABLE - That surface in an unconfined water body at which the pressure is atmospheric. It is defined by the levels at which water stands in wells that penetrate the water body just far enough to hold standing water. In wells which penetrate to greater depths, the water level will stand above or below the water table if an upward or downward component of ground-water flow exists.

U.S. CUSTOMARY AND METRIC UNITS

Abbreviations of units and factors for converting U.S. Customary Units to metric units are listed below:

Multiply U.S. Customary unit	by	To obtain metric unit
acre	0.405	hectare (ha)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	1.233×10^{-6}	cubic kilometer (km^3)
acre-foot per square mile (acre-ft/mi^2)	476	cubic meter per square kilometer (m^3/km^2)
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	1.093×10^{-2}	cubic meter per second per square kilometer [(m^3/s)/km^2]
foot (ft)	.035	meter (m)
foot per mile (ft/mi)	.189	meter per kilometer (m/km)
gallon (gal)	3.785	liter (L)
gallon (gal)	3.785×10^{-3}	cubic meter (m^3)
gallon per minute (gal/min)	6.309×10^{-2}	liter per second (L/s)
gallon per day per square mile[(gal/d)/mi^2]	1.461	liter per day per square kilometer [L/d)/km^2]
gallon per day per mile [(gal/d)/mi]	2.352	liter per day per kilometer [(L/d)/km]
gallon per day per square foot [(gal/d)/ft^2]	.041	meter per day (m/d)
gallon per day per foot [(gal/d)/ft]	1.242×10^{-2}	square meter per day (m^2/d)
gallon per minute per foot [(gal/min)/ft]	.207	liter per second per meter [(L/s)/m]
inch (in)	2.540	centimeter (cm)
mile (mi)	1.609	kilometer (km)
pound per square inch (lb/in^2)	7.037×10^{-2}	kilogram per square centimeter (kg/cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
ton (short)	.907	megagram (mg)

ABSTRACT

McPherson, Edmunds, and Faulk Counties comprise an area of 3,304 square miles of till plains in north-central South Dakota. A large supply of water generally is available for many present and future needs but in part of the study area shallow supplies are inadequate. Some of the water is of unsuitable quality for municipal, industrial, and irrigation requirements.

Water is obtained from many lakes and ponds, and from a few streams. Total streamflow averages about 14,500 acre-feet per year. Water storage in lakes and ponds is greatly depleted by evapotranspiration in summer and during drought but averages about 70,000 acre-feet.

The quality of surface water varies areally. The concentration of dissolved solids averaged 1,200 milligrams per liter for 21 samples from lakes and 600 milligrams per liter for 18 samples from ponds, but ranged up to 17,000 milligrams per liter in a saline lake.

Ground water is obtained from glacial and bedrock aquifers. Glacial aquifers store about 5.5 million acre-feet of water beneath one-third of the study area. An aquifer can yield more than 500 gallons per minute to a pumping well at many places. Sandstone bedrock aquifers store about 200 million acre-feet beneath the entire area at depths of more than 1,000 feet and can yield 500 gallons per minute or more to a well. Additional supplies of water can be obtained from limestone and dolomite which underlie the sandstone aquifers in the western part of the area.

The quality of ground water varies areally and with depth. In glacial aquifers, dissolved solids average about 1,000 milligrams per liter and range from 260 milligrams per liter to 3,200 milligrams per liter. In bedrock aquifers, dissolved solids average about 2,000 milligrams per liter and range from 1,600 milligrams per liter to 2,600 milligrams per liter. Much of the ground water is unsuitable for irrigation use because of high dissolved solids and sodium and bicarbonate concentrations.

Withdrawals from glacial aquifers have practically no effect on water levels or storage because pumpage is dispersed and is much less than recharge. Large withdrawals of water from bedrock aquifers have greatly reduced the pressure and flow of artesian wells.

INTRODUCTION

The study was made in cooperation with the South Dakota Geological Survey, and was financed by State, Oahe Conservancy Sub-District, and County funds matched by federal funds. Several state and federal agencies provided useful information, as did many residents and well drillers.

The report on the geology and water resources of the Counties is published in three parts. The geology of the Counties is described in Part I of this Bulletin (Christensen, 1977). This report, Part II, is an appraisal of the water resources. The basic data collected and used in the preparation of these reports are available on request in separate open-file reports.

Purpose and Scope

The aims of this study were to: (1) determine the availability of surface and ground water, (2) describe the hydrologic system as it influences water availability, (3) describe the water quality, and (4) estimate the effects of development of water supplies on the availability and quality of surface and ground water.

The study concentrated largely on glacial aquifers because little was known of their extent, thickness, depth, storage, recharge, discharge, water levels, well yields, and water quality. This report is a general appraisal of the water resources; any large-scale water development should be preceded by test drilling and detailed hydrologic studies.

Methods

About 400 test holes were drilled to bedrock in order to determine the location, composition, and thickness of glacial aquifers. Logs of these test holes and other basic data will be made available as an open-file report at a later date. Electric logs were run in about 200 wells and test holes to determine the depth and thickness of glacial and bedrock aquifers. Records of about 2,000 wells were obtained to determine aquifer depth, water quality, and well yields. Water samples from about 400 wells, 3 streams, and 80 lakes and ponds were analyzed for water quality. Water levels were measured periodically in 50 wells to determine changes in storage and water movement. Streamflow data were collected at one gaging station, seven crest-stage partial-record stations, and at four single-measurement sites. The data are published in several reports (U.S. Geol. Survey, 1964, 1969, 1971, 1972, and 1973). The stages of 30 ponds and lakes were measured periodically to determine the effects of rainfall, runoff, and evapotranspiration.

Site-Numbering System

Wells, test holes, and surface-water sampling sites are located according to a numbering system based on the Federal land-survey system used in South Dakota (fig. 1). The location number for this area consists of township number followed by the letter N for north, range number followed by the letter W for west, and section number. This is followed by a maximum of four

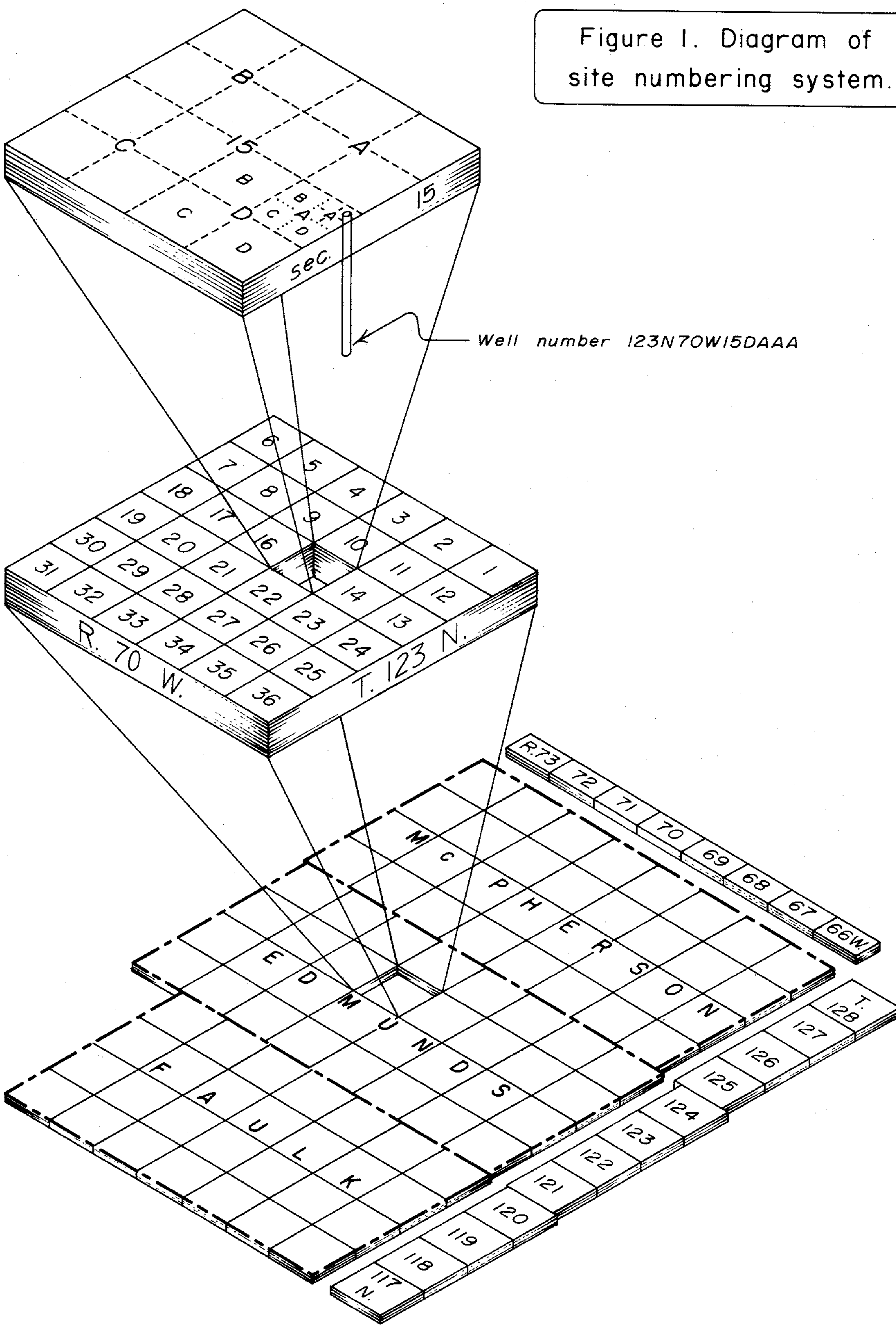


Figure 1. Diagram of site numbering system.

letters that indicate, respectively, the 160-, 40-, 10-, and 2 1/2-acre tract in which the well is located. These letters, A, B, C, and D, are assigned in a counterclockwise direction beginning with "A" in the northeast quarter. A serial number following the last letter is used to distinguish between wells in the same tract. Thus, well 123N70W15DAAA is in the NE 1/4 NE 1/4 NE 1/4 SE 1/4 sec. 15, T. 123 N., R. 70 W.

Station numbers for gaging stations and crest-stage partial-record stations are those used in the annual series of reports entitled "Water Resources Data for South Dakota."

Geography and Climate

McPherson, Edmunds, and Faulk Counties comprise 3,304 square miles in north-central South Dakota, along the boundary between the Central Lowland and the Great Plains physiographic provinces. The eastern part of the Counties is in the James Basin and the western part is in the Coteau du Missouri (fig. 2).

Figure 2 is a photomosaic, which was prepared from negative prints of MSS-7 (near-infrared band) imagery obtained by Landsat-1 (Earth Resources Technology Satellite) in May 1973. Numerous small lakes barely can be detected as white specks, fallow fields are light gray, rangeland is gray, and cultivated fields are dark gray. Oahe Reservoir on the Missouri River can be seen as a conspicuous white, meandering, band in the upper center of the mosaic, 30 miles west of the study area.

The population of 14,463 persons (1970 census) is supported principally by agriculture and most of the land is used for range and field crops (U.S. Dept. of Agriculture, 1970). Agriculture has been adapted to a semiarid, continental, climate that is characterized by cool, wet springs, hot, dry summers, and long, cold winters. The mean annual temperature is about 7 degrees C (44 degrees F) but mean monthly temperatures average below freezing 5 months of the year. During most of this time, lakes, ponds and streams are covered by ice, so livestock must be watered from wells.

Normal annual precipitation is only 17 inches, and is more than 3 inches below normal 3 out of 10 years. Fortunately more than three-fourths of the precipitation occurs during the growing season. Nevertheless, supplemental irrigation during drought could maintain crop yields and stabilize the economy. Less than one-fourth of the precipitation accumulates as snow, and this limits the supply of water in spring which is needed to restore soil moisture, recharge aquifers, and furnish runoff to streams, lakes, and ponds.

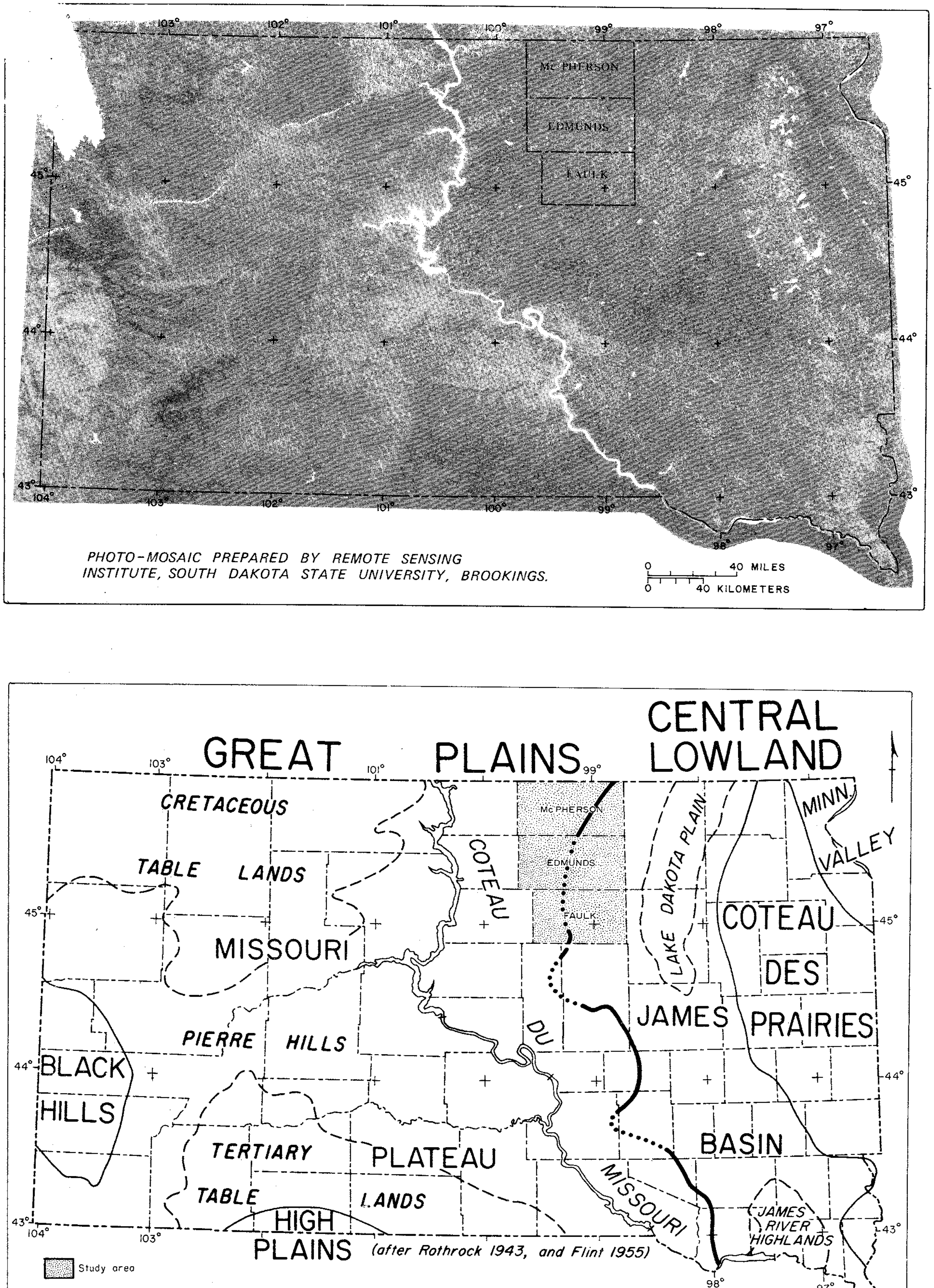


Figure 2. Landsat imagery photomosaic and index map of South Dakota showing major physiographic subdivisions and counties in this study.

Topography and Drainage

The eastern part of the study area, which is in the James Basin, is a gently undulating plain that is dissected by eastward-flowing tributaries of the James River. Local relief rarely exceeds 10 feet per square mile except where tributaries are incised about 30 feet into the plain. The narrow stream valleys are about one-quarter mile wide and are capable of confining flood waters and limiting the extent of flood-prone areas. Slopes of the stream channels increase gradually from a few feet per mile in their lower reaches to about 100 feet per mile in their headwaters on the Coteau du Missouri. The lower reaches have numerous pools of water during many years but the upper reaches drain rapidly and generally contain water only in dugouts and behind stock dams.

The western part of the study area, which is in the Coteau du Missouri, is characterized by rolling hills that are separated by numerous poorly-drained depressions--"prairie potholes"-- that are lakes and ponds in wet years. Local relief rarely exceeds 50 feet within a square mile. The northwestern part of McPherson County is drained by Spring Creek, a tributary of the Missouri River, and the southwestern part of Faulk County is drained by the South Fork of Snake Creek, a tributary of the James River. The remainder of the western part of the area has no external drainage (fig. 3).

WATER AVAILABILITY

A large supply of water, which generally is adequate for most uses, is available from lakes, ponds, streams, and glacial and bedrock aquifers in the study area (table 1). The glacial and bedrock aquifers offer the most dependable supply because surface-water supplies are highly variable due to depletion by evapotranspiration in summer and by periods of drought.

SURFACE WATER

Surface water is available from lakes, ponds, and dugouts, and from streams that drain about 60 percent of the area. About half of the runoff from the study area is through the South Fork of Snake Creek. Reservoirs are needed to provide supplies that are adequate for irrigation, municipal, and industrial supplies because streams flow intermittently. About 700 flowing wells discharge an estimated 4,000 gallons per minute, or 6,450 acre-feet per year, to ponds and streams but this does not noticeably augment storage or streamflow because the wells are widely dispersed.

Most streams in the study area flow only in spring and then only if there is sufficient snowmelt and rainfall. Runoff is increased relative to snow accumulations some years because prior

TABLE 1. Summary of water availability and suitability for various uses

Source / Use and considerations	Surface water			Ground water			
				Glacial aquifers		Bedrock aquifers	
	Snake Creek	Small streams	Lakes and ponds	Elm, Selby, Spring Creek and others	Grand aquifer	Dakota Formation	Fall River Formation and underlying aquifers
Municipal and industrial **Quantity** - 0.15 ft^3/s, 70 gal/min, or 100,000 gal/day per 1,000 population.	Adequate supply. Average flow of 11 ft^3/s or 8,000 acre-ft per year at station 06473500 (fig. 3).			Adequate supply. Well yields of more than 100 gal/min are possible.	Adequate supply. Well yields of more than 500 gal/min are possible.	Adequate supply. Well yields of up to 500 gal/min are possible.	Adequate supply. Well yields of more than 500 gal/min are possible. Available everywhere.
Quality - Water should not be polluted and, preferably, not saline, corrosive, or excessively hard.	Flow is intermittent. Requires reservoirs and alternative supplies during years of little flow. Treatment required for removal of pollution and excessive hardness.	Inadequate supply.	Inadequate supply generally. Slightly to moderately saline. Treatment required for removal of pollution and excessive hardness.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.
Rural domestic and stock **Quantity** - 5 gal/min.	Adequate supply with reservoirs.	Adequate supply with reservoirs.	Adequate supply.	Adequate supply. Flowing wells in a few areas.	Adequate supply. Flowing wells in a few areas.	Adequate supply. Flowing wells in much of the eastern part of the area.	Adequate supply. Flowing wells nearly everywhere.
Quality - Water should not be polluted and preferably, not saline, corrosive, or excessively hard.	May require alternative supplies during winter and dry years. Treatment required for removal of pollution and excessive hardness.	Requires alternative supplies in winter and dry years. Treatment required for removal of pollution and excessive hardness.	Requires alternative supplies in winter and dry years. Treatment required for removal of pollution and excessive hardness.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline and corrosive. Salty taste may make the water unpalatable. Treatment may be required for removal of excessive hardness, iron, and manganese.	Slightly saline. Treatment may be required for removal of excessive hardness, iron, and manganese.
Irrigation **Quantity** - 1 ft^3/s, or 450 gal/min per 40 to 60 acres.	Adequate supply in reservoirs most years.		Some lakes have adequate supply.		Adequate supply.	Adequate supply.	Adequate supply.
Quality - Low concentrations for total dissolved solids sodium, and bicarbonate, depending on soil and drainage.	Adequate flow only in spring. Requires reservoirs.	Inadequate supply many years, even with reservoirs.	Locally unsuitable quality because of high dissolved solids, sodium, and bicarbonate.	Inadequate supply generally. Multiple wells may provide adequate supply.	Unsuitable quality generally, because of high concentrations of dissolved solids, sodium, and bicarbonate.	Unsuitable quality because of high concentrations of dissolved solids, sodium, and bicarbonate.	Unsuitable quality because of high concentrations of dissolved solids.
Recreation							
Adequate depth and area for water sports.	Inadequate area in most reservoirs.	Inadequate depth and area.	Inadequate depth and area for most lakes.				
Fish and wildlife habitat	Adequate supply.		Adequate supply.				
Adequate depth and quality for fish.	Inadequate for fish except in reservoirs.	Inadequate supply many years even in reservoirs.	Inadequate for fish in most ponds.				

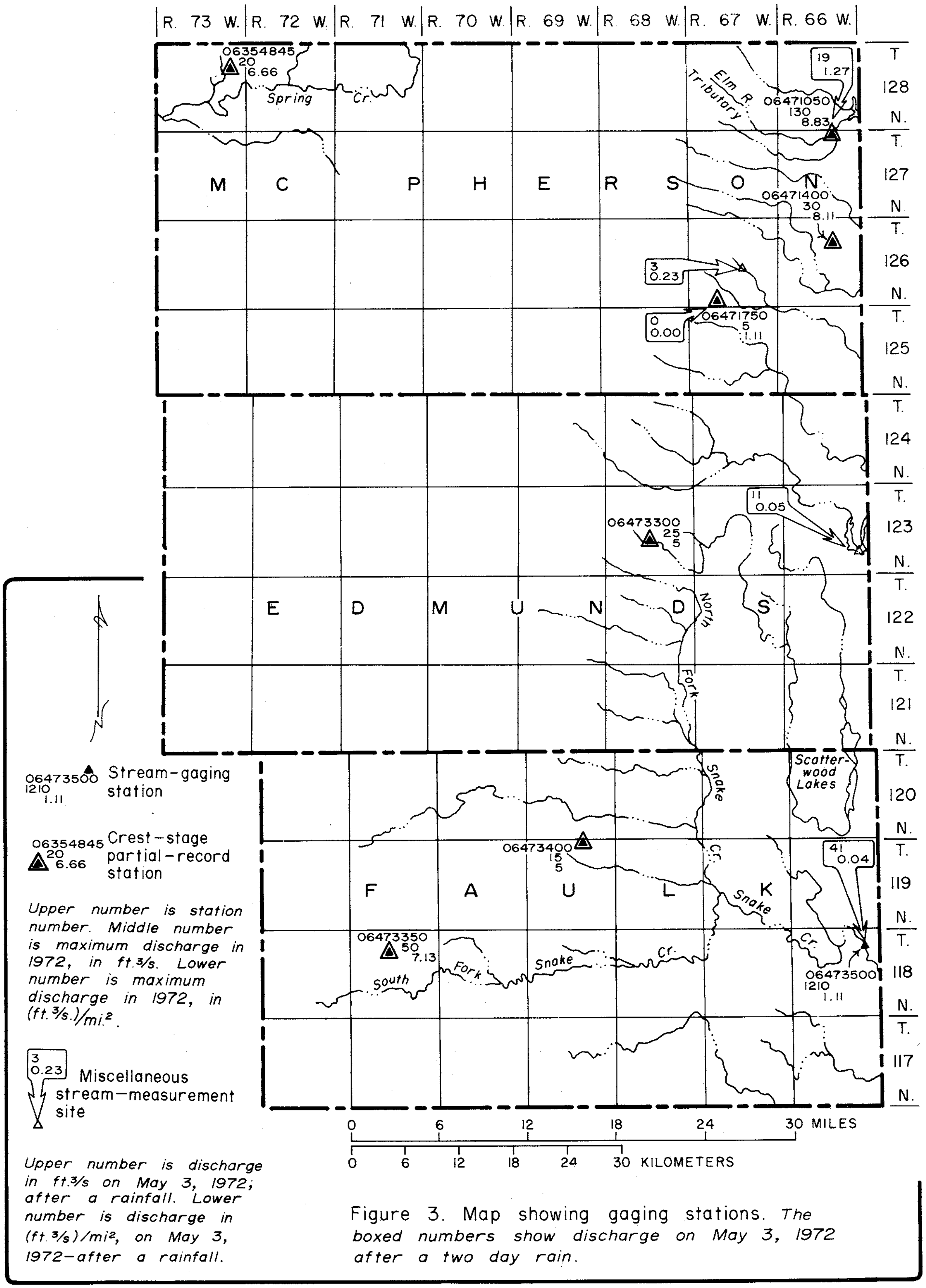


Figure 3. Map showing gaging stations. *The boxed numbers show discharge on May 3, 1972 after a two day rain.*

precipitation saturates soil and fills lakes and ponds to overflowing. Drifting of snow into drainageways and freezing of saturated soil also contribute to an increase of runoff. As a result of all of these conditions being met, annual runoff for 1972 was two times normal even though the snowfall and annual precipitation were about normal. On March 17, the maximum discharge (instantaneous peak) for 1972 was 1,210 cubic feet per second for the South Fork of Snake Creek in eastern Faulk County (station 06473500, fig. 3). This maximum was the third-highest discharge for the 23 years of record.

Although many maximum discharges occur as a result of heavy rainfall, figure 3 shows that discharges measured on May 3, 1972, after a 2-day rainfall were a small fraction of the maximum discharges after snowmelt, even though the water equivalents for snow and rainfall accumulations were about the same, 2 inches. The smaller discharges of May resulted from rainfall replenishing soil moisture which had been reduced by evapotranspiration.

The bottom discharge value for the stations in figure 3 shows that the flow per unit drainage area was four to eight times larger for small headwater streams than for the main stem of Snake Creek. However, total runoff per unit area probably was similar for all stations because the duration of flow was greater on the main stem.

Mean Annual Flow

The mean annual flow of the South Fork of Snake Creek (station 06473500, fig. 3) from 1950 to 1972 was about 11 cubic feet per second, equivalent to an average annual runoff of 8,000 acre-feet. The mean annual flow of other streams in the area was estimated by regression analysis (Larimer, 1970) to total 9 cubic feet per second, equivalent to an average annual runoff of 6,500 acre-feet. Thus, the estimated mean annual flow of all streams in the area totals 20 cubic feet per second, or about 14,500 acre-feet.

Flow Duration

The duration of streamflow is very short in this area because of low precipitation, high evapotranspiration, and the small amount of ground-water seepage (baseflow) into streams. Discharge from flowing wells does not noticeably increase streamflow. Thus, ground-water supplies or reservoirs are needed to supply water during periods when streams do not flow. A flow-duration curve can be used to show the percentage of time a specific discharge was equaled or exceeded. For example, a daily discharge of 1 cubic foot per second is equaled or exceeded about 20 percent of the time on the South Fork of Snake Creek (fig. 4). Similarly, a discharge of 0.1 cubic foot per second is equaled or exceeded about 30 percent of the time. The steep slope of the

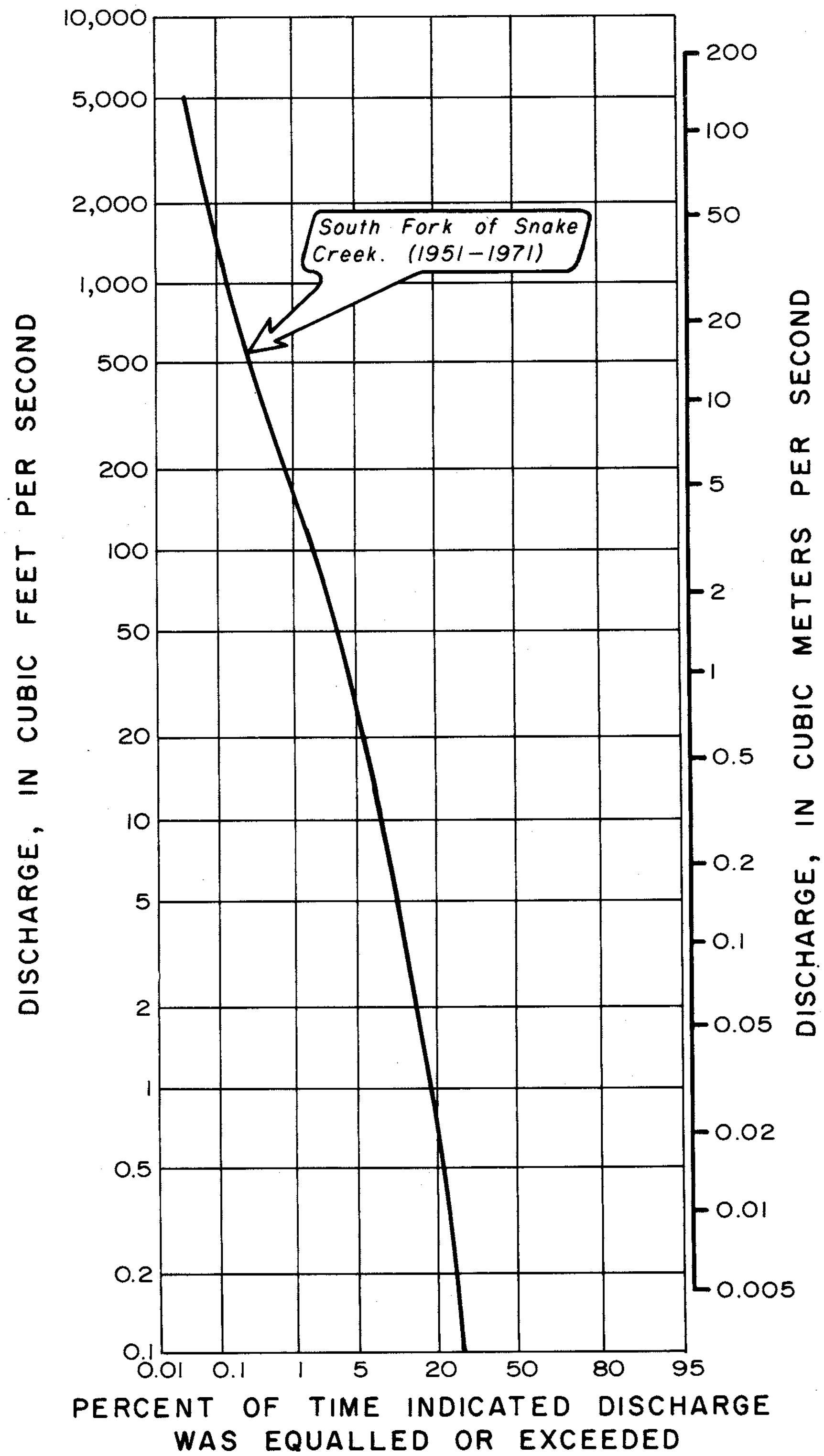


Figure 4. Flow duration curve for the South Fork of Snake Creek shows that a mean daily discharge of one ft^3/s was equaled or exceeded about 20% of the time.

curve indicates that there is no baseflow during prolonged dry weather. Flow-duration curves for other ungaged streams in the area can be expected to have similar slopes and be displaced downward toward lower flows that are proportional to their drainage areas.

Floods

Floods occur from heavy rainfall or following rapid melting of snow in spring. Floods do not occur every year because snowfall is normally small, melting occurs gradually, and lakes, ponds, and loamy soils retain most of the snowmelt. The flood-frequency curves in figure 5 show the probable recurrence interval of a given discharge and the percent chance that the discharge has of occurring in any one year. A maximum discharge of about 5,000 cubic feet per second can be expected on an average of once in 25 years or, has a 4 percent chance of occurring in any one year, on the South Fork of Snake Creek. A similar recurrence can be expected for a discharge of about 600 cubic feet per second on an Elm River tributary (06471050, fig. 3). The large difference in magnitude of the 25-year maximum peak discharges is due primarily to the fact that the area drained by Snake Creek is 74 times that of the Elm River tributary. The maximum discharge at the station on the South Fork of Snake Creek was 6,810 cubic feet per second on April 7, 1969. The maximum discharge for the station on the Elm River tributary a day later, was 720 cubic feet per second. Runoff per square mile was nearly eight times greater for the tributary, mainly because of steeper slopes. Other factors such as drainage density and snow cover also account for these differences.

Information on floods in small drainage basins is being obtained by the U.S. Geological Survey at crest-stage partial-record stations, seven of which are in the study area (fig. 3). Floodflows at ungaged sites can be approximated by the use of a regression equation developed by Larimer (1970, p. 26).

Lakes and Ponds

Location and Size

A Landsat-imagery photomosaic (fig. 6) shows water (white tone) on May 14, 1973. Lakes, water areas of more than 40 acres, are mostly located in the coteau and particularly in the middle third of McPherson County. A few man-made lakes are located in drainageways.

The two largest lakes in the area cover 3 square miles in northeastern Faulk and southeastern Edmunds Counties. They are fed by ground-water seepage, and are reported to have nearly dried up during prolonged droughts. Although ponds, water areas of 40 acres or less, occur throughout the study area, the largest, more

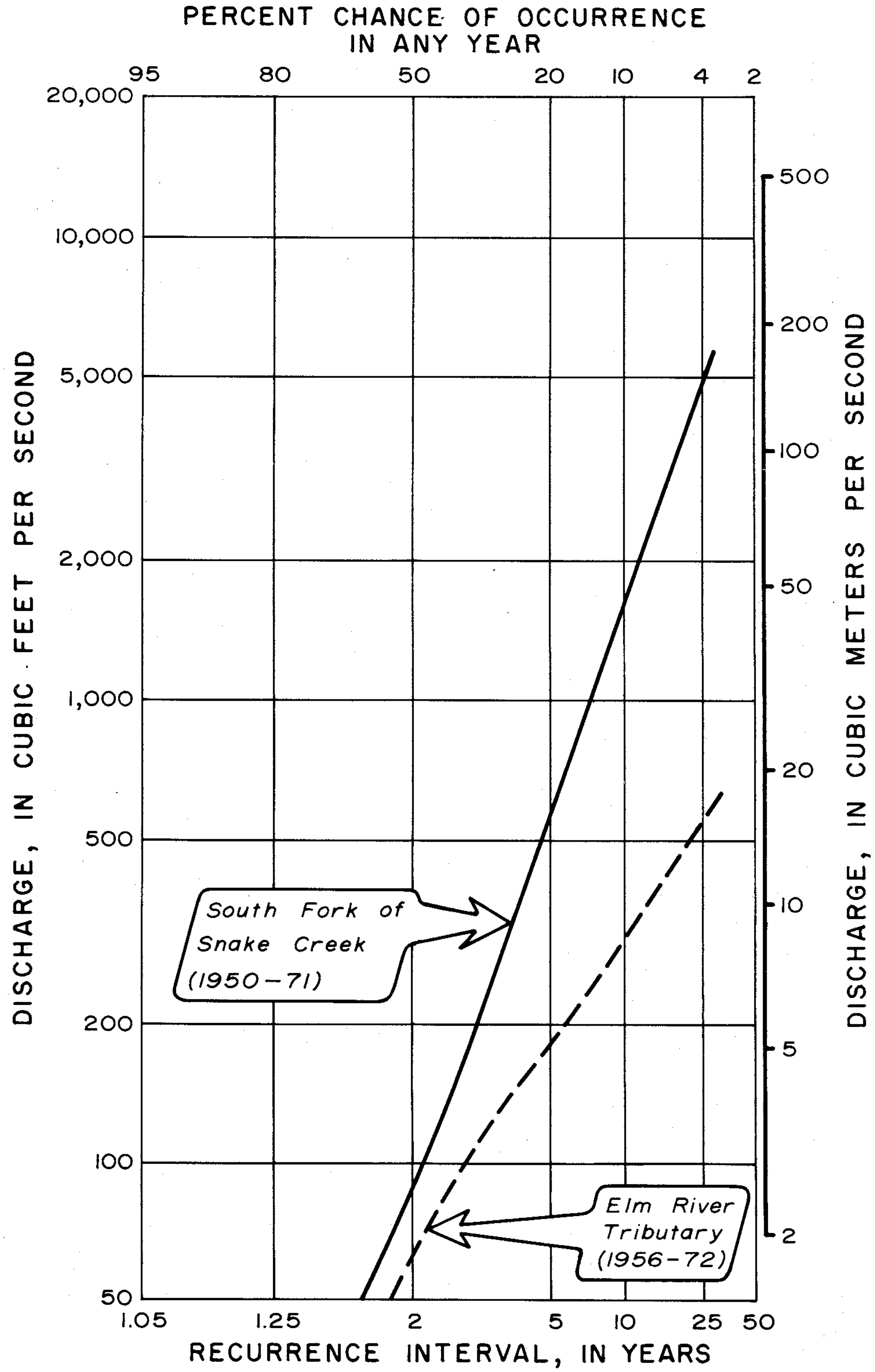


Figure 5. Flood frequency curves for the South Fork of Snake Creek and an Elm River Tributary showing that on an average of once in 25 years *(or a 4% chance any year)* an expected maximum peak discharge would be 5,000 $ft.^3/s$ and 600 $ft.^3/s$ respectively.

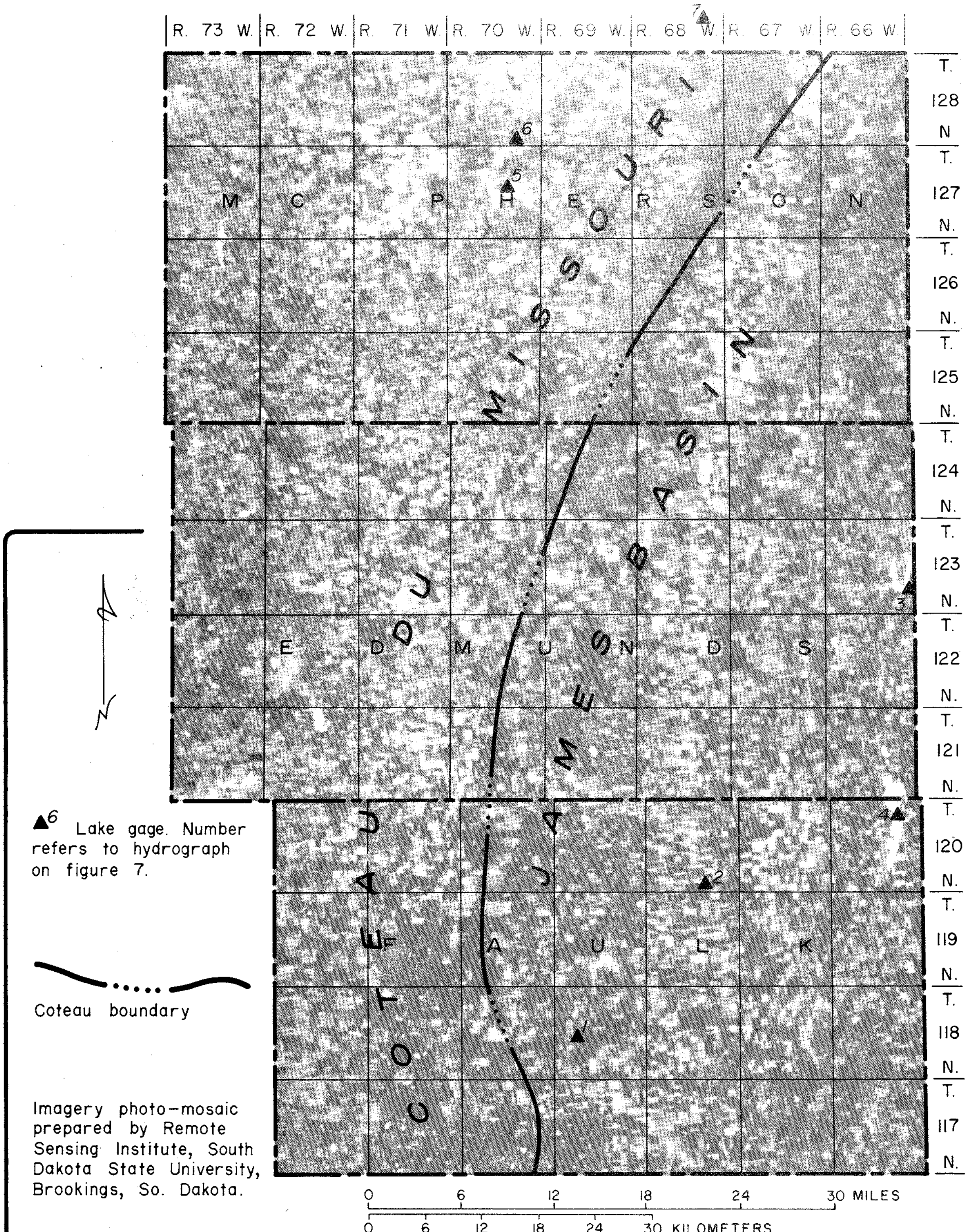


Figure 6. Landsat imagery showing lakes and ponds *(white areas)*, which covered 8% of the coteau in western McPherson, Edmunds and Faulk counties, in May 1973.

permanent ones occur in the coteau. Their generalized hydrology is described by Eisenlohr and Sloan (1968).

The area of ponds is typically from 1 to 2 acres in the James Basin and is about 10 acres in the coteau. Generally, ponds smaller than 5 acres contain water only during wet springs, as in 1972. Ponds of 2 acres or less in size cannot be distinguished on Landsat imagery.

During the period 1969-73, when precipitation and runoff were above normal, lakes and ponds covered about 8 percent of the coteau, including 10 percent of western McPherson County, 7 percent of western Edmunds County, and 4 percent of western Faulk County. During the extreme drought of the 1930's most ponds and lakes reportedly were dry.

Water Levels and Storage

Fluctuations of water levels for six lakes and a pond during 1970-72 are shown in figure 7. The pond is located 2 miles north of the study area but its fluctuations of water levels are representative of many ponds in the study area. To facilitate comparison of the relative decline of water levels in summer, the water levels were adjusted by shifting each hydrograph up or down so that each level on May 1, 1972, would read 6.0 ft. Water levels rose and storage increased greatly in lakes and ponds early in 1972 as a result of runoff from snowmelt and rainfall. By late summer of 1972 levels had declined several feet as a result of outflow and evaporation. The declines were relatively small for seepage lakes such as lakes 5 and 6 because they have no surface inlets or outlets and are sustained almost entirely by ground-water seepage. Loss of storage by evaporation was partly compensated for by ground-water seepage.

Drainage lakes, which are those with surface inlets and outlets, had a maximum water-level range of 3.5 feet in 1972 because they receive much runoff in spring. Their water-level decline in summer and autumn also was large because of surface outflow, evaporation losses, and very little ground-water inflow. The decline in the level of lake 4 was not as large as for the other drainage lakes because it has no surface outlet. Lake 4 also receives ground-water discharge.

The range in water level of 2 feet for pond 7 in 1972 was nearly the same as for some drainage lakes. The range in water levels for six other ponds (not shown) was nearly the same as for pond 7. The large fluctuation in levels was due to large inflows of surface water and ground water in spring and large evapotranspiration losses in summer.

Surface-water storage during 1969-73 was higher than average. Using data from land and water inventories (U.S. Dept. of Agriculture, 1970), average surface-water storage is estimated to be

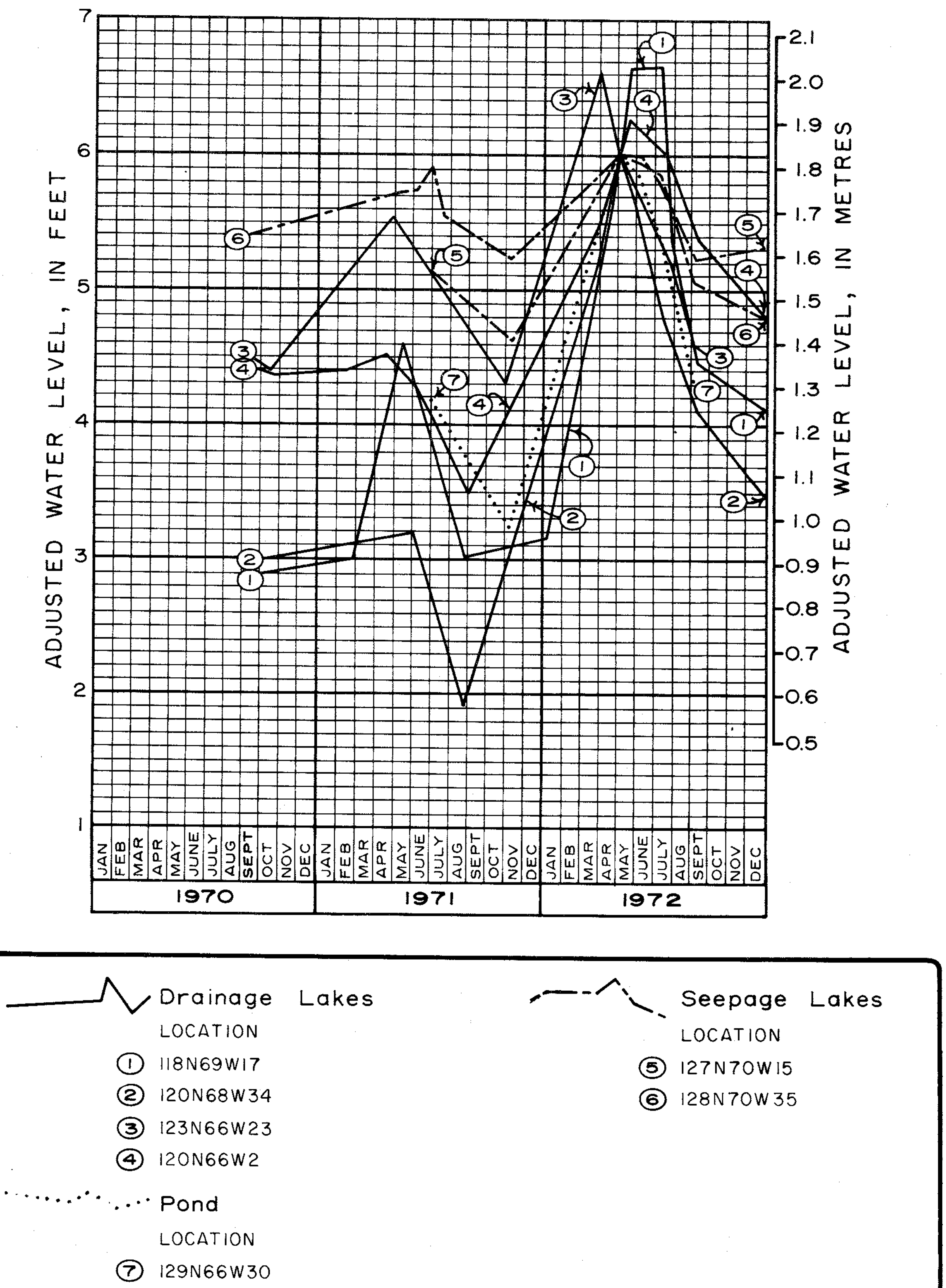


Figure 7. Hydrographs showing surface-water levels, 1970-1972. *The maximum water level range in 1972 was 3.5 feet for drainage lakes, 1.2 feet for seepage lakes, and about 2.0 feet for a pond.*

70,000 acre-feet, assuming an average water depth of 1 foot in lakes and ponds. Storage can increase 100 percent in spring after heavy snowmelt runoff and decrease nearly 100 percent below average during extreme drought lasting several years.

Surface-Water Quality

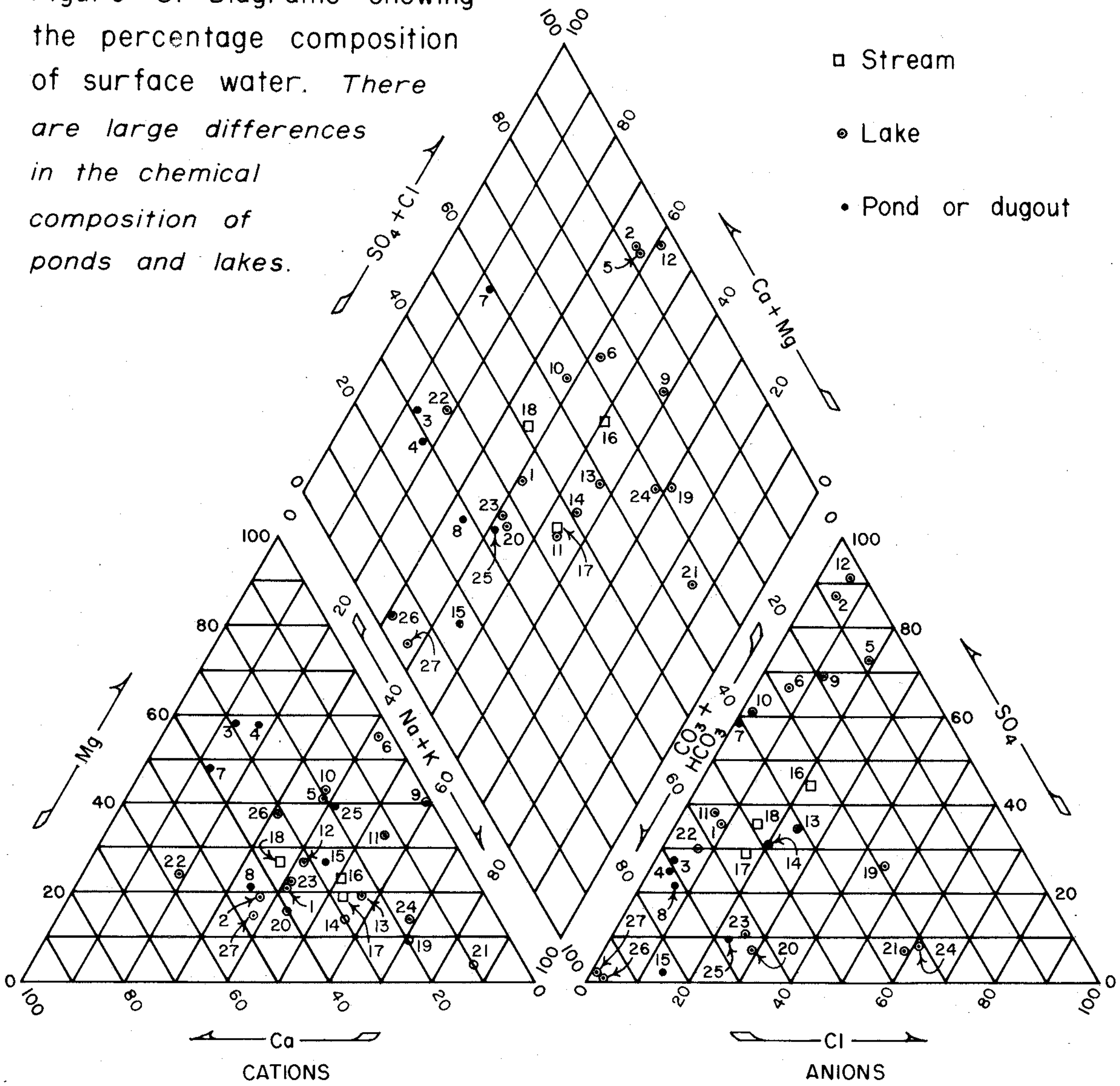
The quality of surface water varies with the seasons and precipitation. The water, particularly that in lakes on the coteau in McPherson County, is characterized by high hardness, exceeding 500 milligrams per liter, and high concentrations of dissolved solids, exceeding 1,000 milligrams per liter.

Chemical Composition

The dissolved constituents in surface waters in the study area are mostly sodium, calcium, magnesium, bicarbonate, and sulfate ions which are leached from soil and till. The chloride concentration is high in a few lakes which receive high-chloride water discharged by artesian wells. Because concentrations of ions are greatly affected by precipitation and evaporation, areal differences in chemical composition are more easily understood if the concentrations, in milliequivalents per liter (meq/L), of an ion are expressed as percentages of anions or cations.

The scatter of data points on the trilinear, percentage-composition diagrams (fig. 8) shows that there are large differences in the chemical composition. The numbers along the margins of the diagrams are percentages, increasing from zero to 100 in the direction of the arrows, for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), carbonate (CO3), bicarbonate (HCO3), sulfate (SO4), and chloride (Cl). In the anion diagram most plotted points are on the left side. These points show that chloride generally makes up less than 30 percent of the composition and that the water is basically various mixtures of bicarbonate and sulfate ions. Samples 2 and 12 were collected from lakes in McPherson County which contain about 90 percent sulfate anions because they receive large amounts of sulfate-rich water from artesian wells. The anion composition for other lakes in the County (samples 5, 6, 9, and 10) also is more than 60 percent sulfate because the lakes receive sulfate-rich ground water from seeps and springs. Sulfate-rich ground water also contains large percentages of calcium and bicarbonate ions but the latter are precipitated in the lakes, leaving the water with higher percentages of other ions. Ponds near hilltops in McPherson County (samples 3, 4, and 7) have low percentages of sodium. Soils in these hills are well drained and have been leached of sodium. Sodium percentages are higher in Faulk County, particularly in several lakes (samples 19, 21, and 24) that also have high chloride percentages. The probable sources of sodium and chloride ions are natural ground-water discharge, flowing wells completed in the Dakota, and domestic sewage. Potassium makes up as much

Figure 8. Diagrams showing the percentage composition of surface water. *There are large differences in the chemical composition of ponds and lakes.*



SAMPLE NUMBER	LOCATION OF SAMPLE	MONTH AND YEAR SAMPLED
	McPherson County	
1.	128N66W36BB	8/70
2.	126N67W17AD	8/70
3.	128N67W6AD	5/63
4.	128N67W6AD	10/63
5.	126N69W10AD	8/70
6.	127N70W3AA	8/70
7.	125N71W12BB	7/60
8.	126N71W4BA	8/59
9.	127N71W27CC	9/63
10.	128N71W21AC	8/70
11.	128N73W33CA	8/70
12.	127N73W34DD	8/70
	Edmunds County	
13.	123N66W25AC	9/65
14.	123N66W25AC	8/70
15.	121N70W20CB	9/57
	Faulk County	
16.	118N66W11AD	6/69
17.	118N66W11AD	3/72
18.	118N66W11AD	6/72
19.	117N66W16CD	8/70
20.	120N66W2DB	8/70
21.	118N67W30AA	8/70
22.	118N69W17BC	8/70
23.	120N68W27DC	8/70
24.	120N69W3BA	8/70
25.	119N69W12CA	10/57
26.	118N70W35AC	8/70
27.	118N71W20CA	8/70

as 10 percent of the cations but has been included with sodium in the diagrams.

Many users of water are interested in concentrations of dissolved solids expressed in milligrams per liter rather than percentages in milliquivalents per liter. Milligrams per liter is equivalent to parts per million (ppm). The concentrations of dissolved solids averaged 1,200 milligrams per liter for 21 samples from lakes and 600 milligrams per liter for 18 samples from ponds. Dissolved-solids content generally is higher in lakes than in ponds in the study area because most lakes are in low ground, intercept more ground water, and seldom lose salts by overflow. Concentrations in ponds were as low as 70 milligrams per liter in spring because of dilution by runoff. Also, most ponds lie on high ground relative to lakes and tend to lose water and salts by overflow and seepage. Most lakes and ponds with dissolved-solids concentrations above 1,000 milligrams per liter are in McPherson County. The maximum concentration (estimated from the specific conductance of the water) was 17,000 milligrams per liter in this County (Twin Lakes, 127N70W14) but the second highest concentration of 9,000 milligrams per liter was for a small pond in northeastern Faulk County (120N66W1). Both bodies of water have no outlets and receive much ground-water inflow, hence dissolved constituents accumulate in them and become concentrated by evaporation.

Concentration of dissolved solids tend to decrease with an increase of discharge for Snake Creek (fig. 9). The trend of the graph is reasonably smooth, except for samples collected on March 30, 1972, and July 3, 1969. The first is affected by snowmelt dilution and the second by dilution from a heavy rainstorm. Concentrations of nitrate and phosphate increased during snowmelt on March 17, 1972, probably the result of a large amount of fertilizer being mixed with snowmelt runoff. During the winter wind erosion on bare, fallow fields is common and mixes soil and fertilizer with the snow in ditches.

Although concentrations of dissolved solids tend to decrease with an increase of discharge, a large part of the annual dissolved-solids load is discharged during short periods of high flows. For example, calculations based on data in figure 9 indicated that at a discharge of 19 cubic feet per second and a dissolved-solids concentration of 670 milligrams per liter the dissolved-solids load is 34 tons per day. In contrast, at a discharge of 1,120 cubic feet per second and a concentration of 180 milligrams per liter the load increases to 550 tons per day.

The average annual load of dissolved solids for the South Fork of Snake Creek at station 06473500 was estimated to be 8,000 tons for the period 1969-72.

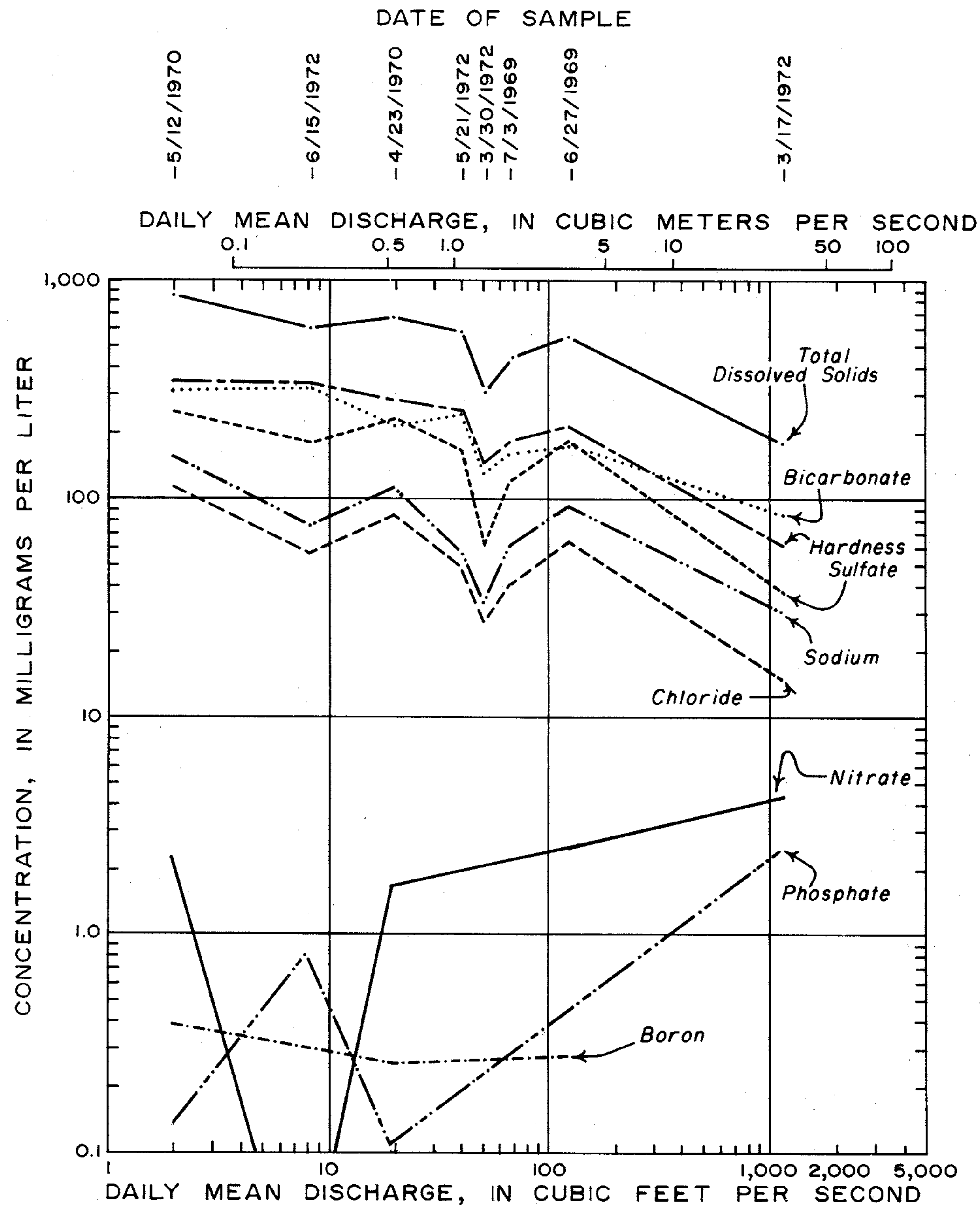


Figure 9. Graph showing concentrations of dissolved solids, constituents, and hardness at different discharges for the South Fork of Snake Creek (station 06473500).

Hardness

Most surface water in the study area is classified as hard to very hard. Hardness ranged from 60 milligrams per liter in streams in the spring to 5,000 milligrams per liter in a lake at 127N70W14 during 1970-72. The hardness of water from many lakes in the coteau exceeds 500 milligrams per liter. Excessive hardness is caused by seepage of very hard ground water into the lakes and also by concentration of dissolved solids by evaporation. Maximum hardness probably occurs during winter when formation of ice leaves a concentrated solution beneath the ice.

GROUND WATER

A supply of ground water adequate to meet most needs is available from the glacial aquifers and underlying bedrock aquifers (table 1). A properly developed well in either type of aquifer may yield more than 500 gallons per minute.

Geology and Soils

This section describes only the general geology and soil characteristics which affect the availability of water. A detailed discussion of the geology can be found in Part I of this Bulletin (Christensen, 1977). Stratigraphic nomenclature and classifications used in this report are those of the South Dakota Geological Survey. The names differ only slightly from those adopted by the U.S. Geological Survey.

A thick sequence of consolidated sedimentary rocks, shale, sandstone, limestone, and dolomite overlies Precambrian granite in the study area (table 2). The lower part of the sequence contains bedrock aquifers of sandstone, limestone, and dolomite. The total thickness of these rocks ranges from 1,300 feet in the southeast to 3,800 feet at the northwest end of the area. The average thickness of sandstone in bedrock totals about 250 feet. The aquifer units that are tapped by most bedrock wells are the Dakota Formation, which has a maximum thickness of 310 feet, and the Fall River Formation, which has a maximum thickness of 360 feet. The maximums do not, however, occur in the same area. Depths to the top of the Dakota Formation range from about 900 feet in the southeast to 1,800 feet in the northwest part of the area.

Unconsolidated Quaternary deposits, mostly poorly permeable till, overlie the Pierre Shale. The thickness of these deposits averages about 30 feet in the James Basin and about 300 feet in the coteau in the study area. Some of the deposits are as much as 600 feet thick in the coteau, where they cover a former river valley which was eroded deeply into the Pierre Shale. A contour map of the bedrock surface (Christensen, 1977) shows the location of the valley and its tributaries.

TABLE 2. Principal rock units and their water-bearing characteristics

System	Series	Rock unit	Description	Maximum thickness (ft)	Water-bearing characteristics
Quaternary	Holocene	Soil	Loam over clayey subsoil.	5	Poorly permeable. Not an aquifer.
		Alluvium	Sand and gravel, clayey, silty. Sorted and stratified. Deposited by streams.	20	Permeable. Yields moderate amounts of water to wells.
	Pleistocene	Till	Clay, silty, and unsorted mixtures of sand, gravel, and boulders. Deposited by glaciers.	560	Poorly permeable. Yields small amounts of water to wells from sand and gravel lenses.
		Outwash	Sand, fine to coarse, well-sorted, and gravel with coal. Lower part may contain much silt, clay, shale pebbles and boulders. Deposited by glacial meltwater.	175	Highly to moderately permeable. Forms major aquifers and can supply wells yielding more than 500 gal/min.
		Lake deposits	Silt, clayey, and fine sand. Sorted and stratified. Deposited by glacial lakes.	153	Poorly permeable. Yields small amounts of water to wells.
Cretaceous	Upper	Pierre Shale	Shale.	800	Poorly permeable. Yields small amounts of mineralized water to wells.
		Niobrara Formation	Shale, calcareous.	160	Poorly permeable. May yield small amounts of mineralized water to wells.
		Carlile Shale	Shale.	170	Impermeable.
		Greenhorn Limestone	Shale, calcareous.	160	Poorly permeable. May yield small amounts of mineralized water to wells.
		Graneros Shale	Shale.	410	Impermeable.
	Lower	Dakota Formation	Sandstone and shale.	310	Permeable. Can supply wells yielding as much as 500 gal/min.
		Skull Creek Shale	Shale.	130	Impermeable.
		Fall River Formation	Sandstone and shale.	360	Permeable. Can supply flowing wells yielding as much as 40 gal/min.
Jurassic	Middle	Sundance Formation	Sandstone and shale.	220	Permeable. Can supply flowing wells yielding more than 1,000 gal/min.
Permian	Lower	Minnelusa Formation	Sandstone, limestone, and shale.	150	Permeable. Can supply flowing wells yielding more than 1,000 gal/min.
Pennsylvanian					
Mississippian	Lower	Madison Group	Limestone.	300	Unknown, probable aquifer.
Ordovician	Upper	Red River Formation	Dolomite.	400	Unknown, probable aquifer.
	Middle	Winnipeg Formation	Shale and sandstone.	200	Unknown.
Precambrian			Granite	- ----	Impermeable, except locally along shallow fractures.

TABLE 3. Major glacial aquifers.

Aquifer name	McPherson		Edmunds		Faulk		Total		Composition	Maximum thickness (ft)	Maximum well yield (gal/min)	Well depth (ft)
	Area (sq mi)	Storage (million acre-ft)	Area (sq mi)	Storage (million acre-ft)	Area (sq mi)	Storage (million acre-ft)	Area (sq mi)	Storage (million acre-ft)				
Grand	70	0.50	170	1.10	120	0.80	360	2.40	Sand, fine to very coarse, silty, and silty gravel. Contains thin beds of silty clay.	175	880	150-600
Elm	------	------	63	0.16	24	0.14	87	0.30	Sand, fine to medium, silty, and silty gravel. Contains beds of silty clay.	77	300	20-150
Selby	47	0.20	------	------	------	------	47	0.20	Sand, fine to coarse, silty, and silty gravel. Contains thin beds of silt and clay.	91	100	40-140
Spring Creek	160	0.50	------	------	------	------	160	0.50	Sand, very fine to coarse, silty, and silty gravel. Contains beds of sandy clay.	85	50	20-200
Other aquifers	230	0.75	270	0.65	200	0.75	700	2.15	Sand, very fine to coarse, silty, clayey, and silty gravel. Contains beds of sandy, gravelly, clay.	73	500	20-600
Total	507	1.95	503	1.91	344	1.69	1,354	5.55				

Outwash deposits of sand and gravel compose most of the glacial aquifers in the study area. Although these deposits can be found in much of the study area, they are thickest above and within the former river valley. This maximum known thickness of sand and gravel is 175 feet in southwestern McPherson County.

Lake deposits of clayey silt and fine sand compose part of the glacial aquifers in southwestern McPherson County and northern Faulk County.

Soil in the study area is not deep enough to be an aquifer, but does have a high moisture-holding capacity. The soil retains most precipitation and thereby slows both runoff and recharge. Most subsoil is poorly permeable clay which further slows infiltration and recharge.

Glacial Aquifers

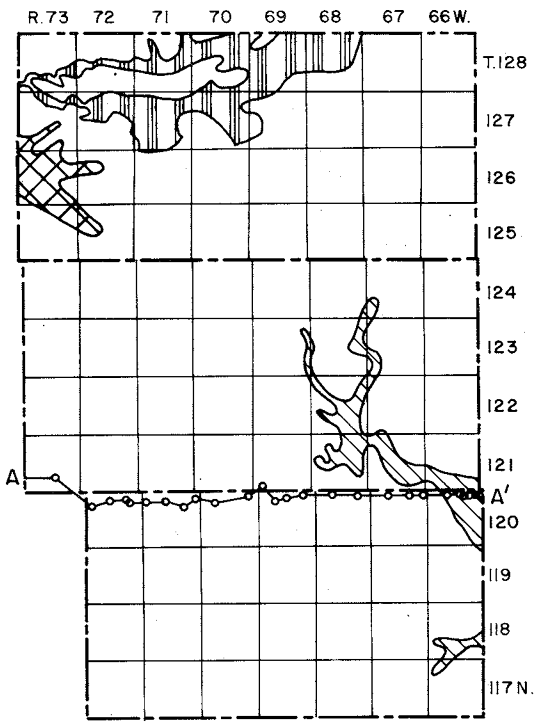
Glacial aquifers, which underlie 1,354 square miles or 40 percent of the study area, are listed in table 3. They are mostly unconsolidated deposits of sand and gravel, outwash deposited during periods of melting of a continental ice sheet which once covered the entire area. The sand and gravel which composes the Grand Aquifer was deposited on top of shale bedrock by meltwater from the ice sheet. The Grand Aquifer subsequently was buried under the coteau by hundreds of feet of till and by outwash deposits which compose the shallower aquifers.

Extent

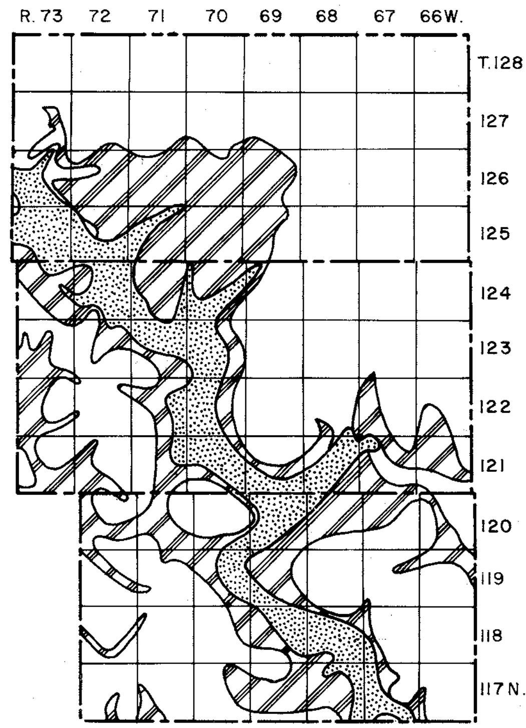
The most extensive of the glacial aquifers (fig. 10) is the Grand aquifer, which underlies an area of 360 square miles. The Grand aquifer lies within a broad, branching, buried valley which was carved into bedrock by preglacial streams. The aquifer, which has an average width of about 4 miles extends westward into Campbell County (Koch, 1970, Hedges, 1972) and southeastward through the study area.

The Grand aquifer is overlain by the Selby aquifer, which covers an area of 47 square miles in southwestern McPherson County and extends westward into Campbell County. A branch of the Grand aquifer in southeastern Edmunds County is overlain by the Elm aquifer, which extends over 87 square miles in Edmunds and Faulk Counties. The Elm aquifer extends eastward from the study area into Spink and Brown Counties (Koch and Bradford, 1975).

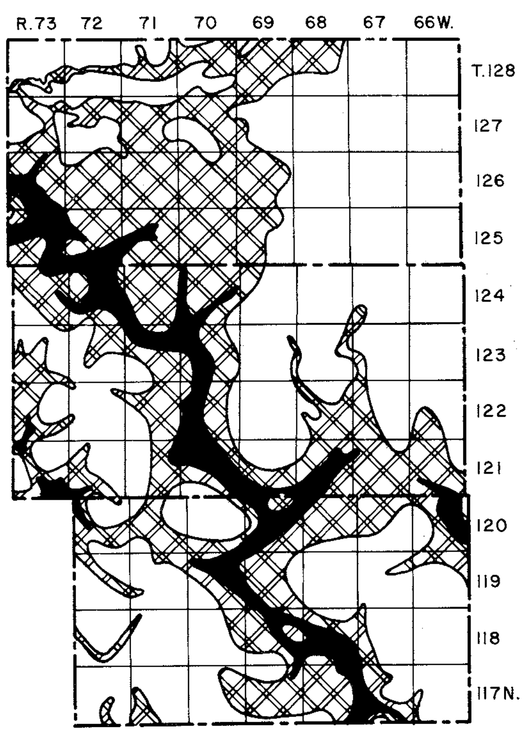
The Spring Creek aquifer underlies an area of 160 square miles in northern McPherson County. Although the aquifer narrows in northwestern McPherson County, it extends westward into Campbell County.



Map showing the areal extent of the Spring Creek, Selby, and Elm aquifers.



Map showing the areal extent of the Grand and other aquifers.



Map showing the areal extent of the five aquifers and the area where the thickness exceeds 50 feet.

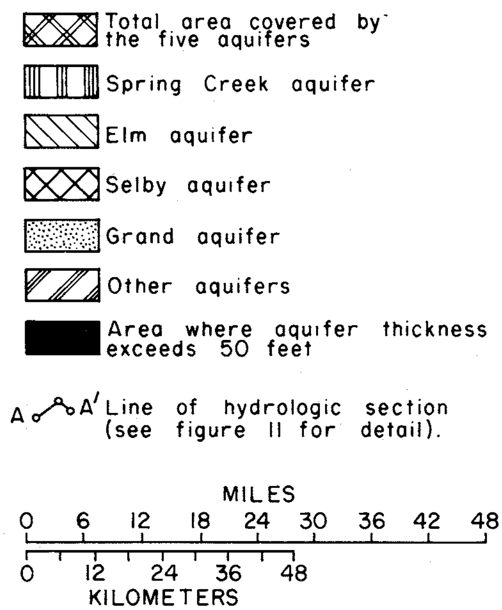


Figure 10. Maps showing the areal extent of glacial aquifers. The Grand aquifer, which is the most extensive, underlies an area of 360 mi².

Lenticular deposits of outwash sand and gravel that generally are no more than 10 feet thick are included with "other aquifers" (fig. 10). These lenticular gravels are extensive but may be absent in some places within the mapped boundaries.

Thickness

The thickness of an aquifer is an important factor in estimating ground-water storage and well yields. The thickness of the Grand aquifer increases sharply inward from its margin and exceeds 50 feet along its entire length (fig. 10). The aquifer generally consists of one bed of sand and gravel in Faulk County but may consist of as many as five beds of sand and gravel separated by till in the other counties. The till contains sandy or gravelly layers that provide hydraulic connection between the different beds. The data in table 3 show that the maximum thicknesses of the aquifer range from 175 feet for the Grand aquifer to 30 feet for the Selby aquifer. However, the average thickness of individual aquifers is about 50 feet for the Grand aquifer, about 30 feet for the Spring Creek and Elm aquifers, and about 20 feet for the Selby and other aquifers. The aquifers may be absent locally near the margins outlined in figure 10.

Detailed studies for city water supplies have shown that the thickness of aquifers generally is below average in 123N68W (Pottratz, 1965), in 123N73W (Ruckstad and Hedges, 1964), and in 118N69W (Christensen, 1962).

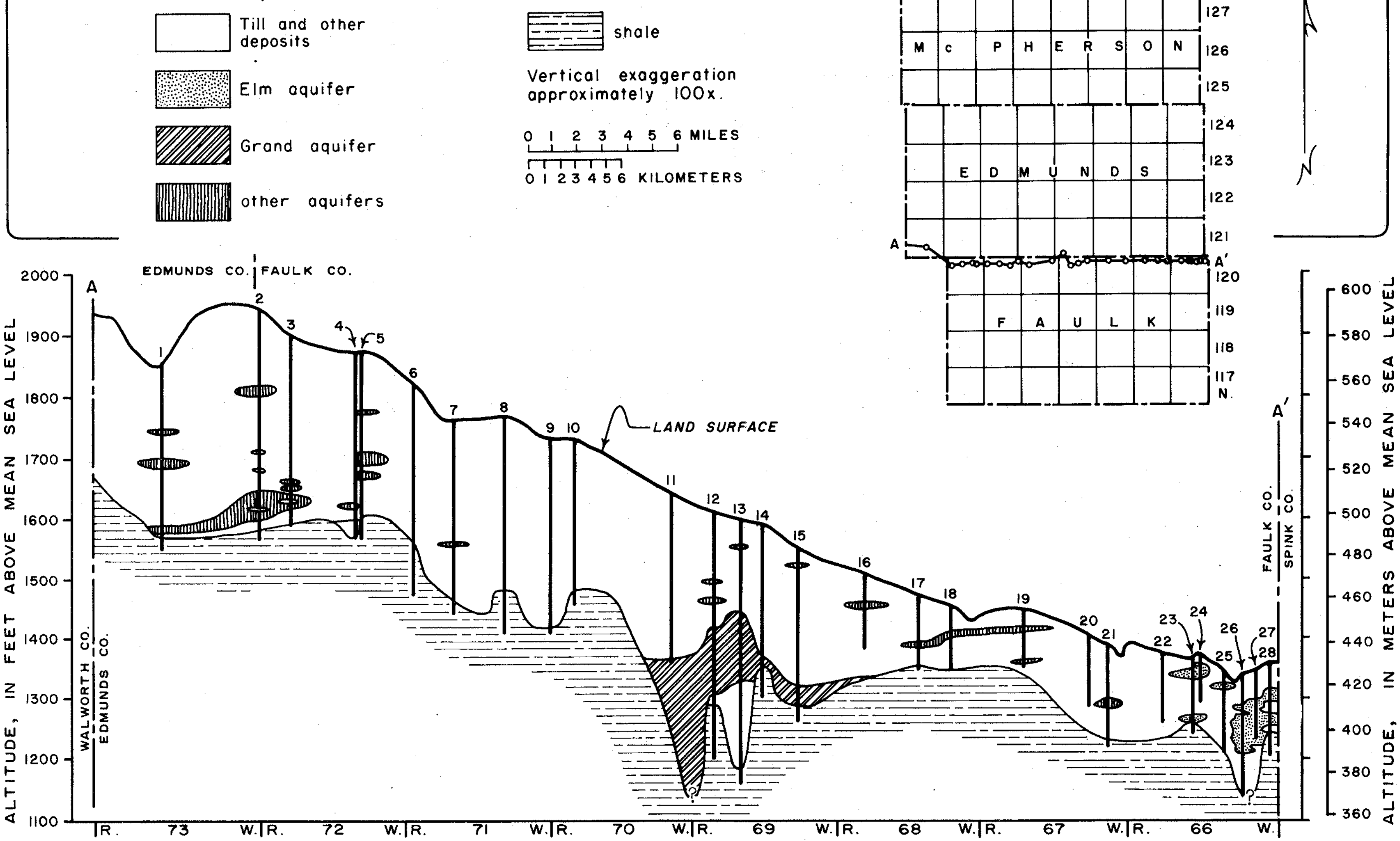
The maximum known thicknesses are 175 feet for the Grand aquifer at 125N73W35CCCB, 91 feet for the Selby aquifer at 126N73W13DAAA, 77 feet for the Elm aquifer at 120N66W24CBCC, 85 feet for the Spring Creek aquifer at 128N70W35DDDD, and 73 feet for other aquifers at 120N72W6BCCC.

Well Depths

Data in table 3 show a wide range in depths of wells which completely penetrate the various aquifers. Well depths for the Grand aquifer increase from about 150 feet in southern Faulk County to about 600 feet in central Edmunds County. Well depths for other aquifers (table 3) range from 20 to 600 feet. The Elm and Spring Creek aquifers are mostly shallow outwash and can be completely penetrated by 20-foot wells at many places. However, the Spring Creek aquifer is buried by as much as 200 feet of till in north-central McPherson County.

Figure 11, a hydrologic section across the northern end of Faulk County, shows that the depth of wells which penetrate aquifers can change greatly within a few miles. For example, the depth of a well in the top of the Grand aquifer would have to be at least 270 feet at well 11. However, at test hole 13, a few

Figure 11. Hydrologic section A–A′ showing glacial aquifers, till or alluvium, and shale.



miles to the east, the depth of a well would only have to be about 150 feet. The section also shows that the depth of wells which completely penetrate the aquifers can also change greatly within a few miles, especially where there are deep channels in shale.

Composition

The composition of an aquifer is an important factor in estimating yields of wells. Coarse sand and gravel is highly permeable, because of its large, interconnected pore spaces, and thus yields water readily. In contrast, beds of clay and silt are poorly permeable and yield water very slowly. Some of the clay and silt that is found in all of the aquifers is mixed in with the sand and gravel. This clogs the pore spaces, thereby reducing the permeability and well yields. In many areas the lower part of the Grand aquifer contains more silt and clay and is less permeable than the upper part of the aquifer. The Grand aquifer is mostly lake deposits, poorly permeable clayey silt and moderately permeable fine sand, in part of southwestern McPherson County and also in northern Faulk County (test hole 13, fig. 11).

Storage

Glacial aquifers store an estimated 5 1/2 million acre-feet of water, nearly half of which is in the Grand aquifer (table 3). The estimates are based on the extent, average thickness, and an estimated specific yield of 20 percent for all aquifers. Total storage is about 2,500 times the amount withdrawn by wells yearly. Although less than half of the storage can be withdrawn by wells, it is not likely to be greatly reduced with increased pumpage. This is because recharge increases as pumpage lowers water levels and induces movement of water into the aquifer. Much of the recharge would be from water that is stored in adjacent till deposits.

Water Movement

A discussion of water movement in aquifers include the source of the water and where it is discharged. Estimates of the rate and amount of movement require that hydraulic gradients and aquifer transmissivity are considered also.

Water in glacial aquifers is recharged from precipitation; the water moves into the aquifers both by vertical infiltration and by lateral inflow from till. Water movement through till is very slow. The rate of flow, under existing hydraulic gradients, is estimated to range from a few feet per year for vertical infiltration to several hundred feet per year for lateral inflow through till. The presence of open joints or fractures locally will increase the rate of flow.

The Grand aquifer is the major conduit through which most ground water moves through the study area. The rate of flow, under existing hydraulic gradients, is estimated to average several hundred feet per year.

The potentiometric surface of the Grand aquifer is shown in figure 12. The arrows and potentiometric contours indicate that water moves in the Grand aquifer from ground-water divides (and recharge areas) toward major discharge areas. These discharge areas are: (1) Southeastern Faulk County, (2) Northeastern Faulk and southeastern Edmunds Counties, and (3) Along the Missouri River west of McPherson and Edmunds Counties (Koch, 1970, p. 19).

The arrows in figure 12 indicate only the general horizontal direction of ground-water flow normal to potentiometric contours because the figure is a two-dimensional representation of a three-dimensional flow system. Actually, in recharge areas near ground-water divides the principal component of flow is downward. In discharge areas the principal component is inclined upward.

Much water moves through the Grand aquifer in the study area because the aquifer is highly permeable. Also its large thickness, exceeding 50 feet along its axis (fig. 10), causes it to have a high transmissivity. Flow through the aquifer can be estimated by the equation

$$Q = TIL$$

where

- Q = discharge (gallons per day)
- T = transmissivity (gallons per day per foot)
- I = hydraulic gradient (foot per mile)
- L = width perpendicular to the direction of flow (mile)

Transmissivities were estimated from descriptive and electric logs of test holes by multiplying the thickness of each unit by an assigned permeability and summing the products. Typical permeabilities assigned were 100 gallons per day per square foot for fine sand, 500 gallons per day per square foot for gravelly clay, and 2,000 gallons per day per square foot for sand and gravel. The average transmissivity was estimated to be slightly less than 100,000 gallons per day per foot, the value obtained from a one-day pumping test of the aquifer (described below).

The results of the flow estimates indicate that flow in the aquifer gradually increases southeastward from the divide in northwestern Edmunds to about 5 million gallons per day in the area north of the divide in north-central Faulk County. The water is discharged eastward into overlying aquifers and till and is eventually consumed by evapotranspiration over an area of about 150 square miles.

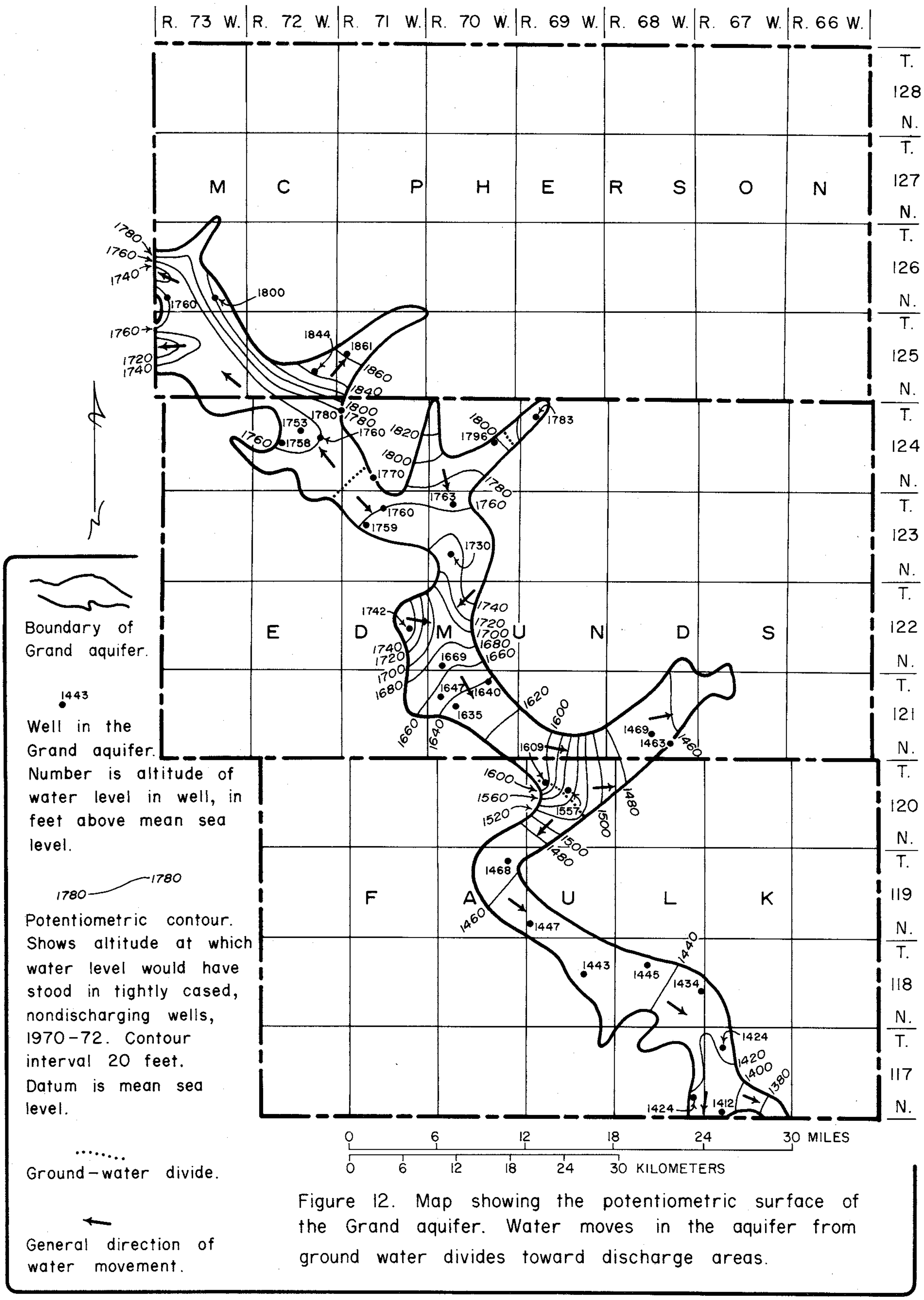


Figure 12. Map showing the potentiometric surface of the Grand aquifer. Water moves in the aquifer from ground water divides toward discharge areas.

Southward flow through the aquifer in southern Faulk County is estimated to be about 2 million gallons per day. Flow from southwestern McPherson County westward into Campbell County is estimated to be about 4 million gallons per day. Thus, total discharge from the Grand aquifer in the study area is roughly 11 million gallons per day and is sustained by recharge.

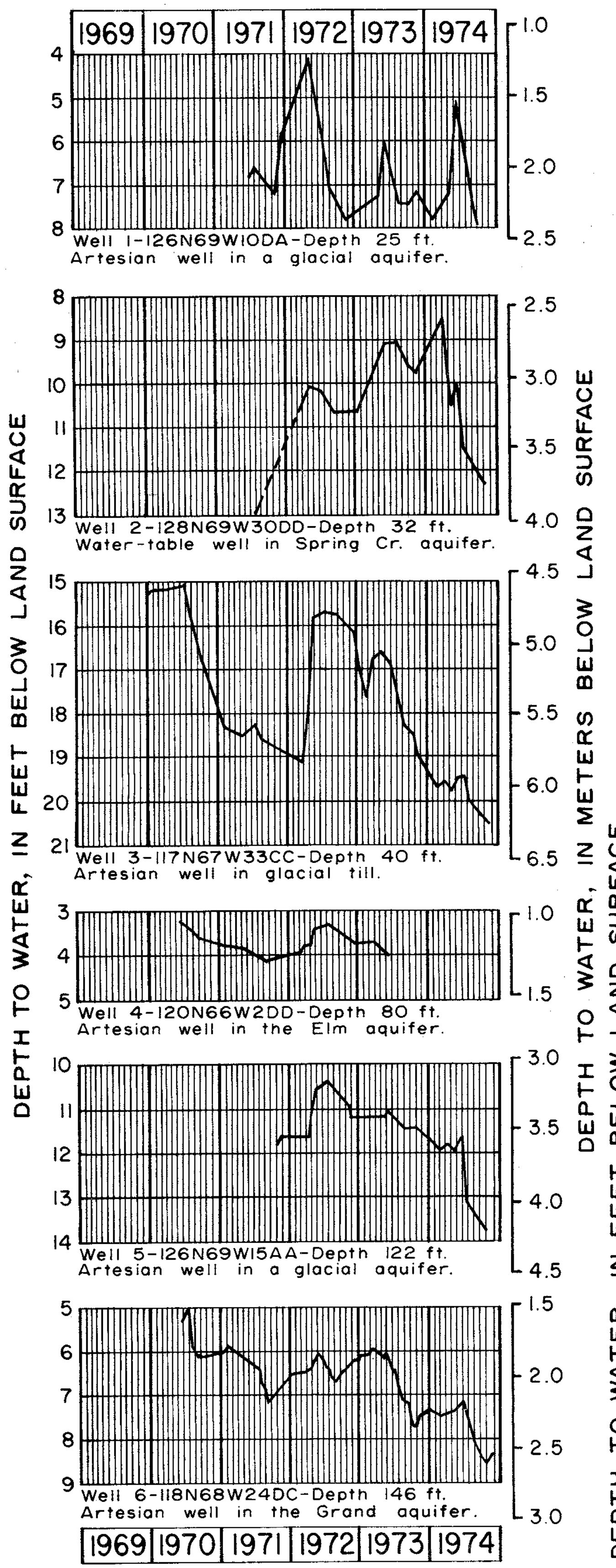
Water Levels

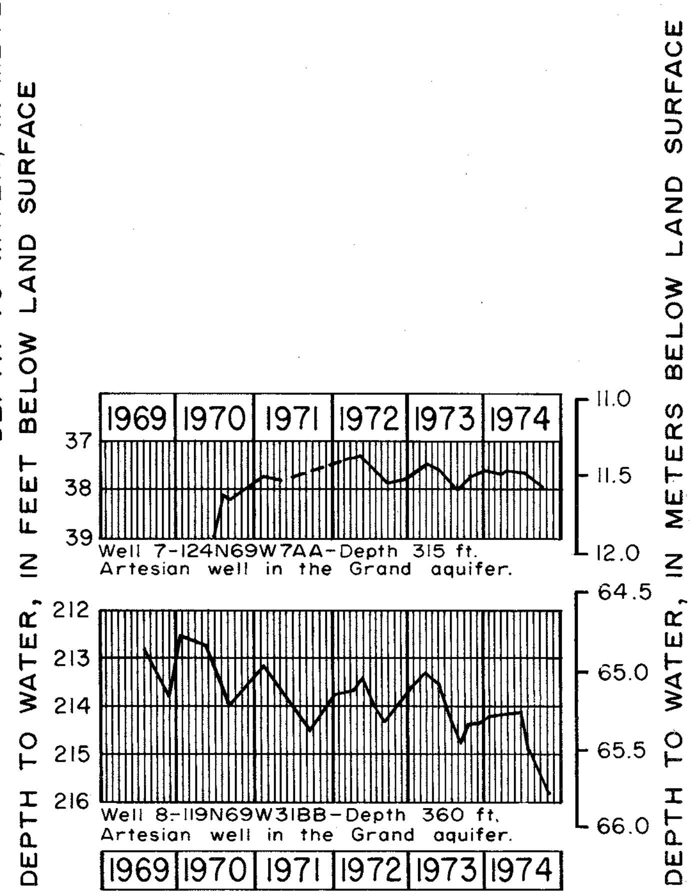
Fluctuations of water levels in wells are caused by fluctuations in the rates of recharge and discharge which change the amount of water stored in an aquifer. Water-level fluctuations in wells in glacial aquifers are both seasonal and long term. Seasonal fluctuations of water levels are caused by differences in recharge or discharge throughout the year. Water levels rise in the spring, when recharge from infiltration of snowmelt and spring rains is greater than discharge by subsurface outflow, evapotranspiration, and pumpage. Conversely, water levels generally decline in the summer, fall, and winter, when discharge is greater than recharge. Seasonal water-level fluctuations are shown in hydrographs (fig. 13) for eight wells that are numbered in order of increasing depth.

The hydrographs for wells 1, 2, and 3, all less than 50 feet deep, generally showed a rise because of increased recharge during the spring. The rise was particularly large in 1972 as a result of heavy precipitation during the previous fall and winter. The subsequent declines were most rapid for the shallowest well because it penetrates an aquifer that is closest to the surface and most influenced by evapotranspiration. The amplitude of water-level fluctuations tends to decrease with depth. Well 4, though shallow, has little amplitude in fluctuation because it is in a discharge area and therefore is relatively unaffected by changes in recharge. The hydrographs for wells 6, 7, and 8 in the Grand aquifer show effects of pumpage. Water levels drop each summer because of increased pumpage for watering gardens and lawns.

Long-term changes in water levels can result from a series of years of above-normal or below-normal precipitation and recharge. Such changes can be seen in figure 13 as a gradual decline in the annual peaks and lows in the hydrographs for wells 3, 5, 6, and 8. The decline after the extremely wet spring of 1969 probably is caused both by increased pumpage and decreased recharge. Water levels should rise again during years when snowmelt and precipitation in spring are above normal. The rise in water level in well 7 in 1970 and 1971 probably was due to locally higher precipitation and recharge.

Figure 13. Hydrographs showing water levels in wells in glacial aquifers and till. The graphs show seasonal and long-term fluctuation.





Well Yields

Potential yields of wells (fig. 14) can exceed 500 gallons per minute throughout an area of 130 square miles. This high yield was estimated for areas where the thickness of the Grand aquifer (fig. 10) exceeds 50 feet. However, well yields may be lower in some areas of 50-foot thickness in northern Edmunds and northern Faulk Counties that are underlain by much fine sand or silty, clayey sand and gravel. A well in clayey fine sand or gravel in such localities may not yield much more than 100 gallons per minute. In the areas where well yields may exceed 500 gallons per minute, specific capacities of properly-constructed wells can be expected to be as much as 20 gallons per minute per foot of drawdown. The specific capacities of wells in low-yield areas can be expected to range from 10 gallons per minute per foot to as little as 0.1 gallons per minute per foot of drawdown.

A two-day aquifer test (one day pumping and one day recovering) was conducted on a fully penetrating test well in a 50-foot thick sand and gravel bed of the Grand aquifer at 118N68W25ABAA. The aquifer is artesian at this site, lying at depths of 100 to 150 feet below the surface. Four observation wells, having static water levels at 8 feet below land surface, were spaced from 22 to 98 feet from the pumped well. The results of an analysis of the data by the Theis (1935) nonequilibrium method (fig. 15) indicates that at this site drawdown for the aquifer should be less than three feet after 1 year at distances of more than 10 feet from a well pumping 114 gallons per minute. The estimates of drawdown were computed from the values of transmissivity and storage coefficient (fig. 15) determined in the test. Theoretically, drawdown in the aquifer would double if the rate of pumping were doubled and would increase 10 times if the rate of pumping were increased 10 times. Actual drawdown can be a few feet above or below these estimates at the higher pumping rates because the drawdown area will expand to the aquifer boundaries after a few days of pumping. Because of the large drawdown available for the aquifer at this site, there would be dewatering of only the upper few feet of the aquifer at a well pumping 1,000 gallons per minute.

Water Quality of Glacial Aquifers

All ground water contains dissolved mineral matter that has been leached from atmospheric dust, soil, and rock. The water in the glacial aquifers in the report area generally is free from turbidity, less susceptible to pollution than surface water, and very hard.

CHEMICAL COMPOSITION

Concentrations of ions in ground water fluctuate with recharge and discharge. Consequently, differences in the chemical compo-

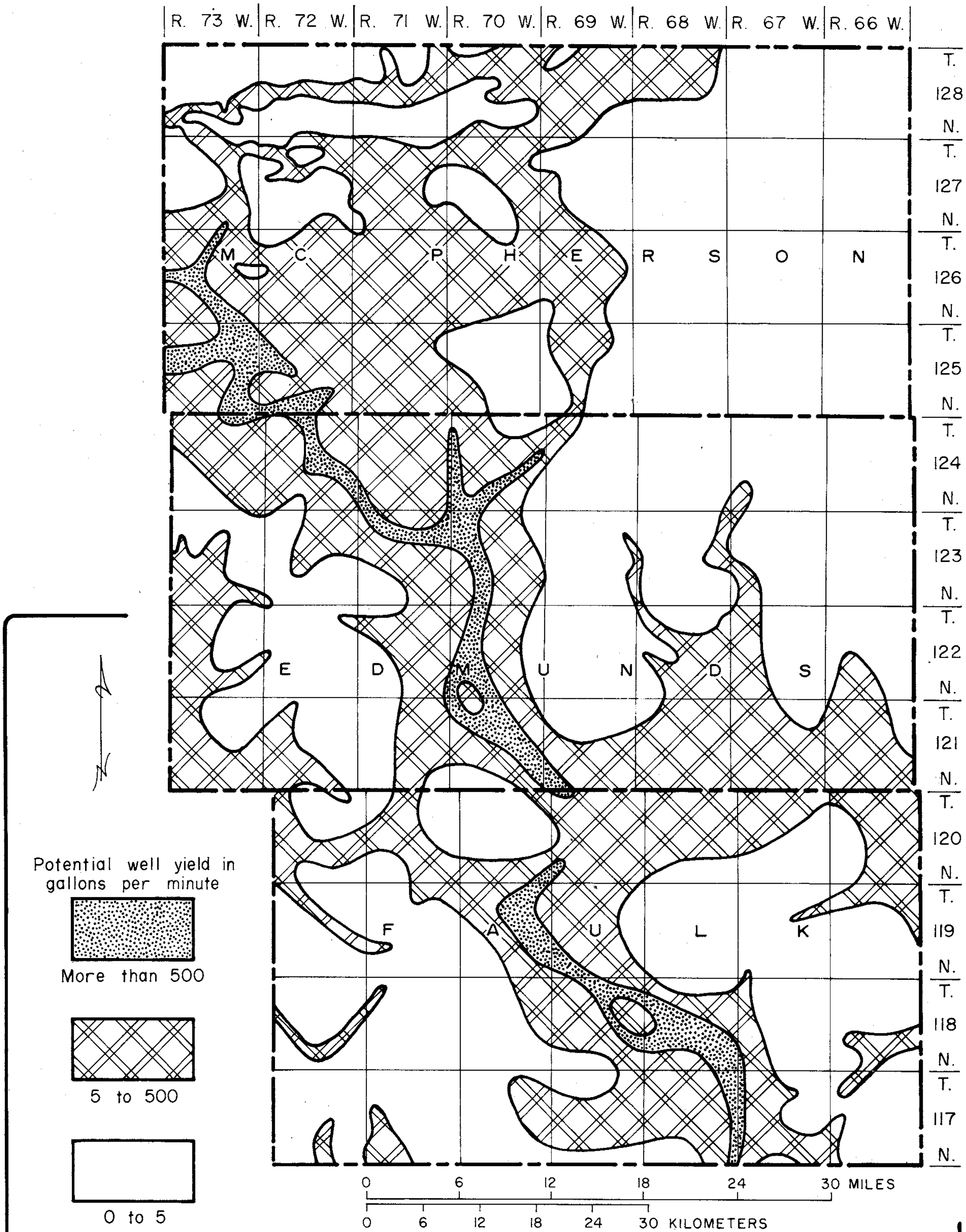
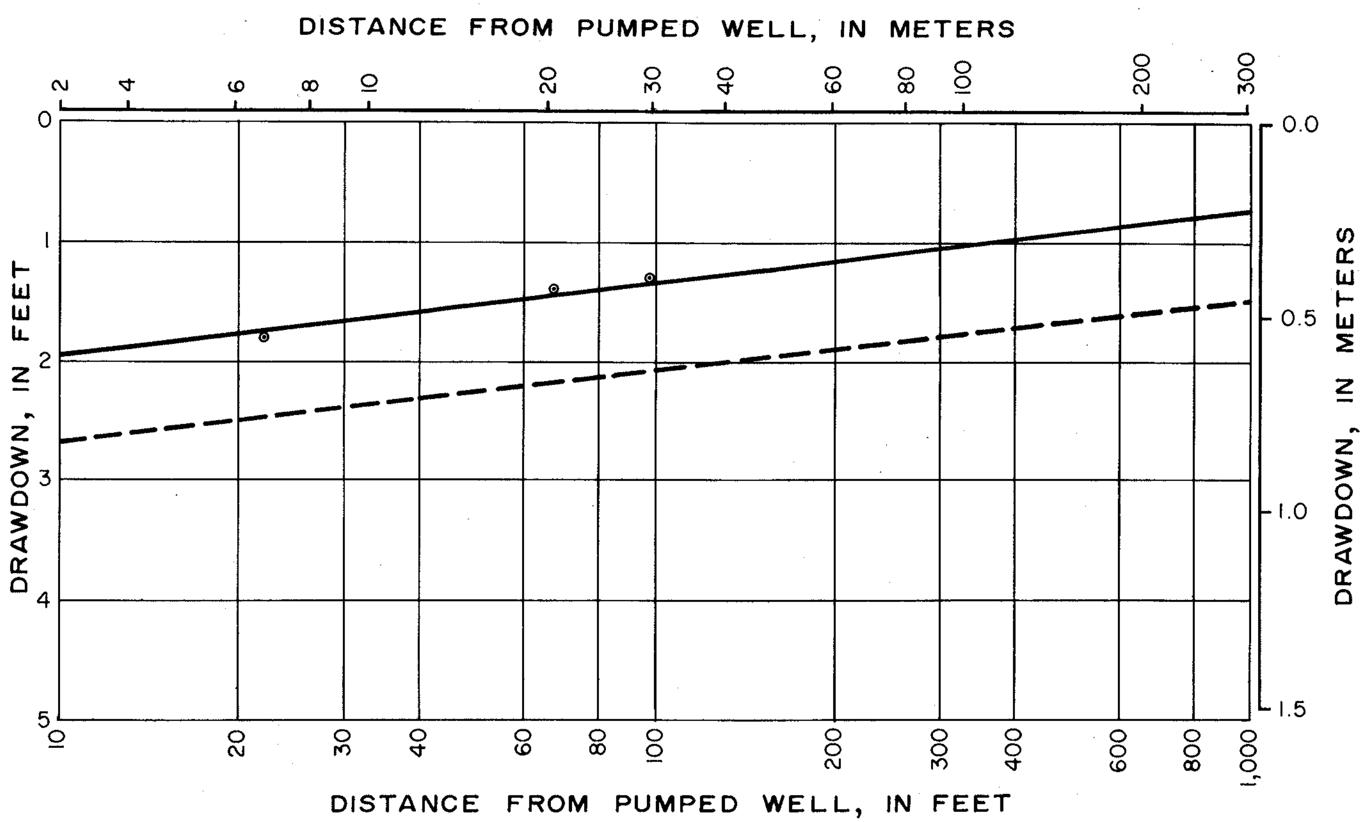


Figure 14. Map showing potential yields of wells in glacial aquifers. *Yields can exceed 500 gal/min over 130 mi²*



Transmissivity = 100,000 (gal./day)/ft.

⊙ Observed drawdown after one day of pumping at aquifer test site–118N68W25AB.

Theoretical drawdown after one day of pumping.

Theoretical drawdown after one year of pumping. *(Not adjusted for boundaries)*

Storage Coefficient = 0.0001

Distance–drawdown curves based on the Theis (1935) non-equilibrium method.

Pumping rate = 114 gal./min.

Figure 15. Distance–drawdown curves for the Grand aquifer at 118N68W25ABAA. *Drawdown should be less than 3 feet after one year at distances of more than 10 feet from a well pumping 114 gal./min.*

sition of water are more easily understood if the concentration, in milliequivalents per liter, of an ion is expressed as a percentage of anions or cations in a diagram (fig. 16). The numbers along the margins of the diagrams are percentages, increasing from zero to 100 in the direction of the arrows, for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), carbonate (CO3), bicarbonate (HCO3), sulfate (SO4), and chloride (Cl). Large differences in the chemical composition of water from the glacial aquifers are caused by areal differences in the percentages of various types of minerals and rocks in soil and glacial deposits. Gypsum is a source of calcium and sulfate, limestone is a source of calcium, magnesium, and bicarbonate, and shale is a source of sodium and chloride ions. Bicarbonate is also added to ground water by oxidation and decay of vegetation.

There are large differences in the chemical composition of the water from glacial aquifers. High percentages of calcium, magnesium and bicarbonate ions are characteristic of analyses of several water samples from the Spring Creek aquifer (samples 1, 2, and 4) and other aquifers (samples 8, 9, and 10). Consequently, these analysis plot in or near the left half of the triangular and diamond-shaped diagrams. In contrast, many of the analyses of water samples from the Grand aquifer plot in the right third of the cation triangle, indicating that the water has a high percentage of sodium ions.

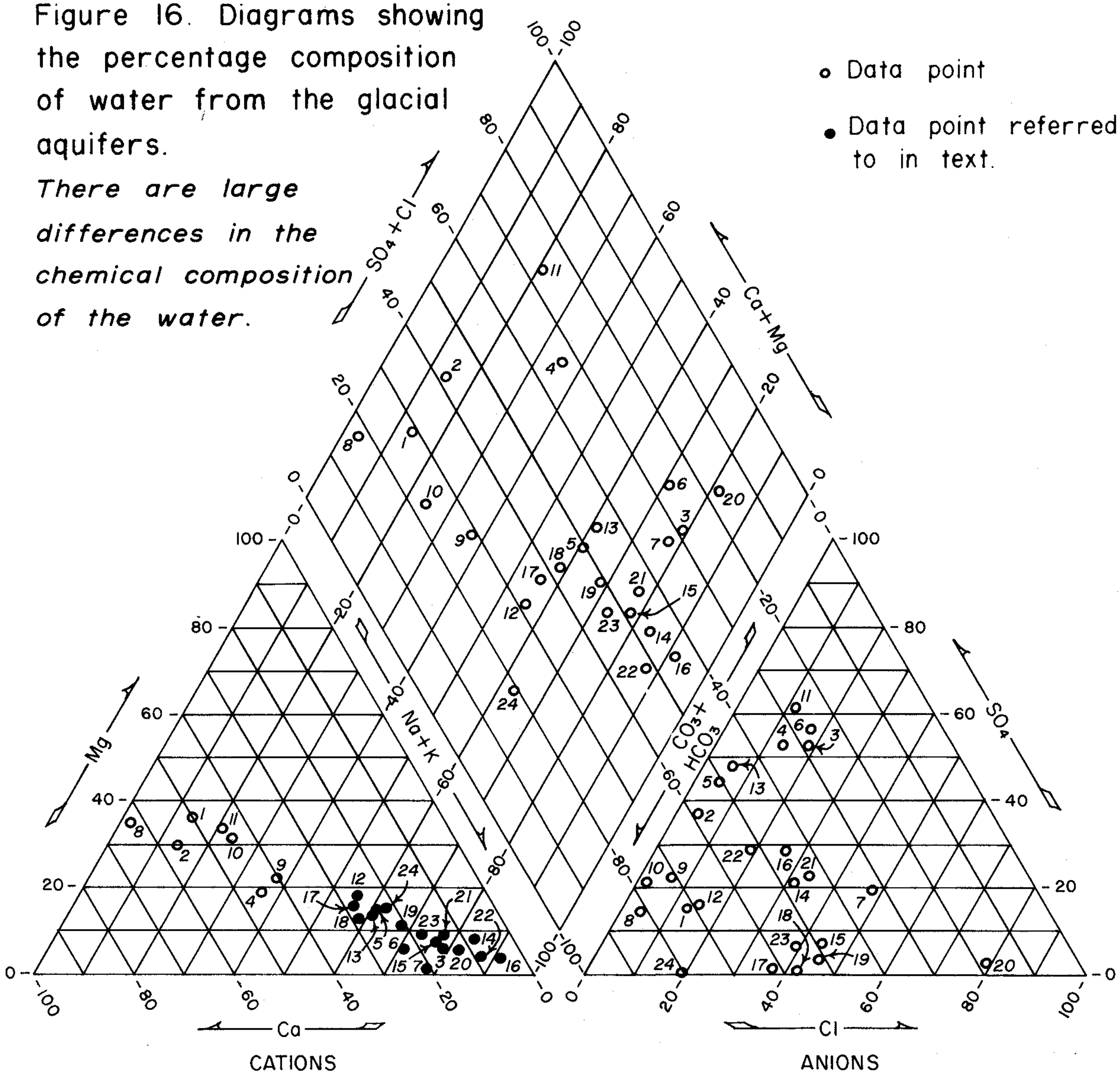
The sequence of sample numbers for each aquifer is in order of increasing depth. Most of the samples from wells less than 100 feet deep have less than 50 percent sodium, with the exception of wells in the Elm aquifer. As water moves to greater depths and away from recharge areas sodium percentages tend to increase because sodium is released from clay minerals by base exchange. Water samples from wells which are more than 100 feet deep indicate that sodium in water from the Grand aquifer (samples 14 through 24, fig. 16) constitutes more than 50 percent of the cations. Some wells in the eastern part of the area yield water that has high percentages of sodium and chloride (sample 7). One source of this water is old, deteriorated flowing wells that leak saline water from bedrock aquifers into glacial aquifers.

The average dissolved-solids concentration of water in the glacial aquifers is about 1,000 milligrams per liter (fig. 17) and exceeds standards set for public water supplies (U.S. Public Health Service, 1962). Nevertheless, such water is used for public supplies in many areas where no other water is available.

Concentrations of dissolved solids and major constituents range widely. Dissolved solids range from 260 milligrams per liter in an aquifer at 123N74W24ADD to 3,350 milligrams per liter in the Elm aquifer at 123N67W19CCCD (Pottratz, 1965, p. 12). Concentrations of dissolved solids are relatively high in the Elm aquifer because it contains many shale pebbles which have easily soluble minerals. The aquifer is shallow, so evapotranspiration also increases the concentration of dissolved solids.

Figure 16. Diagrams showing the percentage composition of water from the glacial aquifers.

There are large differences in the chemical composition of the water.



SAMPLE NUMBER	LOCATION OF SAMPLE	WELL DEPTH IN FEET
	Spring Creek aquifer	
1.	127N70W5AC	20
2.	128N69W32DC	50
3.	127N70W3DD	82
4.	128N69W2CA	210
	Selby aquifer	
5.	126N73W24AB	58
	Elm aquifer	
6.	121N67W7AB	78
7.	121N68W10DD	82
	Other aquifers	
8.	123N74W24AD	24
9.	123N73W28AB	90
10.	123N73W28AD	106
11.	126N69W15AD	112
12.	126N71W17DA	180
13.	125N71W9AB	271
	Grand aquifer	
14.	117N67W7AA	120
15.	118N68W25AB	150
16.	118N69W14BC	230
17.	120N69W5DD	240
18.	121N69W33CD	300
19.	119N70W11CD	340
20.	122N70W4AB	367
21.	123N70W29BA	386
22.	125N72W26AC	390
23.	122N70W31BB	392
24.	124N72W29BB	445

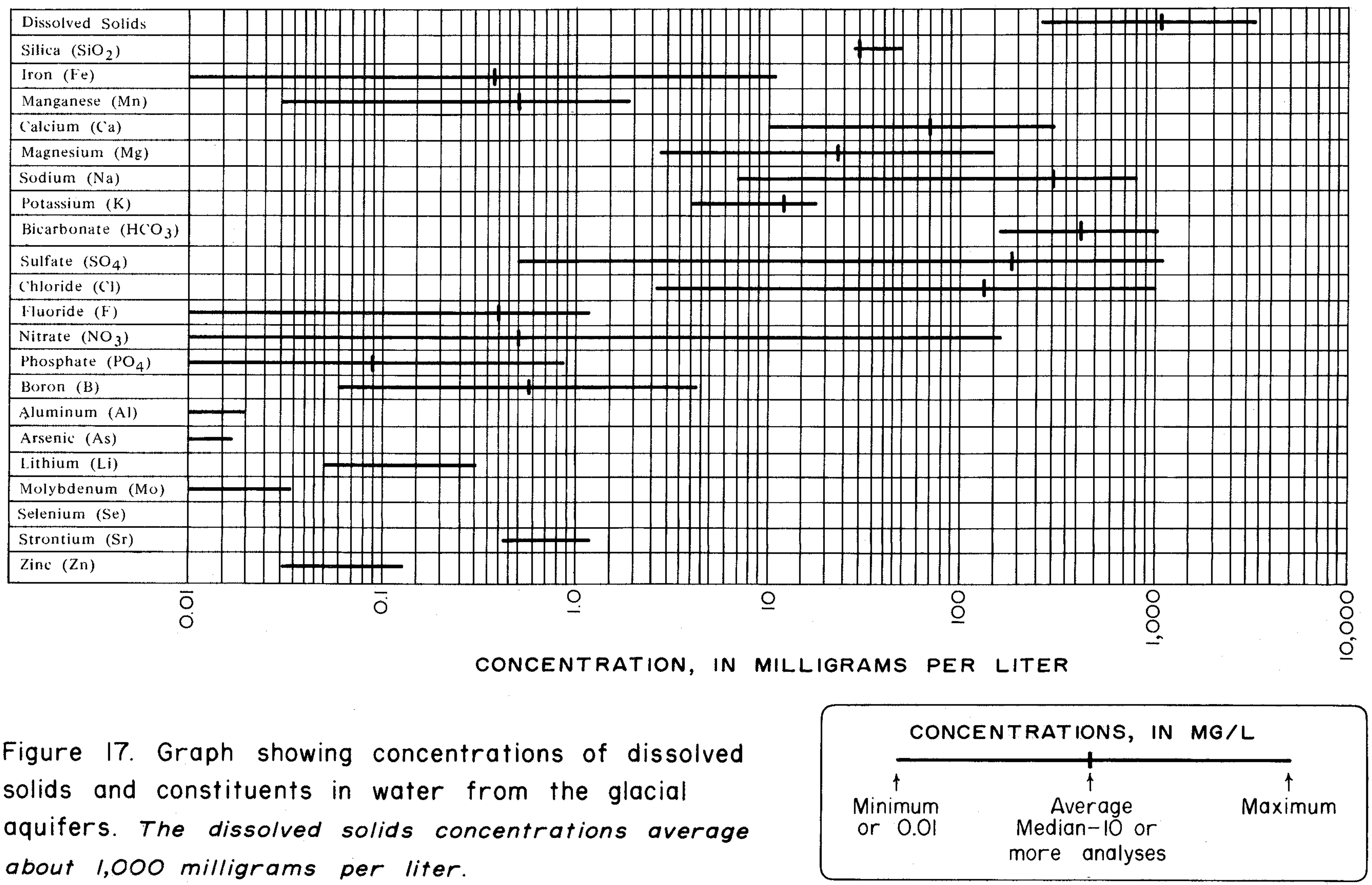


Figure 17. Graph showing concentrations of dissolved solids and constituents in water from the glacial aquifers. *The dissolved solids concentrations average about 1,000 milligrams per liter.*

The relatively high average concentrations for sodium and bicarbonate indicate that much of the water is unsuitable for irrigation.

Concentrations of nitrate range from 0 to 164 milligrams per liter but average only 0.5 milligrams per liter. Only 1 of 40 samples exceed the limit of 45 milligrams per liter as nitrate (NO3) (U.S. Public Health Service, 1962). Although a concentration near or above this limit indicates pollution of the water, probably only the immediate vicinity of the well has become polluted rather than extensive parts of the aquifer.

Concentrations of iron and manganese generally exceed standards set for public water supplies (U.S. Public Health Service, 1962). Manganese concentrations above 0.05 milligrams per liter, and iron concentrations above 0.3 milligrams per liter can cause staining problems for domestic users and encrustations in pipes and on well equipment.

Most other ions are found in concentrations of less than 2 milligrams per liter. Tests for 15 trace constituents were made of four samples. Cadmium, chromium, cobalt, copper, lead, mercury, nickel, selenium, silver, and vanadium either were not detected in the samples or occurred in concentrations of less than 0.01 milligrams per liter. Concentrations of aluminum, arsenic, lithium, strontium, and zinc exceeded this amount because they are present in many types of soil and rock. None of the concentrations of trace constituents was sufficiently high to exceed drinking water standards (U.S. Public Health Service, 1962).

HARDNESS

Most water from glacial aquifers is classified as very hard, that is, hardness exceeds 180 milligrams per liter (fig. 18). The figure shows large variations in hardness, both areally and with depth. Water from several wells in north-central Edmunds County has a hardness of less than 180 milligrams per liter, probably as a result of base-exchange softening of the water by clay minerals in shale-rich gravel. In central McPherson County the hardness of most water exceeds 500 milligrams per liter, resulting from several processes. Poor surface drainage causes runoff to collect in depressions and ponds, where it is evaporated and increased in hardness before it infiltrates to the water table. Slow movement of the ground water through poorly permeable till allows time for further increases in hardness by evapotranspiration before the water can move below the root zone and also allows time for solution of minerals in the till. The till contains large proportions of gypsum and carbonate minerals which increase the hardness when dissolved in water.

The extreme hardness of water in other parts of the study area is caused by one or more of these same processes. Hard water is

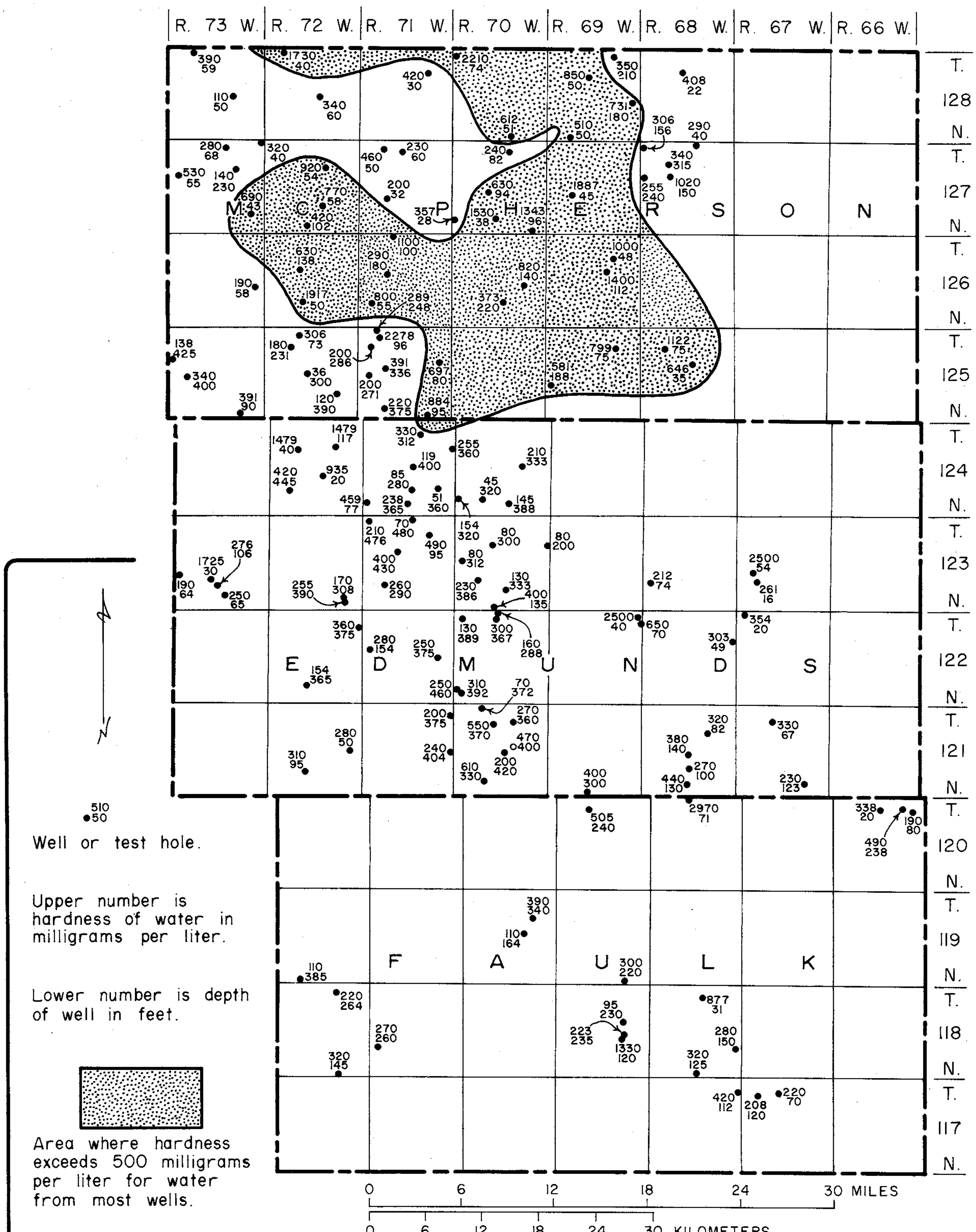


Figure 18. Map showing hardness of water from the glacial aquifers. *The hardness exceeds 180 milligrams per liter for most water and 500 milligrams per liter for some water.*

unsuitable for many domestic, commercial, and industrial uses without treatment because it forms hard scales on boilers, pipes, and water heaters and reduces the cleaning action of soaps and detergents.

TEMPERATURE

The temperature of water in the glacial aquifers averages about 10 degrees C and ranges from 9 degrees C to 11 degrees C (see Definition of Terms). Temperature increases with depth at a rate of about 0.5 degree C per 100 feet.

Bedrock Aquifers

Bedrock aquifers underying the study area include, in descending order, the Dakota Formation, Fall River Formation, Sundance and Minnelusa Formations, and the Madison Group and Red River Formation (fig. 19). Most wells in bedrock tap the first two formations. The amount of water stored in bedrock aquifers is estimated at approximately 200 million acre-feet. Much of the water in bedrock aquifers probably has come from recharge areas in the Black Hills of western South Dakota (discussed by Hopkins and Petri, 1963, Swenson, 1968, and Schoon, 1971).

Dakota Formation

Most artesian wells have been completed in the Dakota Formation, which is 50 to 310 feet thick. The aquifer is composed mainly of many beds of fine-grained, poorly consolidated sandstone that can have a total thickness of as much as 240 feet. The top of the aquifer is 300 to 400 feet below the Greenhorn Limestone, a marker bed for drillers which has been reported to yield small amounts of water for domestic and stock needs. The top of the Dakota ranges in altitude from 455 feet in eastern and southern Faulk County to 100 feet in the northwestern corner of McPherson County (fig. 20). The depth to the aquifer increases from 895 feet in eastern Faulk County to 1,675 feet in northern McPherson County because the land surface rises more than 600 feet and the aquifer dips to the northwest 3 to 5 feet per mile.

Artesian wells in the Dakota Formation can have flows of a few gallons per minute and pressures of up to 10 pounds per square inch in the eastern part of the area. Wells do not flow on the high ground in the Coteau du Missouri.

DISCHARGE AND WATER-LEVEL DECLINES

About 700,000 acre-feet of water has been discharged by wells in the Dakota Formation in the study area since 1885. Artesian pressure decreased as the number of wells and total discharge

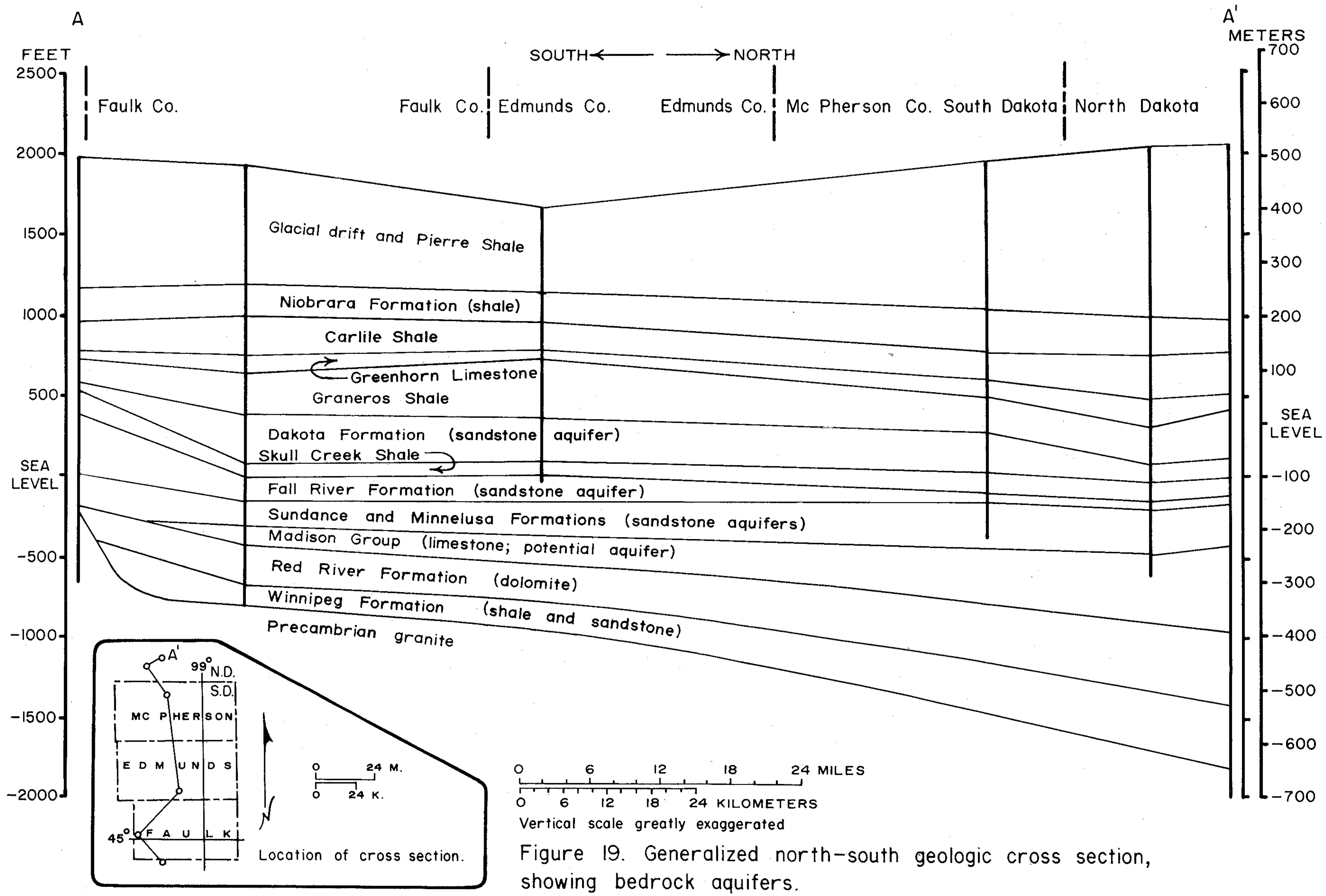


Figure 19. Generalized north-south geologic cross section, showing bedrock aquifers.

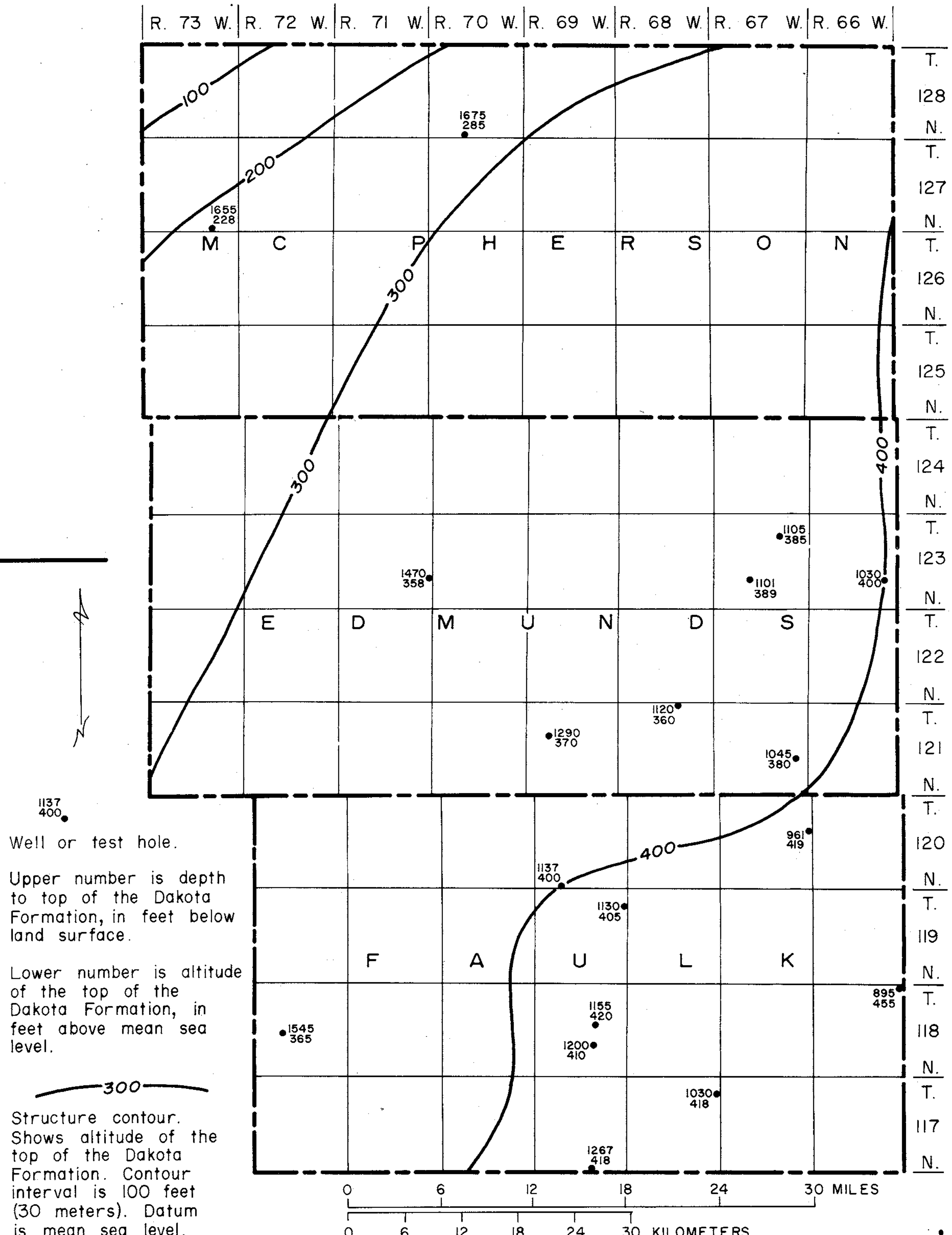


Figure 20. Map showing structure contours on the top of the Dakota Formation, which decreases in altitude northwestward.

increased, and as a result well yields declined. By 1912 discharge was estimated to be 9,000 gallons per minute through 460 flowing wells (South Dakota Planning Board, 1937).

Between 1912 and 1926 the number of wells doubled but their total discharge decreased to about 8,000 gallons per minute. By the 1960's many of the wells had stopped flowing and had been destroyed and replaced by deeper wells. Discharge from the approximately 600 wells in use in 1970 had decreased to about 2,000 gallons per minute or 2.9 million gallons per day.

The decline in water level of wells at Ipswich (123N68W27) during 1885-1915 was more than 250 feet (fig. 21). Initially the rate was 6 feet or more per year; however, this rapid drop in pressure was slowed as yields of wells declined. Many wells failed by silting in or by collapse of iron casings which were rapidly corroded by the salty water. Other factors that may have reduced the rate of decline include: compaction of the aquifer and completion of wells in deeper beds in which the water is under higher pressure. In these deeper wells, perforation of hundreds of feet of casing into the Dakota has tended to equalize pressure vertically, thereby slowing the pressure decline in the upper sandstone beds. As a result, the water level for the Dakota Formation at Ipswich was approximately the same in 1970 as in 1913 (fig. 21).

Water levels in the Dakota Formation may continue to decline as pumpage increases and as pressure is reduced in deeper aquifers by additional flowing wells. However, water levels in six observation wells showed different trends during 1960-73 (fig. 22). After being cleaned out and recased, wells 1 and 4 showed an appreciable recovery in water level and well 3 showed a slight recovery. Water levels appear to have stabilized, probably because the reduced flow of old, deteriorating wells has compensated for increased pumpage from new wells. The nearly steady water-level decline in wells 5 and 6 may be due to increased pumpage but also may be due to gradual deterioration of the well, either from silting-in or from corrosion of the casing.

MOVEMENT

The Dakota Formation is recharged from underlying strata and by water moving in from west of the study area. A large amount of water moves eastward through the Dakota Formation toward the James River lowland, an area of heavy withdrawals east of the study area. The direction of movement is generally down the gradient indicated by the potentiometric contours shown in figure 23. The potentiometric surface slopes eastward at about 10 feet per mile. Total discharge across the 75-mile length of the 1,600-foot contour in the study area is estimated to be 11 million gallons per day. This amount of water is slightly more than the estimated minimum discharge of wells tapping the Dakota For-

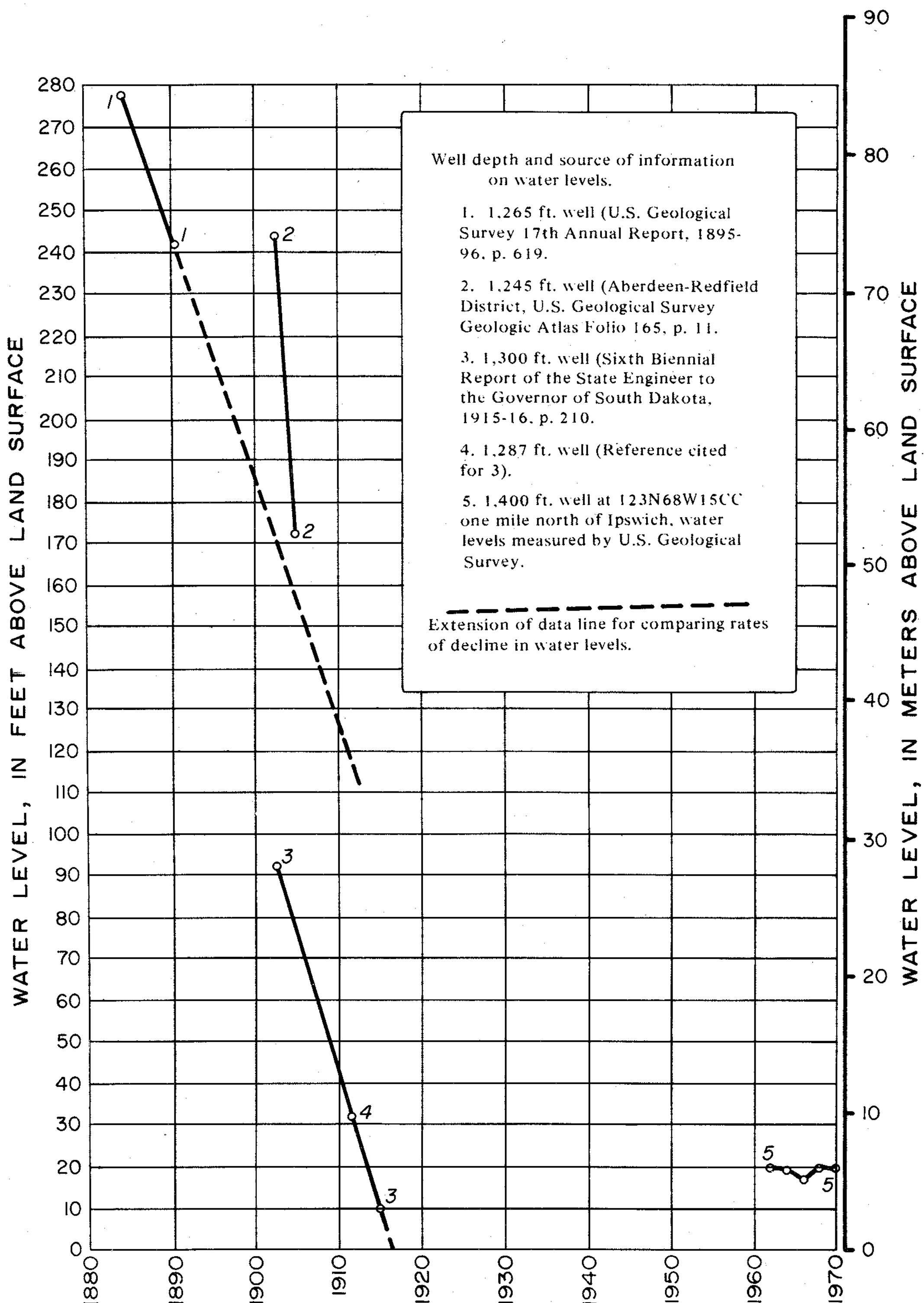


Figure 21. Graph showing water levels in the Dakota Formation at Ipswich. *The levels have declined more than 250 feet since 1885.*

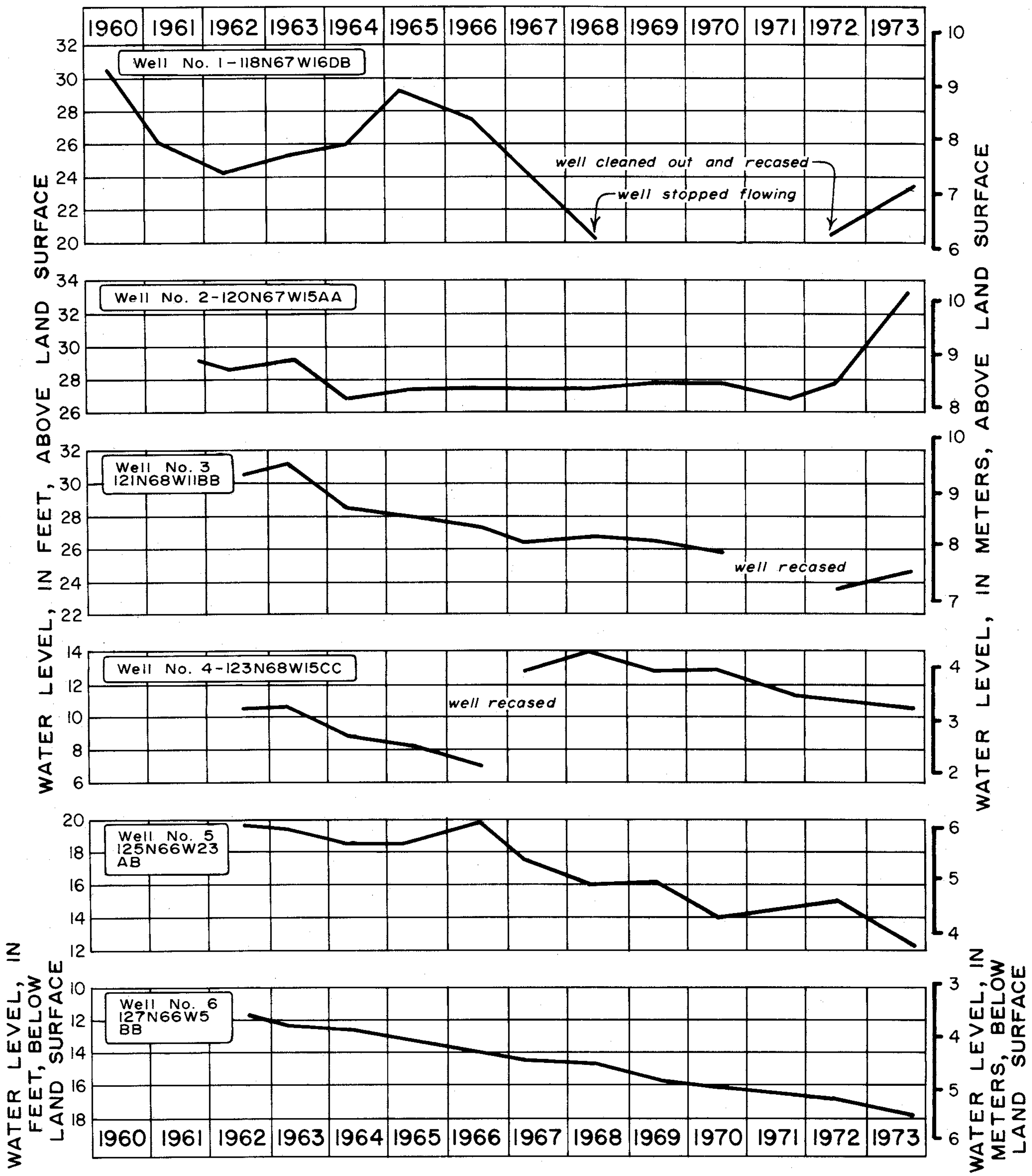


Figure 22. Graphs showing water levels in the Dakota Formation. *The levels showed different trends during 1960–73.*

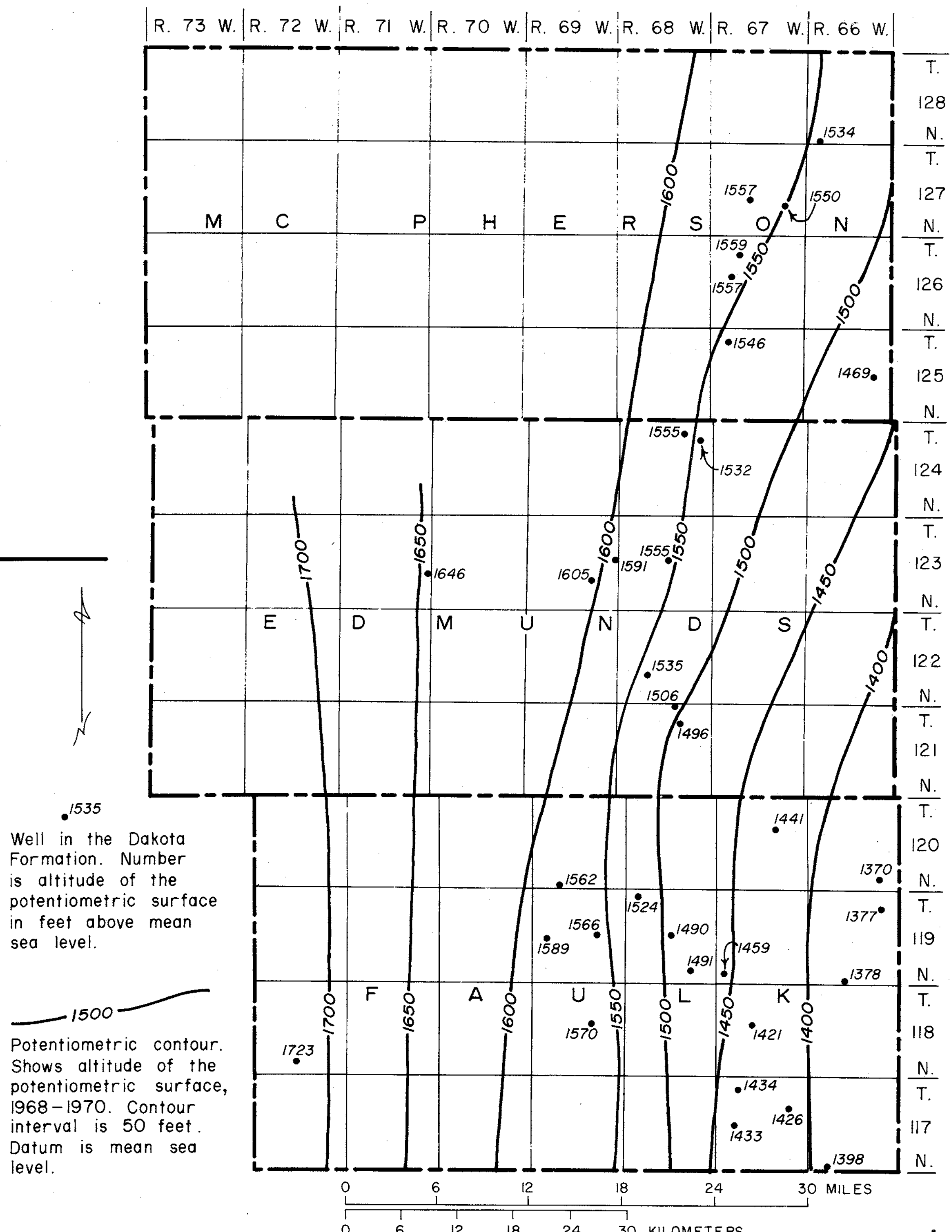


Figure 23. Map showing the potentiometric surface of the Dakota Formation. *The surface slopes eastward at about 10 ft./mi.*

mation in the James River lowland east of the study area from T. 116 N. through T. 126 N. (Hopkins and Petri, 1963, p. 29).

Fall River Formation

The Fall River Formation, which is composed of sandstone and shale, ranges in thickness in the southern part of the study area from 140 to 360 feet, but thins to 40 feet at the north end of the study area. The top of the aquifer is 650 to 800 feet below the Greenhorn Limestone marker bed and 350 to 400 feet below the top of the Dakota Formation. Wells in the Fall River Formation generally have flows of from 5 to 40 gallons per minute and pressure can exceed 90 pounds per square inch. Flow in excess of 1,000 gallons per minute has been reported at Ipswich.

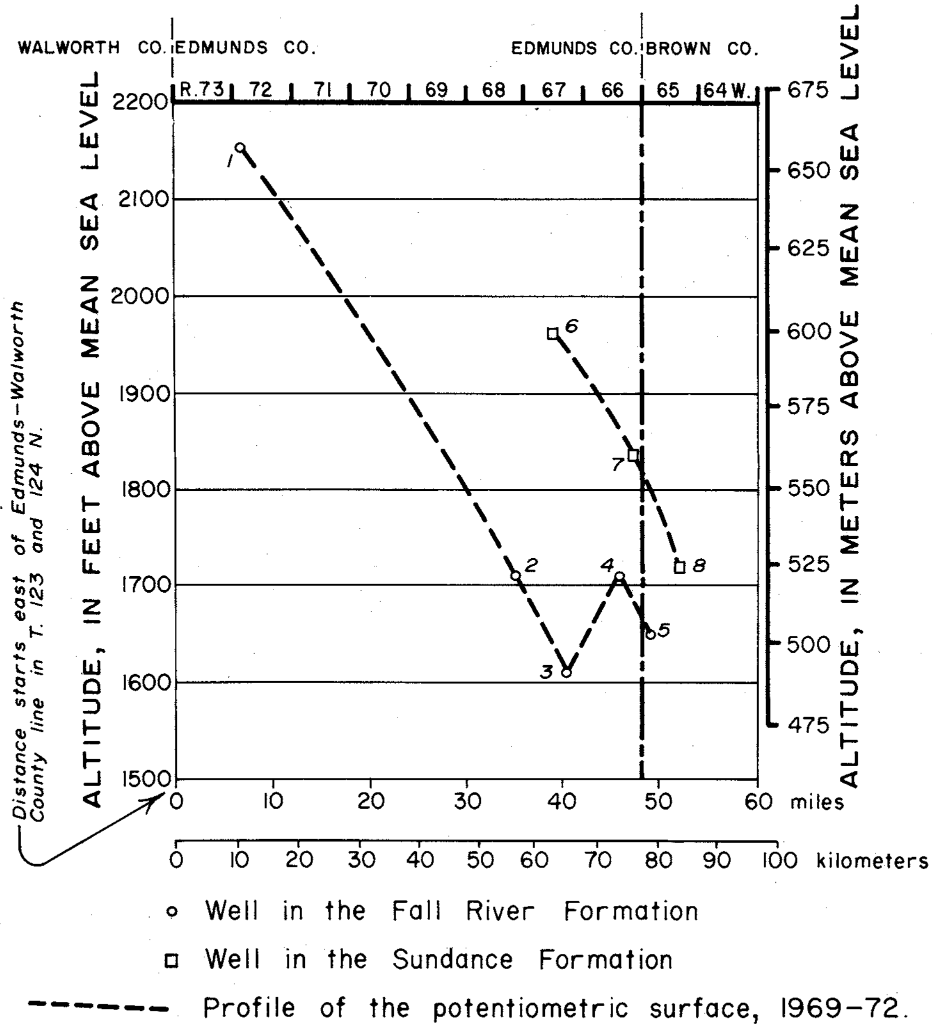
Recharge to the Fall River Formation is by inflow from the west and by upward leakage from underlying formations. Movement is toward the east and upward into the Dakota Formation. The potentiometric surface generally slopes eastward at about 16 feet per mile (fig. 24). The amount of water moving eastward across the entire length of the study area is estimated to total about 5.8 million gallons per day--about one-half that of the estimated flow through the thicker Dakota Formation. The abrupt rise in the potentiometric surface in eastern Edmunds County suggests hydraulic connection there with the underlying Sundance Formation, which contains water under high pressure.

Although observation wells were not available in the study area, 36 miles to the south the head in two wells which tap the Fall River and underlying aquifers has declined from 2 to 9 feet per year during the last 6 to 14 years (Neil Koch, oral communication, 1977).

Water levels in the Fall River Formation in the study area probably are declining because of increased discharge. Discharge through 80 wells in the formation totaled 1,800 gallons per minute or 2.6 million gallons per day in 1969-72 at the surface. Additional discharge into the overlying Dakota Formation probably occurs through corroded well casings. If there is no great increase in future withdrawals, the decline should be slower than it was for the Dakota Formation because the flow from most wells is limited by valves that reduce flow to generally less than 10 gallons per minute. Also, many wells now have casings that are resistant to corrosion and prevent leakage into the Dakota Formation.

Sundance and Minnelusa Formations

These formations, composed of sandstone, shale, and some limestone, have a combined thickness that ranges from about 140 feet in the south to about 270 feet in the north part of the study area. The top of the Sundance Formation is 400 to 500 feet below



WELL NUMBER	WELL DEPTH (IN FEET)	LOCATION
1.	2,005	124N72W29BBCD
2.	1,500	124N68W26ABA
3.	1,538	123N67W11BCCC
4.	1,420	124N66W27ABB
5.	1,329	123N65W32BBDB
6.	1,523	124N67W3BCBC
7.	1,396	123N66W25BBCA
8.	1,343	123N65W22AAD

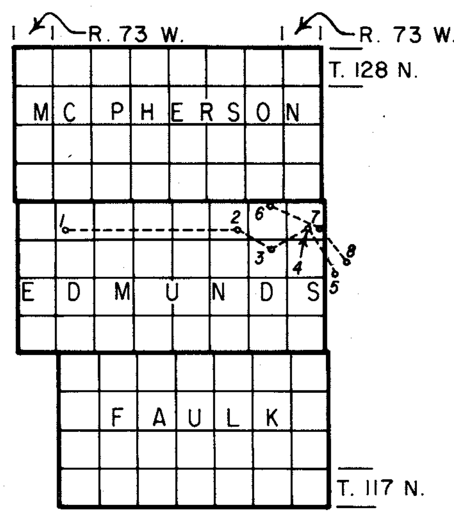


Figure 24. Graph showing profiles of the potentiometric surfaces of the Fall River and Sundance Formations. The profiles generally slope eastward about 16 ft./mi.

the top of the Dakota Formation. Although information is meager, wells in the Sundance and Minnelusa Formations are reported to flow more than 100 gallons per minute. In eastern Edmunds County, flows from wells tapping caverns or open fractures in these formations were reported by the well owners to exceed 1,000 gallons per minute before the wells were plugged to avoid flooding farmland and roads. Pressures of about 200 pounds per square inch have been measured for wells in the Sundance Formation; similar pressures can be expected for wells that penetrate the Minnelusa Formation.

The trace of the potentiometric surface of the Sundance Formation (fig. 24) slopes eastward at about 16 feet per mile. Both formations are recharged from underlying strata and from west of the study area. Eastward flow is probably larger than that for the Fall River Formation, which amounts to nearly 6 million gallons per day. Discharge is by outflow to the east, leakage to overlying formations, and through wells. In the study area, 13 wells in these formations discharge a total of about 400 gallons per minute or 0.6 million gallons per day in 1969-72 at the surface.

Madison Group and Red River Formation

The top of the Madison Group (table 2) is about 700 feet below the top of the Dakota Formation. The Madison Group and Red River Formation, mostly limestone, are about 370 feet thick in western Faulk County. They thin rapidly eastward and may be absent under the eastern part of the area. Limestone of the Madison Group may yield large flows to wells where the limestone is fractured or cavernous. Although data are lacking, artesian pressure may be higher than in overlying formations if the limestone is the main conduit by which overlying artesian aquifers are recharged, as suggested by recent workers (Swenson, 1968, Schoon, 1971).

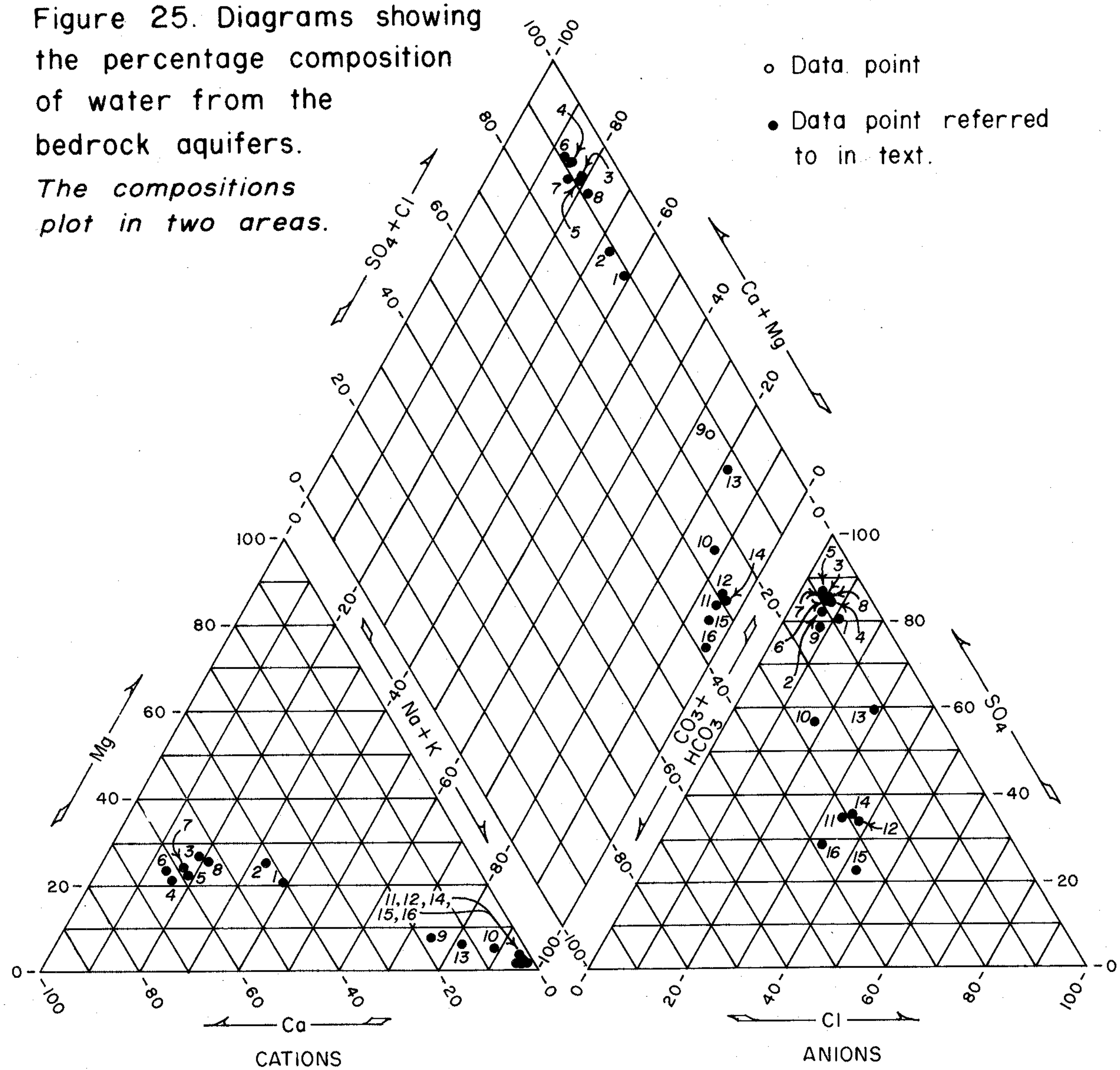
Water Quality of Bedrock Aquifers

Water in the bedrock aquifers contains higher concentrations of dissolved minerals than does water from the glacial aquifers. The minerals in the water were dissolved from rock as the water flowed underground from recharge areas in the Black Hills. Water from the Dakota Formation is soft to very hard, that in deeper aquifers is very hard.

CHEMICAL COMPOSITION

Water from bedrock aquifers is of two different chemical types, and plots in two separate areas of the percentage composition diagrams (fig. 25). The numbers along the margins of the diagrams are percentages, increasing from zero to 100 in the direction of the arrows, for calcium (Ca), magnesium (Mg), sodium

Figure 25. Diagrams showing the percentage composition of water from the bedrock aquifers. *The compositions plot in two areas.*



SAMPLE NUMBER	LOCATION OF SAMPLE	WELL DEPTH OR INTERVAL PERFORATED IN FEET
Red River Formation		
1.	116N73W24AD	2,275-2,593
2.	118N72W20AA	2,500-2,575
3.	118N72W20AA	2,334-2,418
Fall River Formation		
4.	117N70W15AA	1,850
5.	118N69W15DA	1,600
6.	118N71W3BC	1,917
7.	122N70W32DD	1,830
8.	127N73W35DC	2,085
Fall River and Dakota Formations		
9	124N72W29BB	1,923-2,005
Dakota Formation		
10.	118N70W9CC	1,400
11.	118N69W15AD	1,281
12.	118N67W16DB	1,020
13.	119N66W11AB	1,080
14.	123N68W15CC	1,400
15.	126N67W17CD	1,280
16.	123N71W24DD	1,576

(Na), potassium (K), carbonate (CO3), bicarbonate (HCO3), sulfate (SO4), and chloride (Cl).

Water samples 1 through 3, from the Red River Formation, and those numbered 4 through 8, from the Fall River Formation, contain large percentages of calcium and sulfate ions. Therefore, they plot as a group in the upper corner of the total-composition diagram, toward the lower left end of the cations triangle, and in the upper corner of the anions triangle. Similarities in composition suggest that the Red River and Fall River Formations are hydraulically connected through the intervening limestone of the Madison Group (table 2).

Samples 10 through 16, from the Dakota Formation, have higher percentages of sodium ions than samples 1 through 8, probably as a result of base exchange. This exchange consists of a release of sodium ions from clay minerals as the minerals adsorb calcium and magnesium ions from solution. The exchange probably occurs as water from the Fall River Formation seeps upward through clay in the Skull Creek Shale. Sample 9, a mixture of water from the Fall River and Dakota Formations, plots in a position on the graphs that is between the two groups of plotted points for the other types of water. Samples 10 through 13 follow a west-to-east sequence, in the direction of movement of water in the Dakota Formation. The shift in the position of points for samples 10 through 12 indicates that the water becomes higher in percentages of sodium, bicarbonate, and chloride ions as it moves through the Dakota. The reverse shift for point 13 indicates that the sample is from an area where there is more leakage into the Dakota of hard, calcium sulfate type water from underlying formations.

Concentrations average about 2,000 milligrams per liter for dissolved solids and exceed 100 milligrams per liter for many major constituents in water from bedrock aquifers (fig. 26).

Because of the high average dissolved-solids concentrations, much of the water is unsuitable for irrigation and also exceeds standards set for public water supplies (U.S. Public Health Service, 1962). Such water, however, is used for public supplies in many areas where no other water is available. High concentrations of sodium (averaging 720 milligrams per liter), bicarbonate (averaging 600 milligrams per liter), and boron (averaging 5.7 milligrams per liter) indicate that water from the Dakota Formation is unsuitable for irrigation.

Concentrations of iron and manganese concentrations in water from the Fall River and Sundance Formations exceed, on the average, standards set for public water supplies and cause problems of staining and encrustation.

Calcium and magnesium concentrations in water from the Fall River and Sundance Formations are high enough to cause hardness

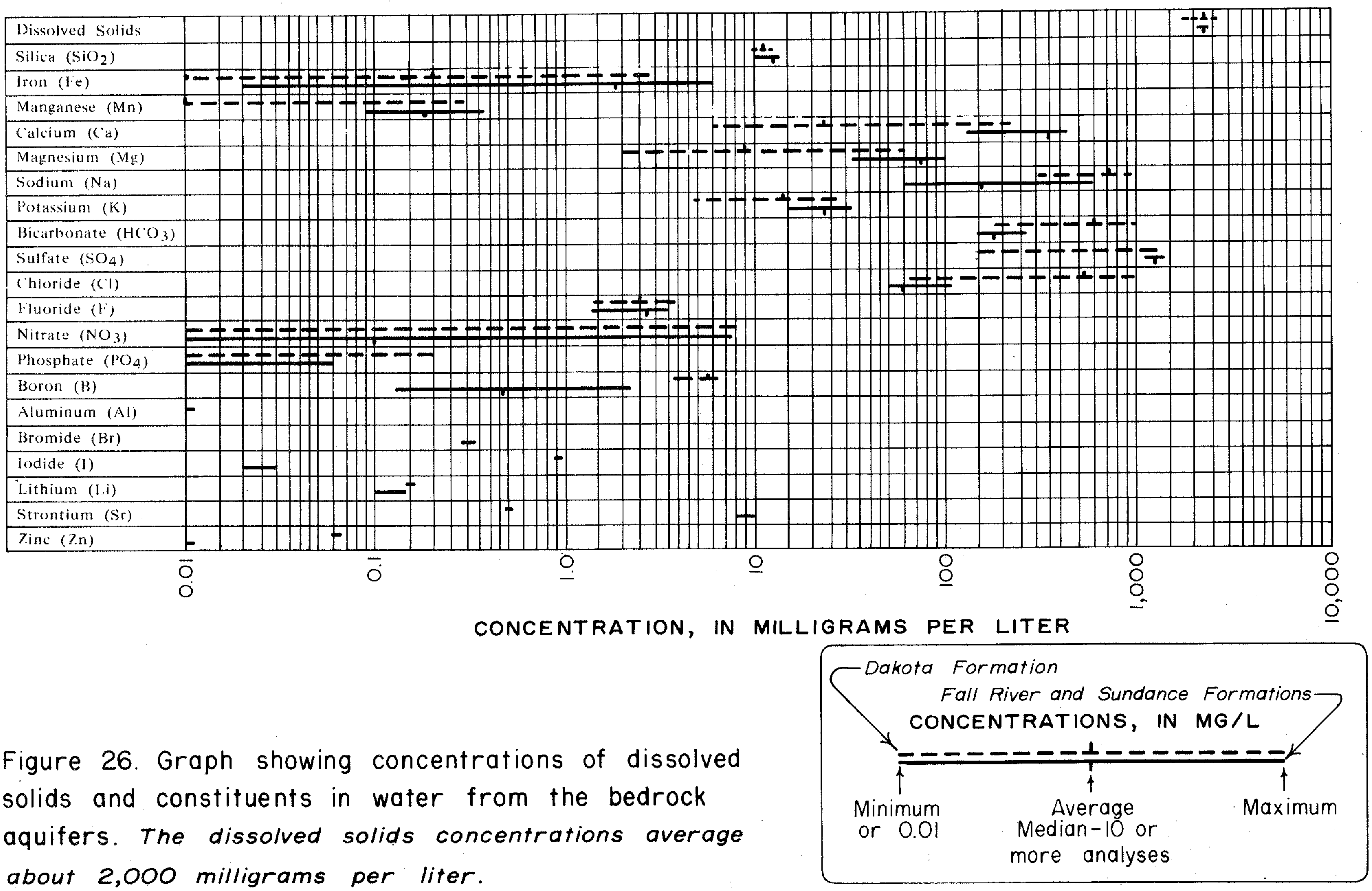


Figure 26. Graph showing concentrations of dissolved solids and constituents in water from the bedrock aquifers. *The dissolved solids concentrations average about 2,000 milligrams per liter.*

problems; the water requires softening to be suitable for many domestic, commercial, and industrial uses.

Sulfate and calcium concentrations in water from the Fall River Formation and underlying aquifers are high enough to produce encrustation problems. Sulfate, in combination with sodium or magnesium, also may cause a bitter taste and laxative effect in drinking water.

Chloride concentrations in water from the Dakota Formation are high enough, in combination with sodium, to give water a salty taste and make it corrosive.

Fluoride concentrations in water from bedrock aquifers are higher than the optimum limit (U.S. Public Health Service, 1962) and may cause mottling of children's teeth.

Most minor and trace constituents are present in concentrations of less than 3 milligrams per liter. Tests for 18 trace constituents were made of three samples. Constituents such as arsenic, cadmium, chromium, cobalt, copper, lead, mercury, molybdenum, nickel, selenium, silver, and vanadium either were not detected in the samples or occurred in concentrations of less than 0.01 milligrams per liter. Concentrations of aluminum, bromide, iodide, lithium, strontium, and zinc exceeded 0.01 milligrams per liter but none exceeded limits set for drinking water (U.S. Public Health Service, 1962).

HARDNESS

The hardness of water from the Dakota Formation ranges from 24 to 818 milligrams per liter and averages about 100 milligrams per liter. Most water samples are from the eastern part of the report area, where there are many flowing wells in the formation. Figure 27 shows that hardness is more than 100 milligrams per liter in part of the eastern and southern areas. The location of the hardness boundaries (fig. 27) is based in part on qualitative information provided by well owners and drillers regarding water quality. Water which they reported as being soft is inferred to have a hardness of less than 100 milligrams per liter. Data are shown for wells tapping either the upper or lower parts of the Dakota Formation. The average hardness of water from the two types of wells is used to draw boundaries of hardness zones where there is a difference in hardness. At many places, water from a well perforated only in the lower part is harder than that from a well penetrating only the upper part of the formation. This difference in hardness fits in with the theory that locally the formation is recharged by much harder water from deeper aquifers. The eastern area probably has areas of substantial recharge from underlying strata because of a thinning of the Skull Creek Shale beneath the Dakota. Also the differential in head between the underlying formations and the Dakota has increased because artesian pressure has been greatly lowered in the Dakota Formation

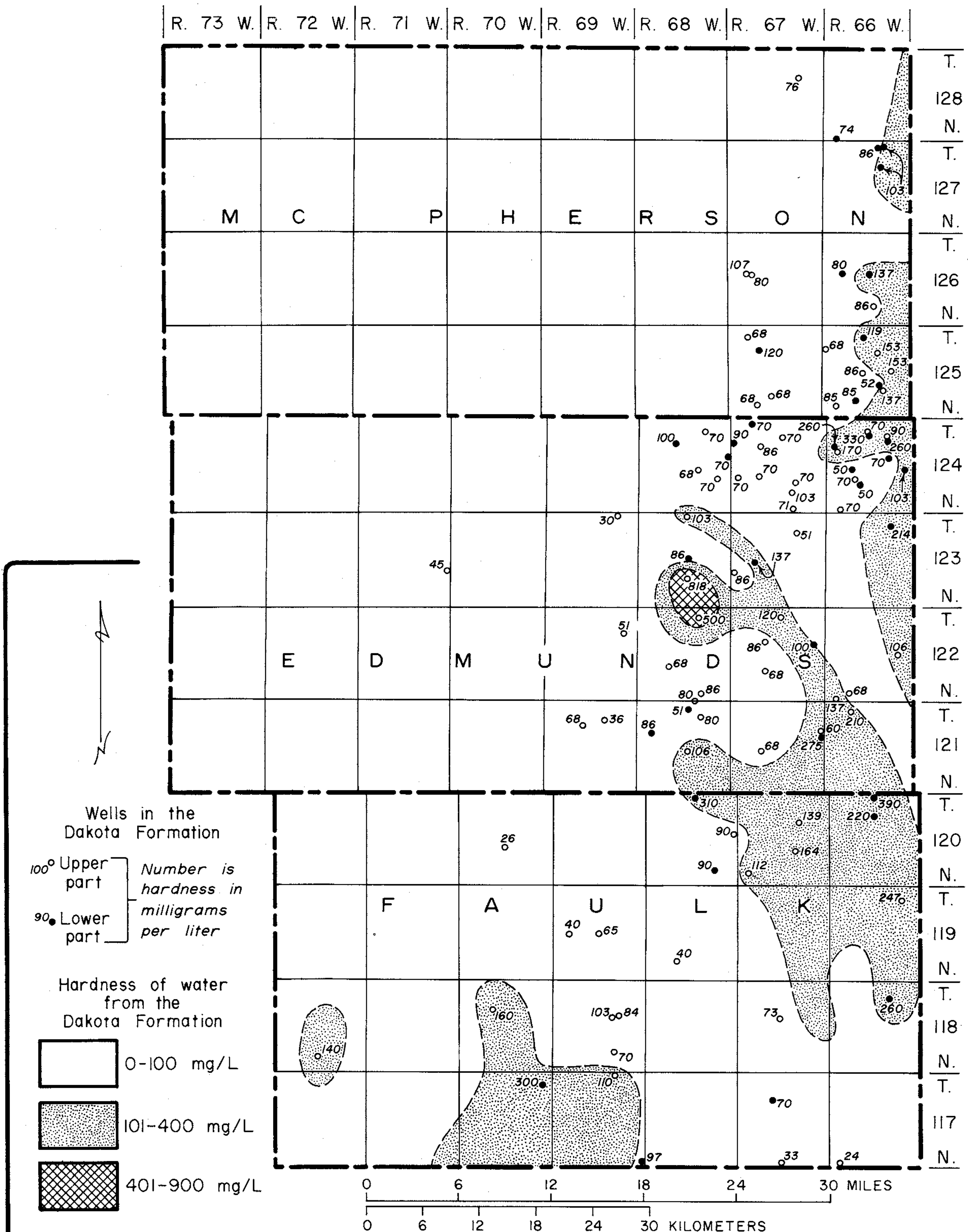


Figure 27. Map showing the approximate distribution of hardness of water from the Dakota Formation. *The hardness exceeds 100 milligrams per liter in part of the eastern and southern areas.*

while the underlying formations still have high pressure. The source of the high pressure and recharge is inferred to be the Madison Group (Swenson, 1968, p. 179), which pinches out along the eastern side of the study area.

The irregular shape of the hardness areas may indicate that recharge from below is unevenly distributed. The northward elongation of the hardness suggests that regional fracture or joint systems control the recharge, permitting upward movement of very hard water along openings that can extend for more than 30 miles in formations underlying the Dakota Formation.

The extremely hard water located in part of T. 122 N., and T. 123 N., R. 68 W. suggest substantial upward flow into the Dakota along numerous fractures, through cavernous openings in limestone, or through the numerous wells that have penetrated the underlying formations but also are open to the Dakota.

In the western half of the area only five water analyses of water from the Dakota are available because of the lack of wells. However, a state-wide study of types of water in the Dakota Formation (Schoon, 1971, fig. 18) indicates that water from the Dakota is mostly of the sodium chloride type in the western part of the study area. Analyses of water samples from the study area show that the sodium chloride type of water generally has a hardness of less than 100 milligrams per liter.

The hardness of water from the Fall River and Sundance Formations ranges from 135 to 1,400 milligrams per liter and averages about 1,000 milligrams per liter. Figure 28 shows that hardness exceeds 400 milligrams per liter in much of the area. In most of the eastern and southern parts of the area hardness exceeds 800 milligrams per liter. This extremely high hardness, in contrast to that of the Dakota Formation, may be due to the formations being closer to, and having better hydraulic connection with, the underlying Madison Group. All water from the Madison Group is very hard and high in concentrations of calcium and sulfate ions (Swenson, 1968, p. 177). Howells (1978) reports that 70 miles west of the study area the hardness of water from the Madison is as much as 1,400 milligrams per liter.

TEMPERATURE

The temperatures of water from wells in the Dakota Formation range from 14 degrees to 23 degrees C and average 19 degrees C; those for wells in the Fall River and Sundance Formations range from 19 degrees to 29 degrees C and average 24 degrees C. Temperatures increase with depth at rates of from 0.5 degree to 1 degree C per 100 feet. The highest temperature reported was 29 degrees C for a 1,503-foot well in the Sundance Formation (124N66W24BAB), a "wild" well with a reported high-pressure flow of more than 1,000 gallons per minute which was uncontrolled for several years. Geologic information from an oil-exploration test

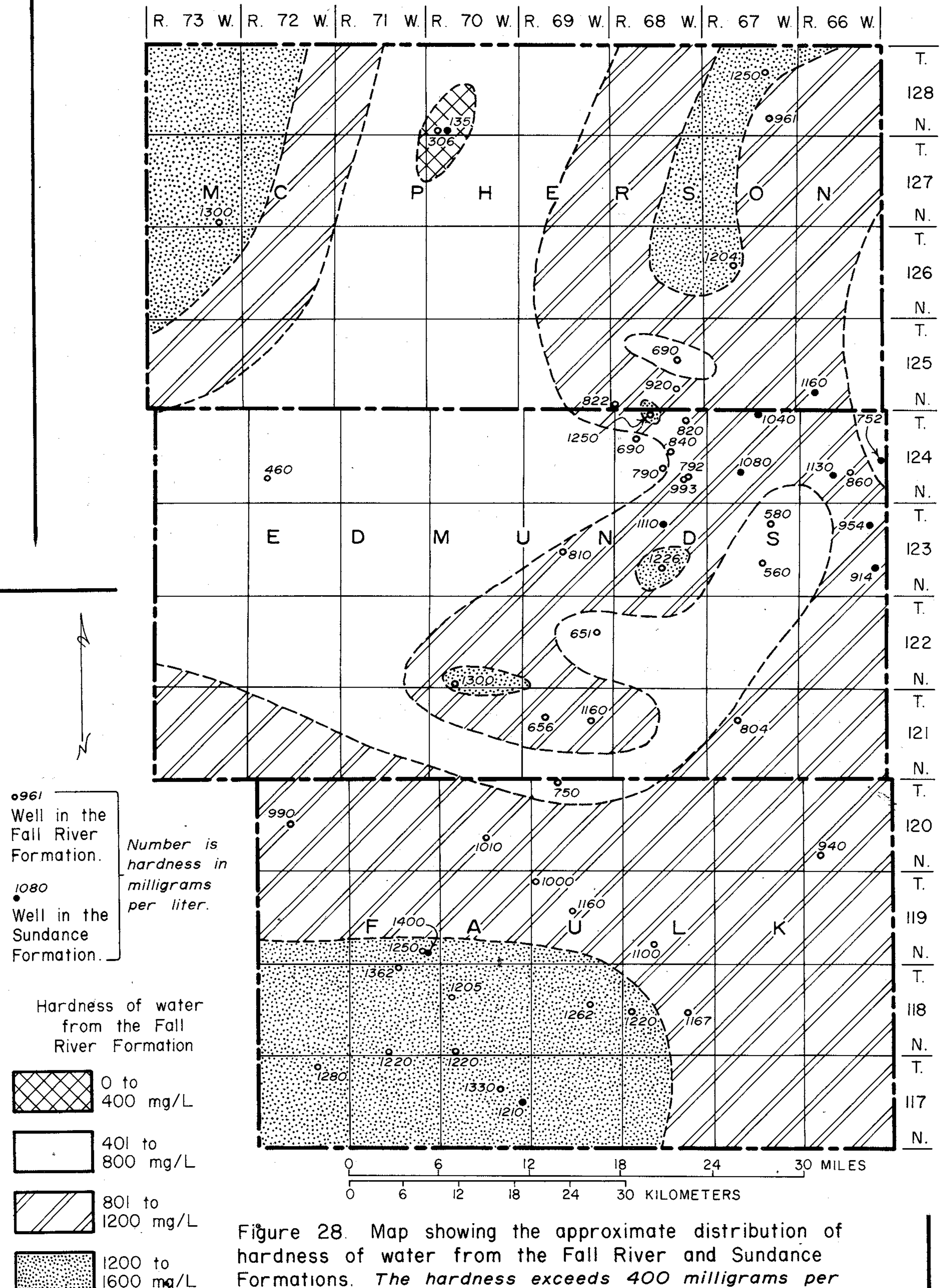


Figure 28. Map showing the approximate distribution of hardness of water from the Fall River and Sundance Formations. *The hardness exceeds 400 milligrams per liter in most of the area.*

hole 5.5 miles northeast of the "wild" well indicates that the flow probably came from formations below the Sundance Formation.

WATER USE

Most of the water used in the study area comes from wells. The discharge of wells, both pumped and flowing, was estimated to average 8.04 million gallons per day during 1970 (table 4). Three-fourths of the discharge was from bedrock aquifers and the remainder was from glacial aquifers. The average discharge in 1969-72 of 782 wells in bedrock aquifers was 5.3 gallons per minute; that of 1,181 wells in glacial aquifers was 1.2 gallons per minute.

Water use averaged 4.09 million gallons per day during 1970 (table 5). Nearly three-fourths of the use was ground water. Use of surface water from streams, lakes, and ponds was estimated to average 1.09 million gallons per day. Adding this to the discharge from wells, withdrawals totaled 9.13 million gallons per day. Less than half of this amount was put to use. Although much of the water discharged by flowing wells was wasted, some was used to supply lakes and ponds used for recreation or wildlife habitat.

Use of ground water and surface water by livestock totaled 3.41 million gallons per day or about 80 percent of the 1970 water use (table 5). Most of the remaining use was equally divided between municipal use and rural domestic use. Irrigation use in 1970 averaged only 0.07 million gallons per day.

The water-use estimates were based on population figures and estimates of average use per capita. Municipal use and rural domestic use was estimated to average 40 gallons per day per person. The estimate for municipal use is only about one-fourth of the national average for cities because the small cities in the study area do not have large water-using industries and do not irrigate golf courses and large parks.

WATER-RESOURCE DEVELOPMENT

Development of water resources in the study area has been extensive but not intensive. Surface reservoirs and dugouts are small and widely scattered. Wells also are scattered and annual withdrawals from each well are small. Nevertheless, these developments have caused some changes in hydrologic properties such as runoff, storage, water levels, and water quality. Serious changes in these properties can be expected to occur with intensive local development. Optimum development of water resources requires testing aquifers and estimating their response to more intensive withdrawals of water. Digital modeling of aquifer responses to stress, using computers, is a common preliminary procedure in planning for intensive development of water resources.

TABLE 4. Estimated 1970 discharge of wells, in million gallons per day

	McPherson		Edmunds		Faulk		Total	
Source	Number of wells	Discharge	Number of wells	Discharge	Number of wells	Discharge	Number of wells	Discharge
Glacial aquifers	408	0.72	393	0.66	380	0.74	1,181	2.12
Bedrock aquifers	84	1.28	229	2.16	469	2.48	782	5.92
Total	492	2.00	622	2.82	849	3.22	1,963	8.04

TABLE 5. Estimated 1970 water use, in million gallons per day

	McPherson		Edmunds		Faulk		Total	
Use	Ground water	Surface water	Ground water	Surface water	Ground water	Surface water	Ground water	Surface water
Municipal	0.10	----	0.11	----	0.06	----	0.27	----
Rural: Domestic	0.11	----	0.14	----	0.09	----	0.34	----
Livestock	0.83	0.35	0.85	0.37	0.71	0.30	2.39	1.02
Irrigation	----	----	----	----	----	0.07	----	0.07
Sub-total	1.04	0.35	1.10	0.37	0.86	0.37	3.00	1.09
TOTAL	1.39		1.47		1.23		4.09	

Aquifer Tests Before Development

The effects of pumpage on storage, water levels, and the potential yields of aquifers may be determined by aquifer tests. Generally, several test holes are drilled through an aquifer in a promising area before the construction of test wells and permanent high-capacity wells. Samples are obtained from the test holes to determine the grain-size distribution of the aquifer. Information on grain size is used to select the size of openings for the well screen or slotted casing and to determine if a gravel pack around the screen would improve the well performance. An electric log is run in a test hole to determine the best depth interval at which to set the well screen. A test well should be pumped at a nearly constant rate, preferably of at least 100 gallons per minute for 1 or 2 days in order to determine drawdown of water levels. The data can be analyzed to estimate the long-term effect of pumping on distant wells and to detect aquifer boundaries that may change the rate of drawdown.

Effects of Ground-Water Development

Storage in bedrock aquifers in the study area has decreased by roughly 50,000 acre-feet since wells were first drilled into the Dakota Formation in the 1880's. The rate of decrease has been slowed by the decreasing flow of artesian wells. Storage in glacial aquifers has not decreased significantly because pumpage is low and recharge is many times greater than pumpage over a period of several years.

Water levels in the Dakota Formation have declined about 250 feet because the unrestricted flow of wells has reduced artesian pressure by more than 100 pounds per square inch. Similar declines in water levels can be expected for deeper bedrock aquifers unless flows from high-pressure wells are restricted. Water levels in glacial aquifers have not declined significantly. The slight decline in water levels in observation wells during 1972-74 (fig. 13) is a natural temporary trend which follows wet years when recharge is greater than normal so that water levels are abnormally high.

Excessive water-level declines in and near high-capacity wells can be avoided by locating and spacing the wells in accordance with information obtained from aquifer tests.

The quality of water in aquifers generally changes only slightly in response to natural changes in recharge and water movement. However, the water from some wells is reported to have changed greatly, becoming salty, very hard, or muddy. Such changes may be due to corrosion and failure of well casings opposite shale or till, rocks units which frequently contain corrosive water of poor quality. The quality of water from a well also can change if the well is perforated in several aquifers. The perforations allow water from high-pressure aquifers to move through the well into low-pressure aquifers. Water in high-pressure aquifers is extremely hard in the study area and can contaminate the softer water in low-pressure aquifers. Contamination of wells and aquifers can be reduced by installing well casing which is resistant to corrosion and by perforating or screening the wells so that aquifers are not connected through the wells to sources of contamination.

Irrigation can change the quality of ground water if irrigation water reaches the water table. In most places where irrigation is practiced, the concentration of dissolved solids in ground water has increased (Hopkins and Petri, 1963, p. 55). However, the dissolved solids will increase only if the concentration in the infiltrating irrigation water is greater than that in the water in the aquifer. Concentrations are increased in the infiltrating water by evapotranspiration and by solution of minerals. The slower the rate of infiltration the greater the effect of these processes will be. Hence, irrigation of slow-draining soils eventually leads to increased mineralization of underlying ground water.

Effects of Surface-Water Development

The principal effect of development on the area's surface water resources has been the loss of about 2,000 acre-feet of water annually by increased evapotranspiration. This has come about by the construction of numerous dugouts and small reservoirs for watering livestock. The construction has increased the area of surface water by about 1,500 acres. Part of the evapotranspiration loss on this acreage has been made up by salvage of runoff which previously left the study area.

SUMMARY

Both surface water and ground water are available in large quantities in McPherson, Edmunds, and Faulk Counties, but streams require storage reservoirs in order to be adequate for many uses (table 1). The South Fork of Snake Creek has the largest supply of surface water with an average discharge of about 8,000 acre-feet per year. However, streamflow is intermittent and many water users would need reservoirs or alternative supplies. Lakes and ponds are shallow and supplies are inadequate for current municipal and industrial demands during drought years. The quality of the water is unsuitable for some uses without treatment.

Individual wells can obtain yields of 500 gallons per minute or more from bedrock aquifers. However, high concentrations of dissolved solids, sodium, and bicarbonate make water from bedrock aquifers unsuitable for irrigation. High hardness and high concentrations of dissolved solids, sulfate, iron, and manganese make water from bedrock aquifers unsuitable for some domestic and industrial uses as well.

Wells in glacial aquifers can yield more than 100 gallons per minute but yields are inadequate for irrigation in many areas. However, aquifer tests may indicate that multiple wells can be developed where the yield of a single wells is inadequate. Well yields of more than 500 gallons per minute can be obtained from the Grand aquifer but the water generally is unsuitable for irrigation because of high concentrations of dissolved solids, sodium, and bicarbonate ions. Excessive hardness and high concentrations of iron and manganese make the water unsuitable for some domestic and industrial uses without treatment.

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