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WATER RESOURCES OF THE RED RIVER OF THE NORTH DRAINAGE BASIN IN MINNESOTA

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 1-72

Prepared in cooperation with the
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16. Abstracts Water problems in the Red River of the North basin in Minnesota include flooding, pollution, and water shortages. In the morainal area, problems generally are absent; but in the flat plain of former Glacial Lake Agassiz, they can be severe. About 5.1 million acre-feet of water is perennially available. Average annual flow in streams tributary to the Red River equals 1.7 inches over the basin. Runoff ranges from less than 1 to more than 4 inches. Glacial sand and gravel in the morainal and in the Halma-Lake Bronson areas are potentially large aquifers. Presently, other sand and gravel aquifers, generally local, provide most supplies. Much saline water occurs at depth in sedimentary rocks in the northwest part of the basin. Regionally, ground water moves westward from morainal area to lake plain or Red River. Locally, ground water in the morainal area moves from high areas to adjacent lowlands. Much deep moving water discharges at the east edge of the lake plain. Ground water in recharge areas is generally calcium magnesium bicarbonate type. Sodium bicarbonate and sodium chloride type waters occur in association with Cretaceous and sedimentary rocks (in northwest part of basin), respectively.

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PREFACE

Water is an essential for life that is too often taken for granted when plenty is available. As long as it is abundant it is given little thought or concern and, when it is too abundant, can even be a serious liability. As population increases and civilization and technologies advance, demands for water increase at an accelerating rate. Water problems commonly are not anticipated or even recognized until opportunities for best solutions to these problems are past because of some irreversible management decision based on little or no knowledge of the hydrology. The effects of some management practices on the hydrologic system may be gradual and not recognized until considerable time has passed. The implication is clear. Knowledge of the hydrologic system including the distribution and movement of water in the system is essential for sound long-range management of water resources, and can serve as the foundation upon which legal, social, and economic aspects of water development and use can be based.

The development of the water resources of the Red River basin for particular needs often was based on limited data and knowledge of the entire hydrologic system. Data have been collected principally on streamflow and precipitation. However, relatively little data have been collected on other aspects of the hydrologic system including water quality, ground water, and water use. Until 1963 when watershed investigations were started, no comprehensive analysis of all available hydrologic data in the Red River basin had been made to show the operation of the hydrologic system and the interrelationships between the parts of the system. Water information was fragmented, dealing only with one or another aspect of the hydrologic system, and indicated no feedback or side effects resulting from changes in the hydrologic system made by man. Hydrologic studies of the eight major watershed units in the basin of the Red River of the North in Minnesota (hereinafter referred to as the Red River basin) were to provide an analysis of the hydrologic system based upon available, though often incomplete, hydrologic data. Necessarily, the deficiency in data had to be compensated for by experience and reasoning. This report appraises the total water resources and problems associated with management of the resources. It describes the hydrologic system for the manager so that water decisions can be based on the most complete hydrologic information available.

The report consists of three principal sections; environmental setting, water resource management, and the hydrologic system. The environmental setting describes the land and people as related to water resources. The section on water resource management is intended to provide practical information needed for the planning and management of water resources. The section on the hydrologic system is a more technical discussion of water in the Red River basin. The section on water management can be used to locate the water, determine the amount available and its quality; whereas, the section on the hydrologic system describes the operation of the system -- how water moves through the system and why the quality is as it is.

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WATER RESOURCES OF THE RED RIVER OF THE NORTH DRAINAGE BASIN IN MINNESOTA

By R. W. Maclay, T. C. Winter, and L. E. Bidwell

ABSTRACT

The drainage basin of the Red River of the North within Minnesota, contains 17,800 square miles and has a largely rural population (1960) of 240,000. The physiography is flat and featureless except for a hilly region containing many lakes in the southeast part. Major water problems of the basin are poor distribution of water supply, drainage of wetlands, extensive areas subject to flooding, and pollution of surface water.

Mean annual precipitation within the basin ranges from about 19 inches in the northwest to more than 25 inches in the southwest; however, large variation in rainfall occurs, and drought periods lasting several years are common. The average annual gross water yield is about 2 million acre-feet or about 1.7 inches of water over the basin. Most of the streams have low sustained natural flows. To develop surface-water supplies as a source of supply storage is required; however, storage sites are generally lacking.

Ground-water supplies adequate for domestic and stock purposes are available from sand and gravel units in the drift at most places in the basin. The principal aquifers are outwash sand and gravel, which generally will yield 50 gallons a minute or more to individual wells. Potentially, the most productive sand and gravel aquifers are in the northern part of the basin in Kittson County and along the Otter Tail River in the southeastern part of the basin. These are capable of yielding 1,000 gallons per minute to individual wells locally.

Chemical quality of some of the waters of the Red River basin prevents their extensive use. Generally, the chemical quality of surface water is adequate for domestic and agricultural use. Water pollution problems occur locally in the basin, but the most serious are in the Red Lake River and the Red River of the North. The quality of ground water in the northwestern part of the basin is commonly very hard and contains high concentrations of iron which restricts its use for nearly all purposes. Calcium bicarbonate, the most common type of water in the basin, occurs in the morainal area and in

the upper part of the ground-water system in the Glacial Lake Agassiz region.

Floods of the Red River of the North and its tributaries are typically sporadic, for although usually occurring in early to late spring, their dates and magnitude are subject to much variation. To alleviate flooding on tributaries, channel modification, principally straightening, has been done along critical reaches of the Red River. Flood control dams have been constructed on Otter Tail and Red Lake Rivers and one is being constructed on the Wild Rice River. Land areas drained artificially in the Red River basin ranged from less than 10 percent in the eastern part of the morainal area to more than 80 percent in the lake plain.

Annual runoff in the basin is generally highest in spring and early summer, and lowest in late winter. Base flow from ground-water storage is relatively small for most of the streams, particularly for those in the lake plain.

Much recharge to the ground-water system originates in the morainal area and discharges locally to nearby streams, lakes, and wetlands. The part of recharge that enters the deeper part of the ground-water reservoir in the morainal area moves laterally and discharges in a belt that lies near the edge of the lake plain and lake-washed till plain. Based on fluctuations of water level in wells and estimated specific yield, annual ground-water recharge to the ground-water reservoir is about 3 to 5 inches.

INTRODUCTION

The drainage basin of the Red River of the North forms a regional hydrologic system covering 38,700 square miles within the United States, excluding the drainage of the Souris River in North Dakota (fig. 1). This report is concerned with the drainage basin of the Red River of the North in Minnesota. It consists of about 46 percent of the total drainage area of the Red River upstream from Emerson, Manitoba, and contributes about 75 percent of the flow to the Red River of the North. It covers 17,800 square miles, or about one-fifth of the State of Minnesota. The basin includes 8 watershed units, as defined by the Minnesota Department of Conservation, Division of Waters (1959), that range in size from 1,128 square miles for the Roseau River Watershed unit to 5,988 square miles for the Red Lake River unit (fig. 2). Individual hydrologic atlas reports were prepared and published for each of the watershed units to show graphically a general description of the hydrologic system, the general availability of ground and surface water resources, and their chemical quality.

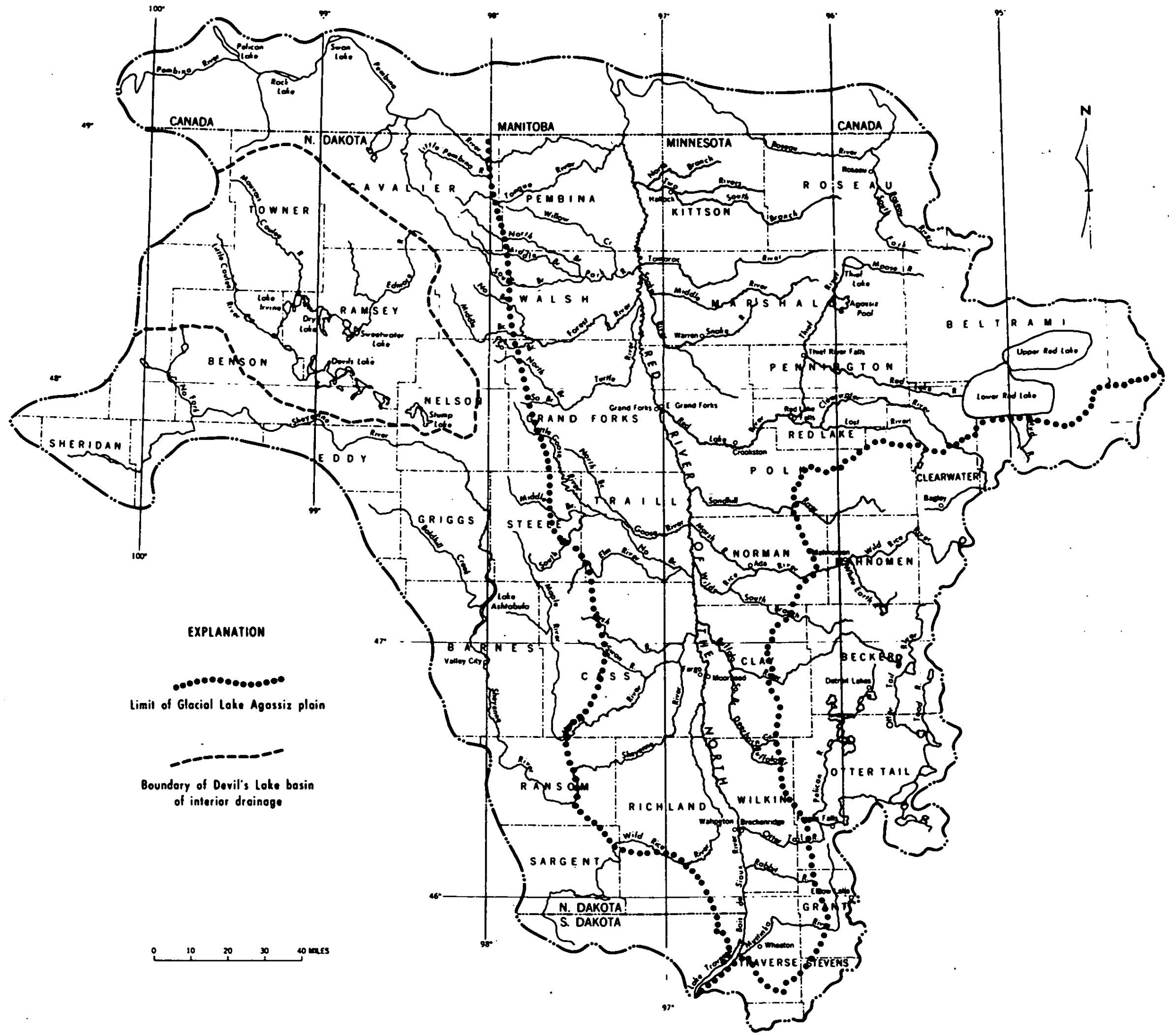
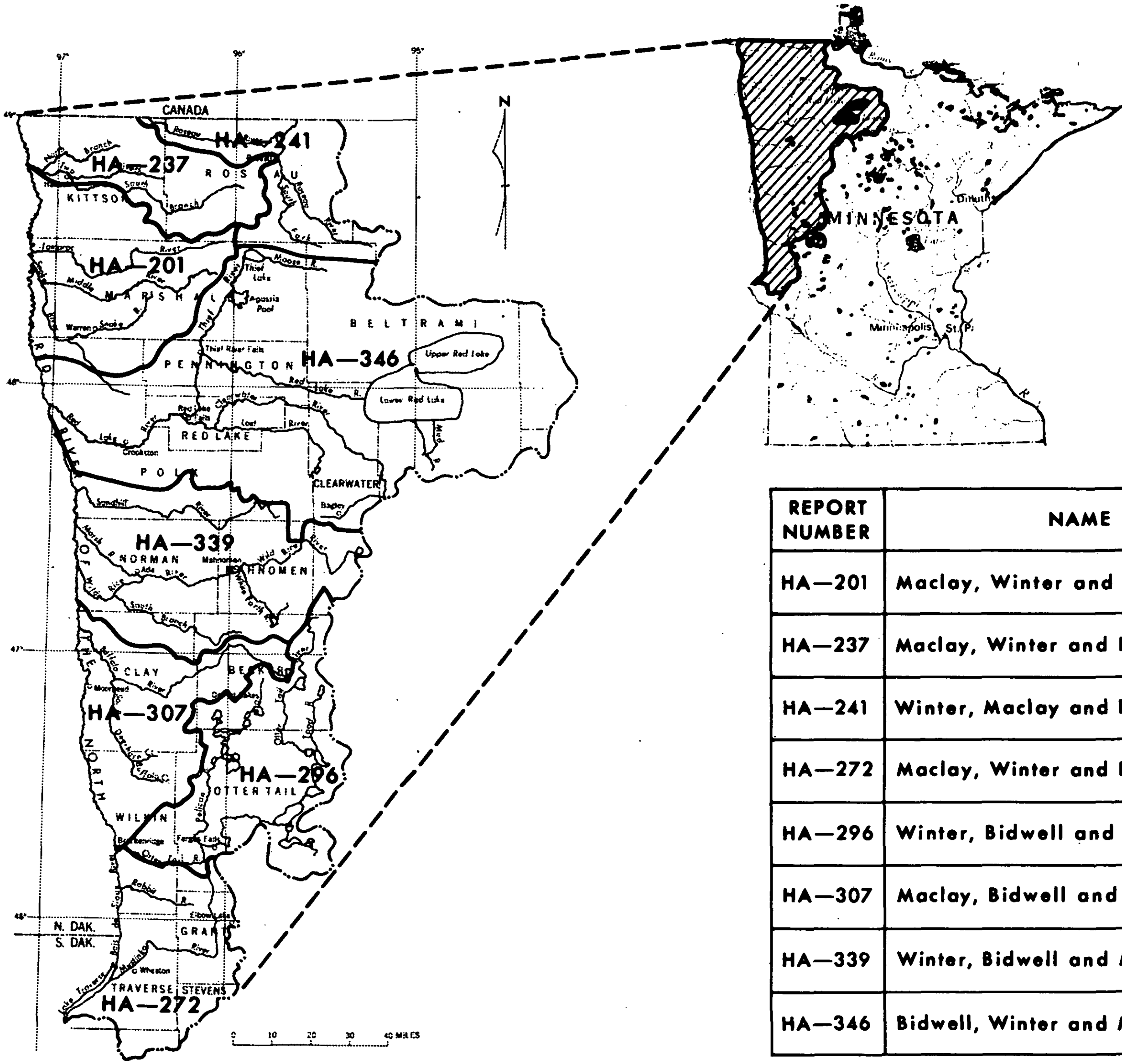


Figure 1.--The largest contributions to flow in the Red River of the North are from tributaries in Minnesota.



REPORT NUMBER	NAME	REFERENCE
HA—201	Maclay, Winter and Pike, 1965	Middle River
HA—237	Maclay, Winter and Pike, 1967	Two Rivers
HA—241	Winter, Maclay and Pike, 1967	Roseau River
HA—272	Maclay, Winter and Bidwell, 1968	Mustinka and Bois de Sioux Rivers
HA—296	Winter, Bidwell and Maclay, 1969	Otter Tail River
HA—307	Maclay, Bidwell and Winter, 1969	Buffalo River
HA—339	Winter, Bidwell and Maclay, 1970	Wild Rice River
HA—346	Bidwell, Winter and Maclay, 1970	Red Lake River

Figure 2.--The Red River of the North basin is in the northwestern part of Minnesota and covers about one-fifth of the State.

Purpose and Scope

The purpose of this report is to describe and appraise the hydrologic system in the Red River of the North drainage basin in Minnesota, and emphasize the ground water, surface water, and water quality components. It is also intended to provide a background of information so water planners and managers can understand the occurrence, movement, and availability of water which is essential in making the best decisions in management of the resource.

This report summarizes on a broad regional scale the results obtained from investigations of the eight watershed units. The investigation of the Red River drainage basin in Minnesota, was a 5-year project started in July 1963 and completed in June 1968.

Previous Investigations

Water resources of the Red River basin has been the subject of study since the late 1800's. Of particular importance is the report by Upham (1895) which is concerned largely with geology but includes the ground-water conditions in each of the counties studied. Other significant studies concerned largely with geology and soils are those by Tyrrel (1896), Johnston (1916), Leverett (1932), and Nikiforoff (1939 and 1947). Two of the earliest reports on water resources of the area is a statewide report by the State Drainage Commission (1910) and a report by Simons and King (1922) concerned with flooding in the Red River Valley. Since that time reports on ground water include those by Byers, Wenzel, Laird, and Dennis (1946); Dennis, Akin, and Worts (1949); Paulson (1953); Bingham (1960); and Schiner (1963). The U.S. Army Corps of Engineers has a number of reports concerned largely with flood control measures in the basin. Augustadt (1955) reported on the drainage of the Red River Valley. A report on pollution of the Red River of the North was published by the U.S. Public Health Service (1965). Selected hydrologic data was published by the Minnesota Department of Conservation, Division of Waters (1965). The most recent report of geologic and some hydrologic significance is a collection of reports resulting from a conference of the Glacial Lake Agassiz region edited by Mayer-Oakes (1967).

Acknowledgments

This report benefited greatly by much information supplied by other individuals and agencies: U.S. Soil Conservation

Service personnel in the counties in the Red River basin for preliminary soil maps; U.S. Fish and Wildlife Service personnel for information on prairie pothole drainage; Minnesota Department of Conservation for data on lakes, drilling logs, well schedules, and water use; Minnesota Geological Survey for drilling logs and well records; municipal officials, particularly water works superintendents, for data on municipal wells and supplies, and in some cases, for permission to use municipal wells for test pumping; and industries in the area of study for data on drilling logs, well schedules, and water use.

Special thanks are due the many well drillers in the area of study who very unselfishly provided us with drilling information and gave us the benefit of their many years of experience, and the well owners in the Red River basin who provided us with much information on their wells.

Conclusions

1. The development of surface water as a source of supply in the flat terrain of the lake plain and lake-washed till plain is a severe problem because of wide variations in streamflow, frequent periods of no flow, and lack of reservoir sites.

2. The most serious problem of water quality exists in the northwestern part of the Red River basin where ground water contains extremely high content of total dissolved solids and chloride.

3. About 5.1 million acre-feet of water is available for manipulation by man on a continuing basis from streams or from aquifers within the watershed of the Red River basin within Minnesota. To approach any significant fraction of this yield, storage of surface water during high flow would be necessary.

4. The average annual flow from the tributaries to the Red River of the North in Minnesota is equivalent to 1.7 inches over the entire basin.

5. The Paleozoic rocks have great potential for yielding water if a need for saline water should develop.

6. In terms of widespread use and total pumpage, aquifers of sand within till are the most important sources of ground water.

7. The outwash sand and gravel in east-central Otter Tail County and in the Halma-Lake Bronson area of Kittson County are potentially the largest yielding individual aquifers

of fresh water in the Red River basin in Minnesota. Yields of 1,000 gpm to individual wells can be developed in these aquifers.

8. Climate is the most significant factor controlling annual water yield.

9. Much of the recharge to the ground-water system is not transmitted from the morainal area to the lake plain but is locally discharged.

10. Ground water in recharge areas is predominantly a calcium bicarbonate type and progressively changes to sulfate or sodium bicarbonate types in the direction of flow.

ENVIRONMENTAL SETTING

The Land

Physiography

The land surface in the Red River basin in Minnesota is generally considered to be flat and featureless. The range in altitude, however, is greater than 1,200 ft; from slightly higher than 2,000 feet above mean sea level in the southwest corner of Clearwater County to slightly lower than 800 feet where the Red River crosses the international boundary. The local relief and general land slope is not uniform over the basin and for practical purposes the area can be separated into three physiographic regions (fig. 3). The lake plain extends along nearly the entire length of the western part of the basin. The lake-washed till plain occurs in the northern part and the glacial moraine in the southeastern part of the basin.

The landscape is the result of glacial advances and retreats within the past 70,000 years and most of the area was covered by glaciers as recent as 13,000 years ago. The morainal area was formed by direct deposition of materials by glaciers or by meltwater streams near the margins of the glaciers. This is a relatively rugged type of landscape that is very hummocky and contains many lakes, potholes, and swamps. Local relief is as much as 200 feet. Elevations in the area are largely 1,200 to 1,600 feet above mean sea level. The exceptions are in the southern part of the area where elevations range to less than 1,100 feet and the east-central part of the morainal area where a small group of hills rise to more than 2,000 feet above mean sea level (fig. 4).

The landscape in the remainder of the basin is the result of a large glacial lake - Glacial Lake Agassiz - which covered

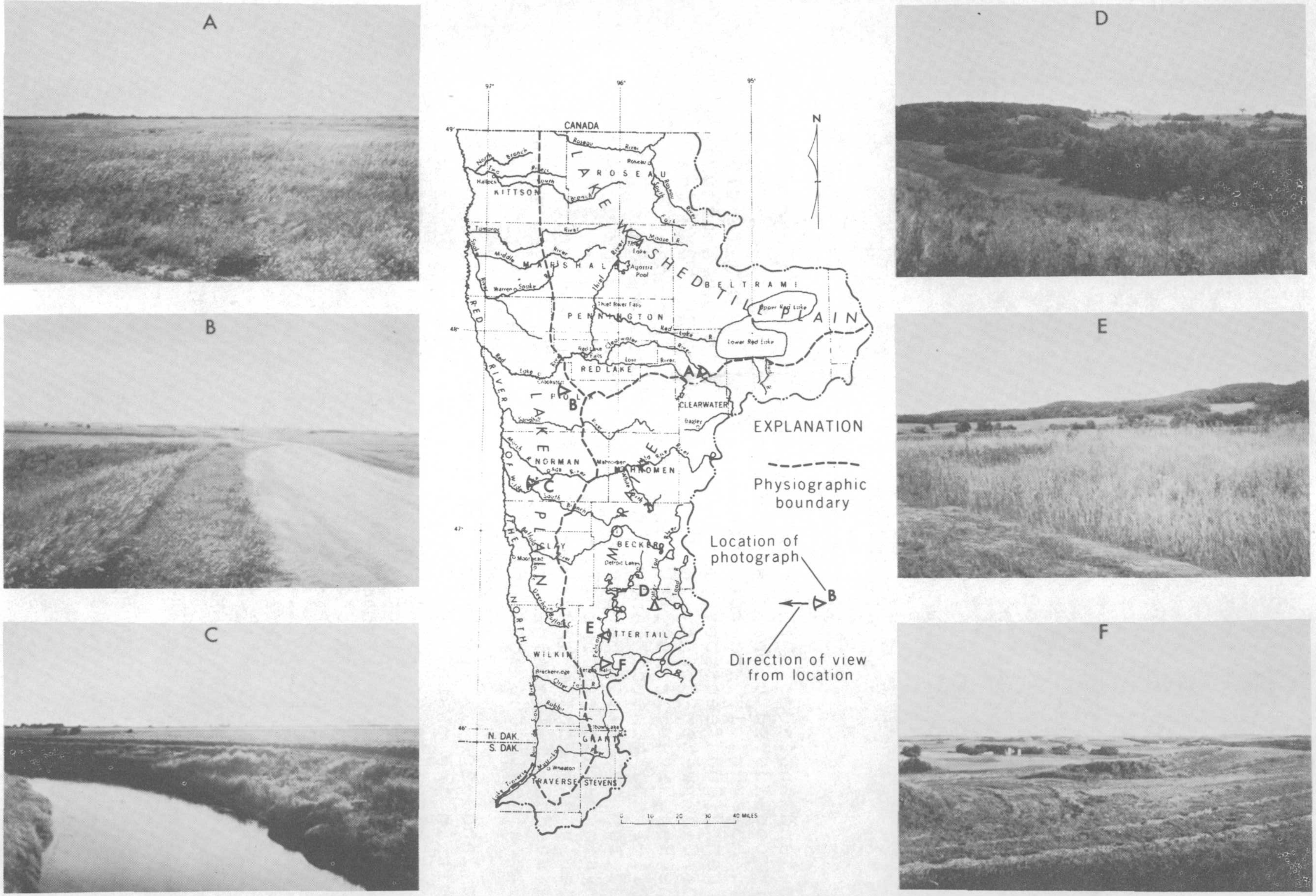


Figure 3.--The Red River basin contains three physiographic regions. Photographs of typical scenes include: A) marshy area in lake-washed till plain near Gonvick; B) beach ridges near Dugdale; C) lake plain near Ada; D) ice-contact hills in moraine near Luce; E) edge of moraine near Erhard; G) low morainal hills near Fergus Falls.

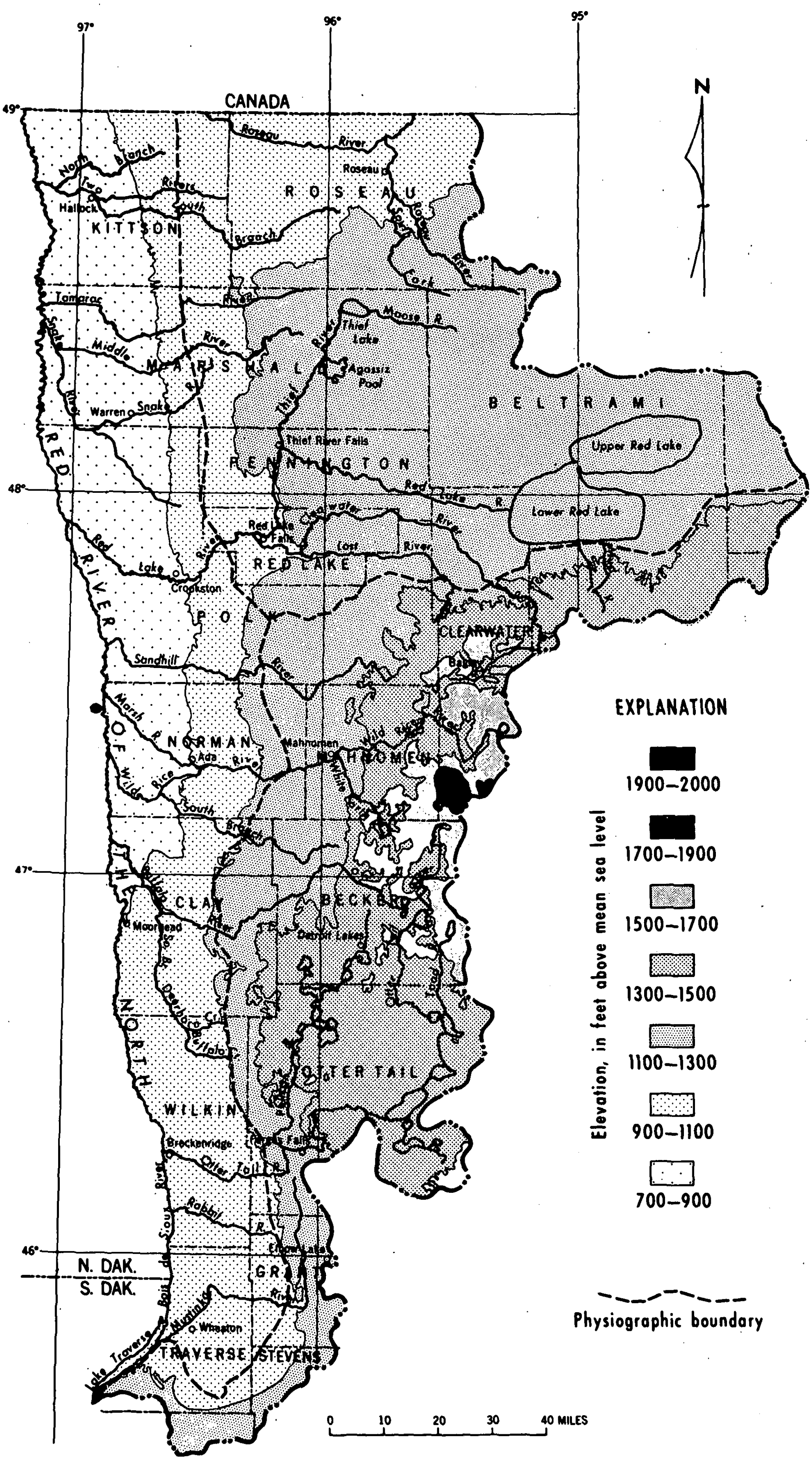


Figure 4.--The topography of the Red River basin ranges from the flat Glacial Lake Agassiz region to the hummocky morainal area. Note the small group of hills that rise to over 2,000 feet above mean sea level in the east-central part of the basin.

the area. The lake-washed till plain is gently rolling and generally has local relief of about 10 feet. It has a very low slope to the west. The lake plain, which is commonly referred to as the Red River Valley, is very flat. Although the lake-washed till plain was covered to shallow depths by glacial lake water, the lake plain was the deeper part of the lake. Shoreline features of the lake plain are long, linear, north-south trending beach ridges along its eastern edge. Local relief is generally less than 5 feet in the western part and about 15 feet in the beach ridge area. The land slope is only a few feet per mile toward the Red River in the western part of the lake plain. Along the axis of the lake plain the Red River itself falls an average of about 0.5 foot per mile from Breckenridge to the international boundary.

A physiographic feature of particular interest to water resource evaluation is the channel cutting by streams flowing across the beach ridge area. The most striking erosion has been along the Red Lake River from several miles upstream from Red Lake Falls to where the river crosses into Polk County. In this reach the valley walls are nearly vertical in places and up to 100 feet high; a most unexpected feature in an otherwise rather monotonous landscape.

Examples of typical physiographic features in various parts of the Red River basin are shown in figure 3.

Surficial Geology, Soils, and Land Use

Soils in the Red River basin are closely related to the glacial deposits of the area (fig. 5). In the morainal area the soils are of three general types. Soils in the southern and western parts are medium- to fine-textured prairie and prairie border soils (Arneman, 1963) formed on a calcareous, silty, glacial till. Erosion control is a problem in this area. Crops commonly grown in the area are small grains, corn, and soybeans in the southern part, and alfalfa in the northern part of the area. Pastureland and wooded areas are also common.

The eastern and northern part of the morainal area is covered by medium textured forest soils formed on till and coarse to medium soils formed on outwash sand and gravel. Forest soils formed on till in hilly areas commonly develop gullies where forests are cut. The land is used largely for forestry and general farming. Small grains and alfalfa are the major crops.

Light-colored forest soils formed on sand and gravel occur northward from northern Becker County (fig. 5). Prairie soils

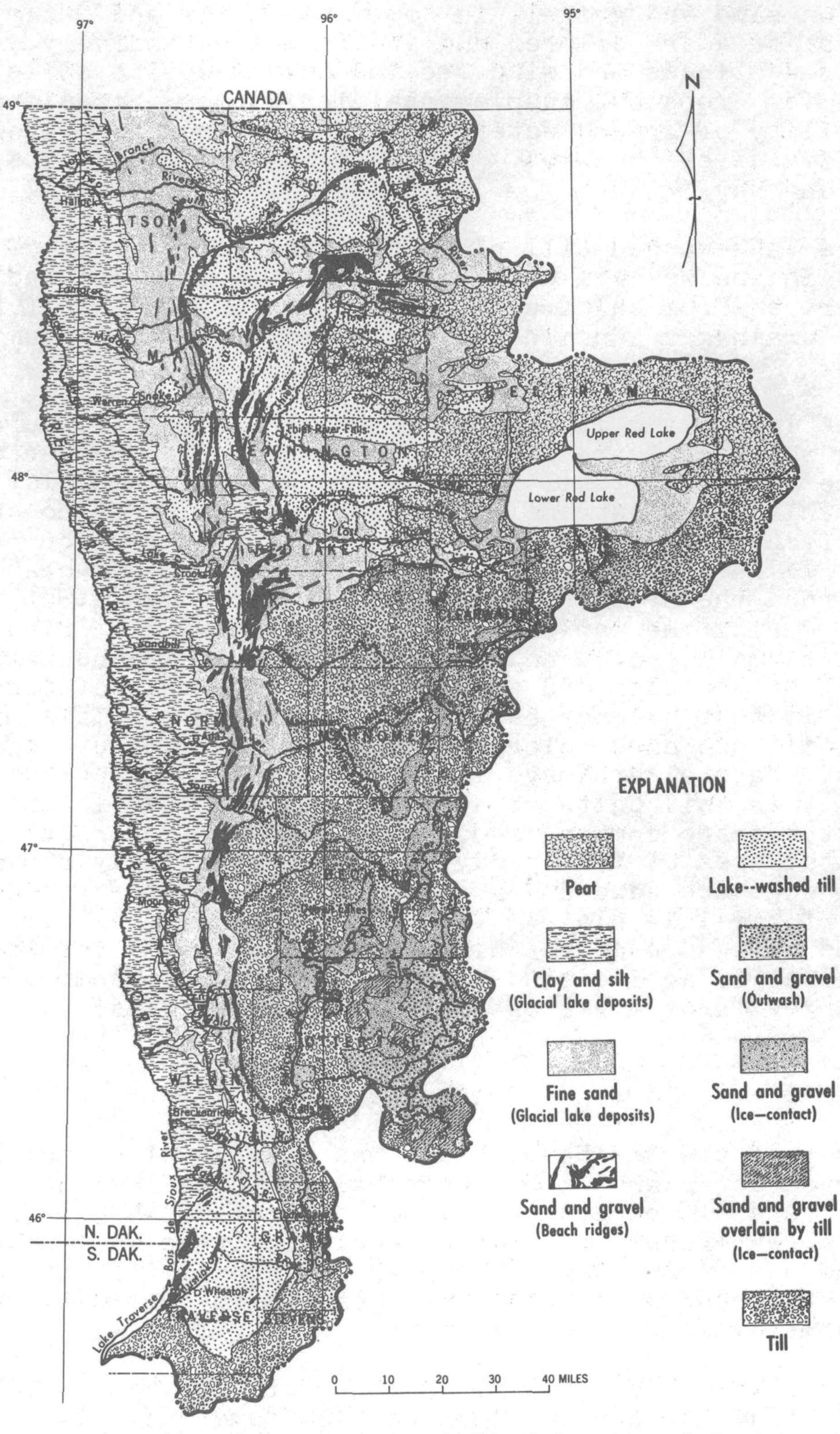


Figure 5.--Deposits formed or modified by Glacial Lake Agassiz are the predominant feature in the Red River basin. Other than the lake deposits the basin consists of till and outwash and ice-contact sand and gravel.

formed on sand and gravel, in southern Becker and Otter Tail Counties, are dark colored and are farmed extensively. In the past, droughtiness and wind erosion have made the soils undesirable for crops but supplemental irrigation, because of the availability of ground water, has greatly increased the potential value of the area. Common crops are corn, oats, soybeans, and hay.

The lake-washed till plain contains large areas of peatlands. In the western part, the soils are dark colored and were derived from calcareous till. A major problem of this area is drainage. Common crops are small grains, legume seeds, and hay.

The lake plain is generally an area of fine textured prairie soils that are intensively farmed. In the western part the deep black soil is formed on glacial lake clay and silt. This is an extremely rich soil and required no supplemental fertilization to produce a profitable crop for many years. It is the soil that produced the abundant wheat crops that earned the area the reputation of "breadbasket of the nation" during the early part of its settlement. Principal crops are small grains and sugar beets. Within the lake plain and east of the clay and silt deposits is a belt of fine, sandy soil that extends nearly the length of the lake plain. These soils are dark colored, sandy and are subject to wind erosion. Natural drainage is inadequate for agriculture in most of this soil belt. Small grains, potatoes, legume seeds, and pastures are common crops in this area. Interspersed within the area of fine sandy soils and especially along the eastern edge are sand and gravel beach ridges that extend the length of the lake plain. The ridges are very well drained and tend to be droughty. Wind erosion sometimes results in local areas of active sand dunes. Pastures are common and many turkey farms are located on the sandy ridges.

Vegetation

Most of the Red River basin was covered with prairie and prairie-border plants. Before settlement the lake plain was entirely prairie except for strips of trees that grew along the major watercourses. The most common trees were cottonwood, elm, and ash (Iron Range Resources and Rehabilitation, 1954). Since settlement many trees were planted to form windbreaks near farmsteads.

The lake-washed till plain is covered by two general types of vegetation - an aspen parkland and bog. The aspen parkland consists largely of aspen, balsam, poplar, and scrub.

Many scattered lowlands contain bog plants within this area. The extremely large bog near Upper and Lower Red Lakes is part of one of the most extensive bog lands in the United States. The bog vegetation makes intriguing patterns which include tear-drop shaped forested islands surrounded by what look like "rivers" of grasses. Heinselman (1963) has described the patterned bogs in detail.

The western part of the moraine was vegetated before settlement with prairie-border types of plants. These consist of oak predominately, but also other hardwoods and some aspen. The forest cover was generally not complete in this area and the intervening areas were covered with prairie plants. With the advent of farming most of the forest was reduced to local woodlots.

On forest soils formed on till in the eastern part of the morainal area the forest consisted of pines and hardwoods. The pine forests were cut extensively and the second growth is largely aspen. Many hardwood species remain, however, consisting of maple, basswood, and oak. Elm and birch are also common (McAndrews, 1966). Within the moraine the areas of sand and gravel are partly covered by extensive stands of jack pine in the northern part and oak in the southern part. Part of the outwash plain in eastern Otter Tail County supported a native prairie vegetation before it became extensively farmed. An account of the vegetational history of the Red River basin is given by Shay (1967). Greater detail of presettlement and present vegetation is provided by McAndrews (1966) and Shay (1967).

Population

Water problems usually are related to people. People may either draw water at excessive rates, use water for a carrier of waste without regard to the streams capacity for self purification or occupy areas that are within the reach of flood waters. Generally, the more people that occupy a given area the more water problems that arise. Because of this it is not only necessary to look at past population patterns, occupations, and related water problems, but to try to predict future population patterns and occupations. From these considerations predictions of future water needs and problems may be made.

Warkentin (1967) gave an example of problems faced by an early settler of the Red River Valley. Not only were waterlogged lands encountered, but a ground-water supply was not readily available. Flooded fields in spring plagued the early settlers but this condition was alleviated somewhat by extensive drainage projects that followed in the late 19th and early 20th centuries.

The drained water eventually increased flooding downstream, and one man's solution became another man's problem. The water supply in the example given by Warkentin was to be derived by diverting water from the Red River. The plan was never executed, but if it were, and people upstream from the intake used the river as a convenient carrier of their waste, a quality problem would replace a quantity problem. Subsequent to the large drainage programs mentioned above, the Red River Valley became extensively farmed. The population of the Red River basin in Minnesota was approximately 240,000 in 1960 or about 14 people per square mile. Approximately 80 percent of the population is rural; that is, people who live on farms or in communities with population of less than 2,500. The 1960 census for population showed rural loss and urban gain in nearly all the counties. The percentage of rural loss from the 1950 census is estimated at about 5 percent. The rate of urban growth is fast for Fargo-Moorhead and East Grand Forks-Grand Forks; whereas, growth in other communities in the basin is moderate.

The population of the major communities in 1960 was:

Community	Population
Moorhead	22,934
Fergus Falls	13,733
Crookston	8,546
Thief River Falls	7,151
East Grand Forks	6,998
Detroit Lakes	5,633

A very general picture of population trends can be seen on figure 6.

Water problems in the area have generally been concerned with: (1) supply; unreliable surface-water supplies or inadequate ground-water supplies near municipalities, or poor quality ground water in some areas for domestic and farm use; (2) drainage of lands for farming; (3) flooding of farm lands and municipalities; (4) pollution of surface waters. Water. Water resource studies and management projects have centered around the solution of these problems. Population and occupation trends must be predicted so that appropriate measures can be taken to insure the optimum management of the water resource.

Without going into a detailed analysis of population trends and water needs, local and nationwide trends show a decrease in farm and an increase in urban population. However, even with the decrease in numbers of farms the larger farms

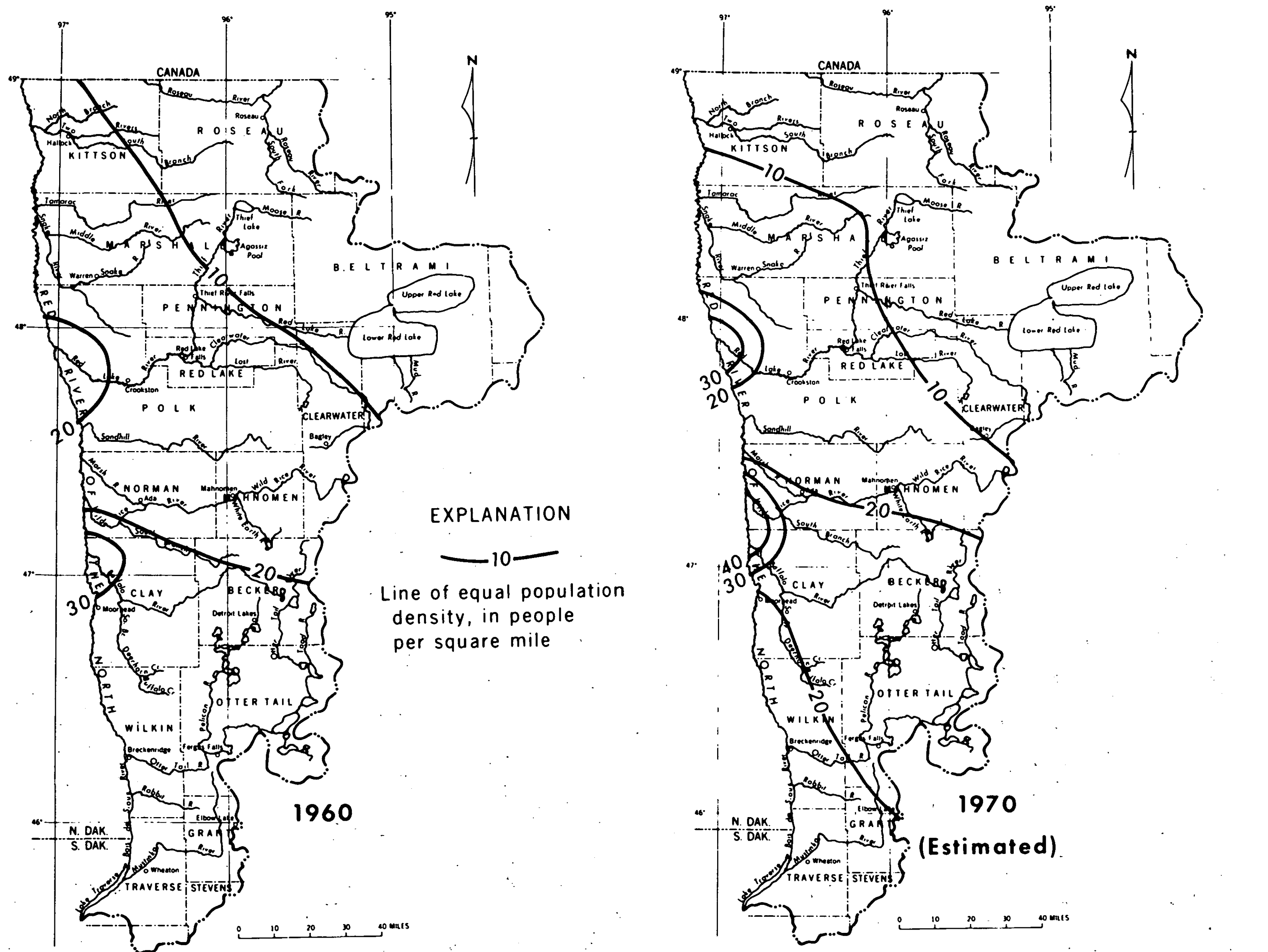


Figure 6.--Estimated increases in population during the 1960's are largest near Moorhead and East Grand Forks.

that result need increasingly larger water supplies. Water demand for supplemental irrigation in the areas of sandy soils may greatly increase the need for ground-water supplies.

With the increase in urban areas, and especially the large anticipated increase in the Fargo-Moorhead and East Grand Forks-Grand Forks areas, the problems of supply will become even more critical as will the problem of waste disposal. Also, with more leisure time, there will be an increasing demand for water-based recreation facilities.

A number of management projects will probably be devised in anticipation of increasing numbers of people, shifts of population, and related water needs. Before any implementation of management developments, however, the entire water resource situation should be examined so that a short term solution does not become a long term problem.

Climate

The Red River region of Minnesota has a continental climate, characterized by a wide variation in temperature, scanty winter precipitation, and a general tendency to extremes. The mean annual precipitation increases from about 19 inches in the northwest to more than 25 inches in the southeast (fig. 7). About 75 percent (16 inches) of the precipitation falls between April and October, usually as thunderstorms. The average number of days without killing frost ranges from about 140 days near Moorhead to about 100 days near Roseau (U.S. Dept. Agriculture, 1941, p. 932). The climate is subhumid but there have been wide fluctuations between wet and dry periods. In the 17 years, 1861-1877, the average annual precipitation was 24.50 inches in the valley of the Red River (Augustadt, 1955, p. 570-571). During the 24 years, 1917 to 1940, the average precipitation was 17.80 inches and from 1941 to 1954 another wet cycle occurred. Averages, however, do not indicate weather extremes. Exceedingly dry years occur during wet cycles and wet years occur during dry cycles (fig. 8).

Erratic climatic conditions through the years have aggravated water problems. In long periods of drought there have been water shortages and no need for drainage. When wet periods occur, drainage and flooding are problems, part of which could have been avoided by action during the dry period. Serious flooding occurred in 1882 and 1883. The valley was flooded again in 1893. In 1897 one of the worst floods on record occurred. The years 1904, 1916, and 1920 also were flood years. From 1920 to 1943 major floods did not occur, but damaging floods in 1943, 1944, 1948, 1950, 1965, 1966, and 1969 caused losses of millions of dollars each year.

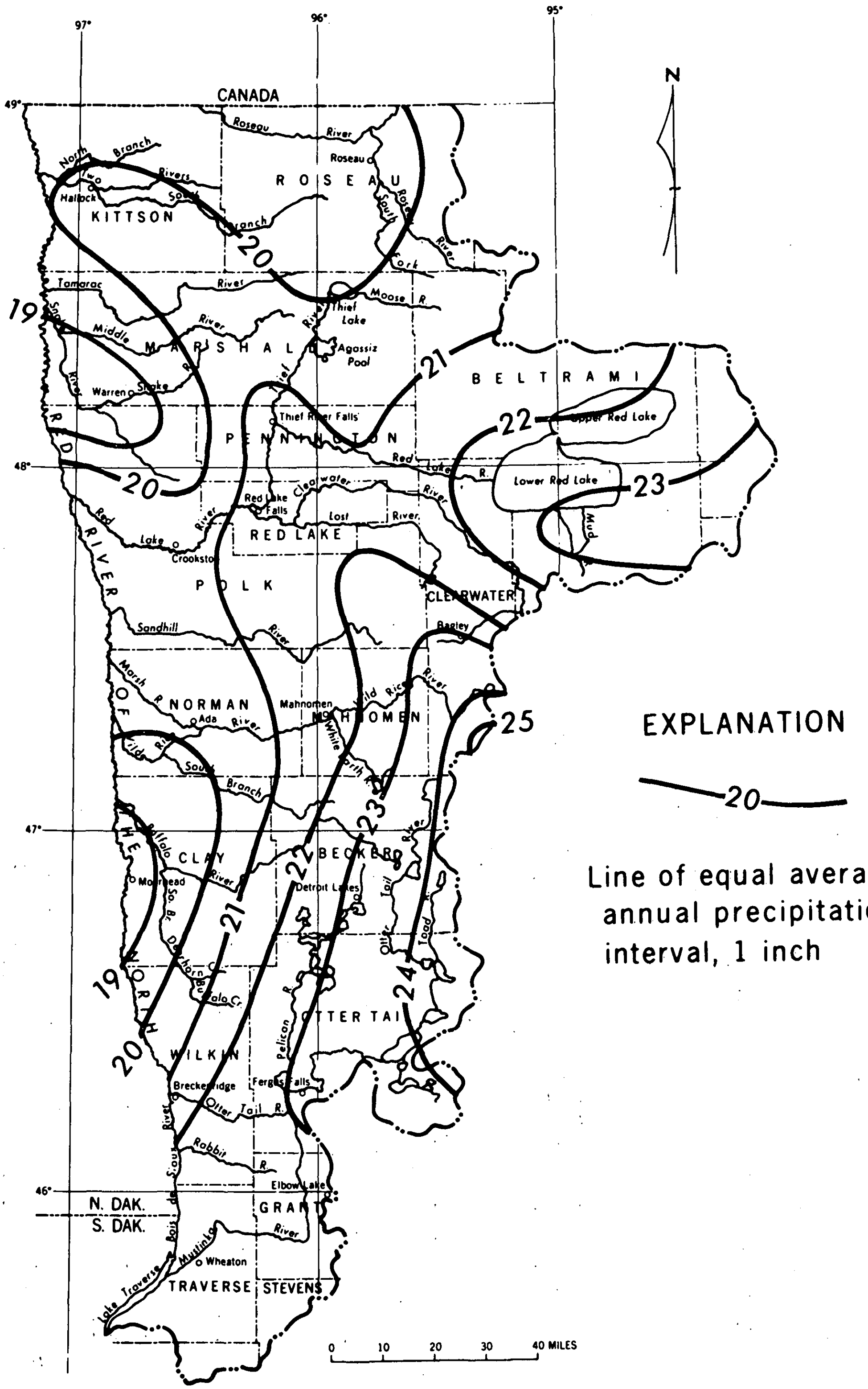


Figure 7.--Average annual precipitation in the Red River basin increases from 19 inches in the northwestern part to 25 inches in the east-central part.

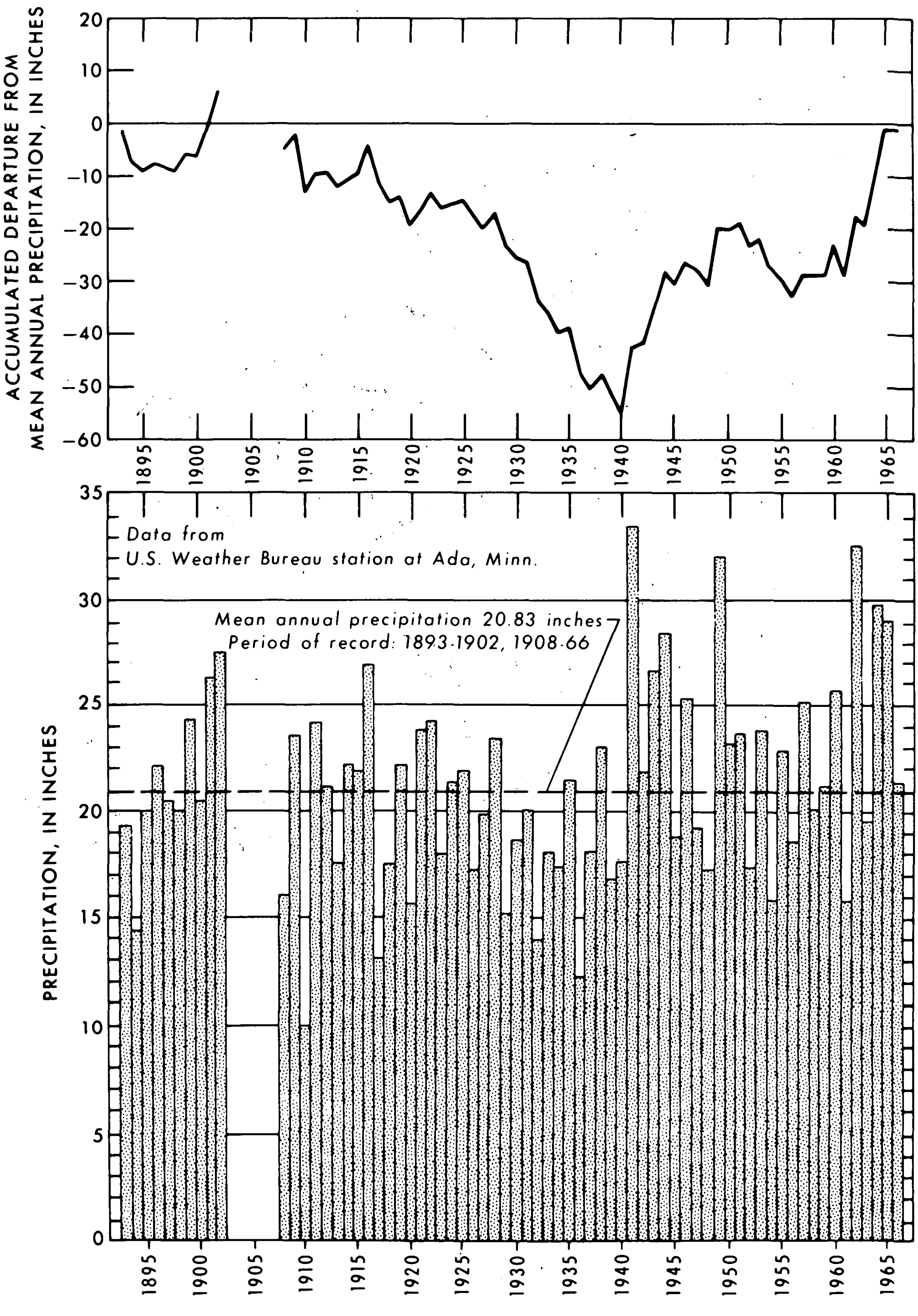


Figure 8.--The greatest rate of accumulated deficiency in precipitation occurred during the drought of the 1930's.

Droughts occur whenever the supply of water to vegetation, either from rainfall or that stored in the soil, becomes inadequate to sustain normal growth. Each day there is inadequate moisture in the root zone is defined as a drought day. Assuming that the soil can store 9 inches of water, the expected minimum number of drought days from May through September for a probability of 5 out of 10 ranges from more than 30 days in the west to about 10 days in the east (fig. 9). For the same soil condition the expected minimum water deficiency in inches per season for a probability of 5 out of 10 ranges from about 5 inches in part of the west to less than 1 inch in the southeast (fig. 10). The relation between evapotranspiration and precipitation based on weather records and using a computational method developed by Thornthwaite and Mather (1957) shows the soil moisture deficiency at Roseau, Ada, and Fergus Falls (fig. 11). The determined values for deficiency of soil moisture using a soil storage capacity of 8 inches and mean monthly precipitation and temperature records are in approximate agreement with values having a probability of 5 out of 10.

Geologic Framework

An understanding of the geology of an area is basic to the understanding of its water resources. The hydrologic characteristics of streams and lakes are controlled significantly by surface geology and topography. Ground water is especially related to geology because it is the rocks that control the movement of ground water and react chemically with the water to determine its quality. Much of this ground water in turn finds its way to streams and has a great influence in many cases on the streamflow characteristics. The rocks in the Red River basin can be separated into three general types: Precambrian crystalline rocks, stratified sedimentary rocks, and drift. These rocks are distinctly different types and have widely varying hydrologic characteristics.

In this report the geologic description will emphasize the characteristics of rocks that are important to water resources. To evaluate the ground-water resources it is important to know the physical characteristics of the rock units such as their overall size and shape and their internal micro features such as grain size, fabric, and porosity. Chemically, it is not only important to know the gross chemical composition of the rocks, but also the mineralogic form in which the elements are arranged.

Precambrian Crystalline Rocks

Crystalline rocks in this report include all igneous rocks, such as granite, and metamorphic rocks, such as schists and

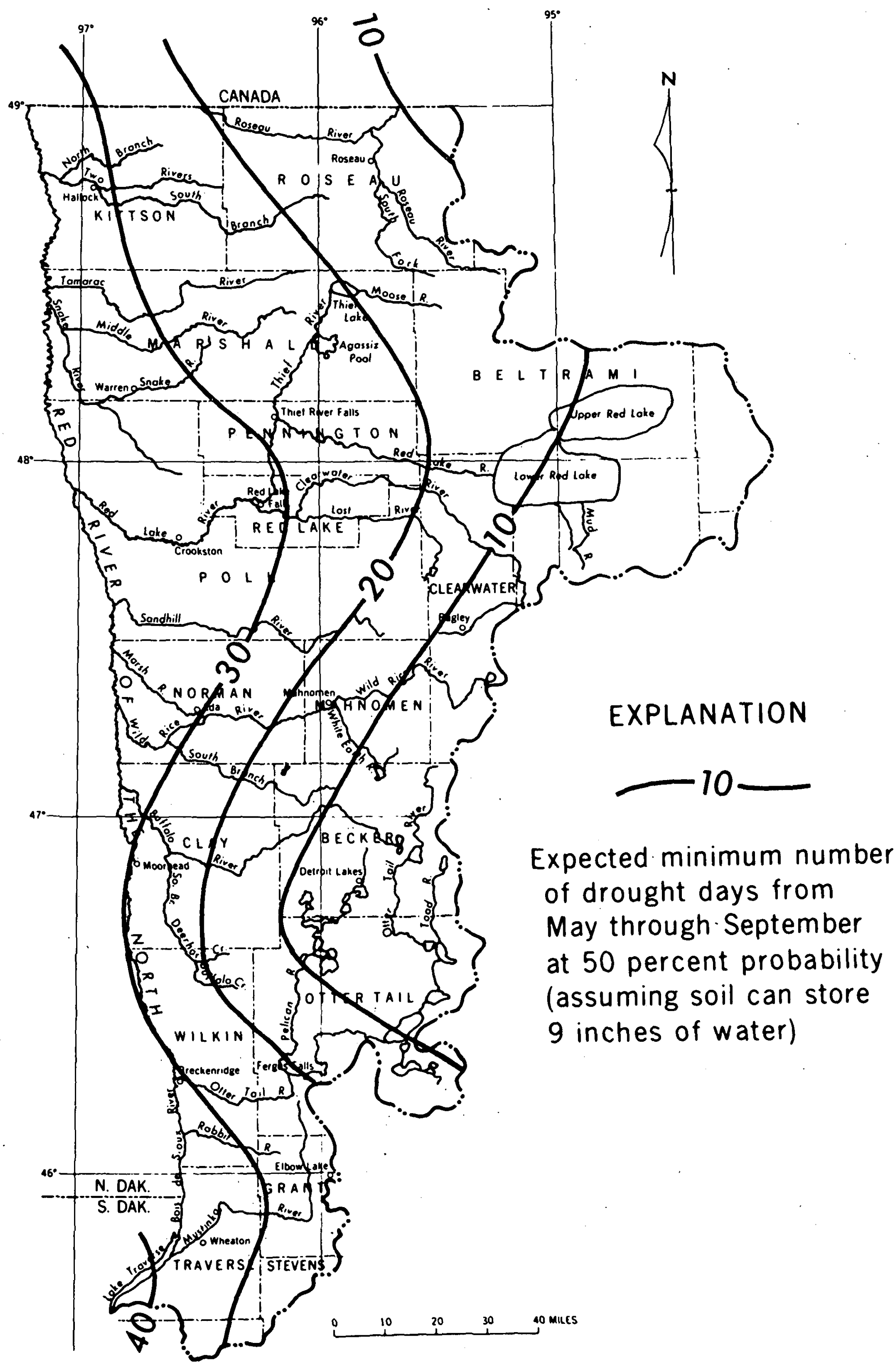


Figure 9.--Expected minimum number of drought days from May through September at 50 percent probability ranges from about 40 at the southwestern tip of the basin to less than 10 along the eastern edge.

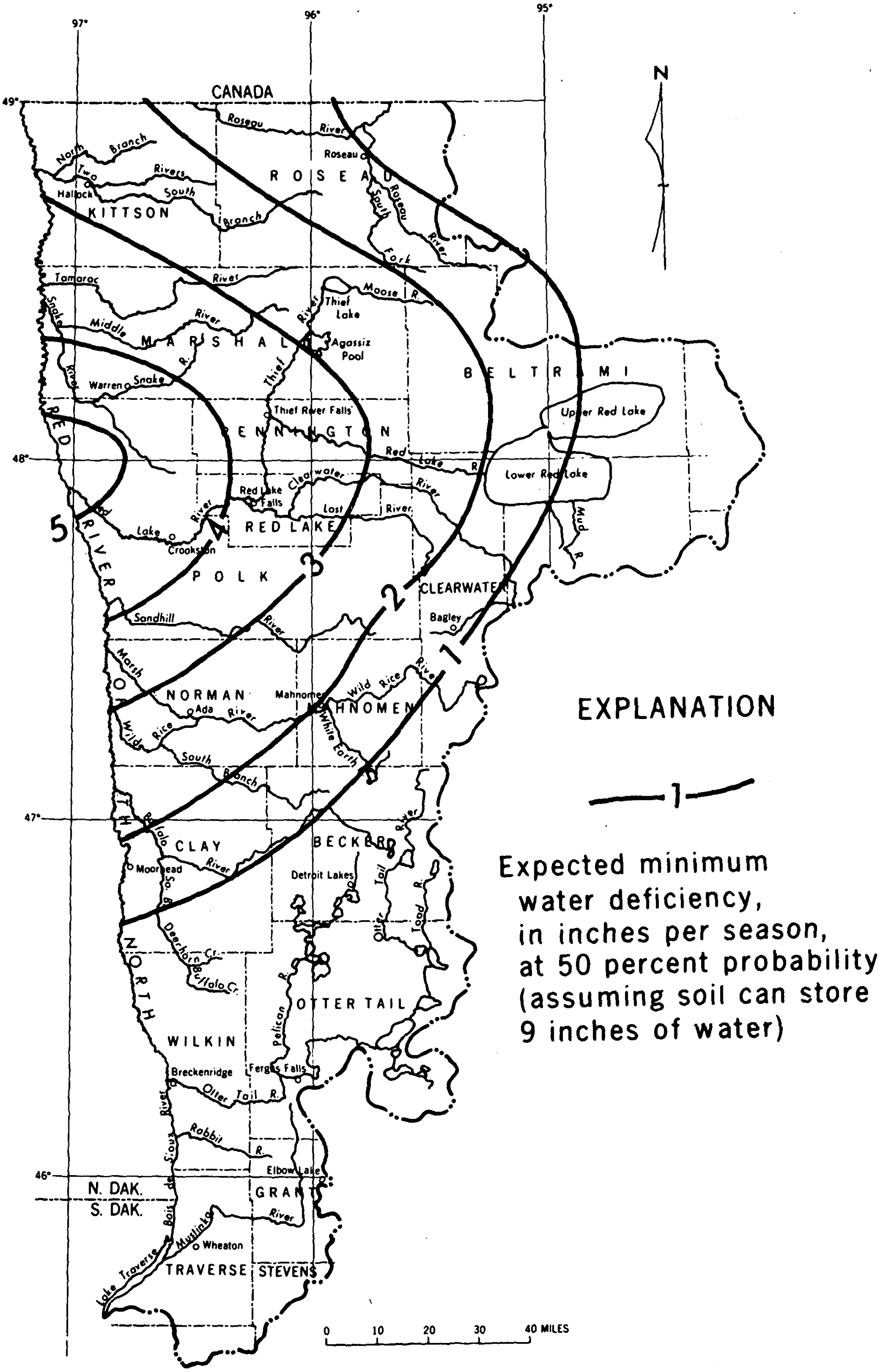


Figure 10.--The expected minimum water deficiency per growing season at 50 percent probability ranges from greater than 5 inches to less than 1 inch within the northern part of the basin. It is less than 1 inch throughout the remainder of the basin.

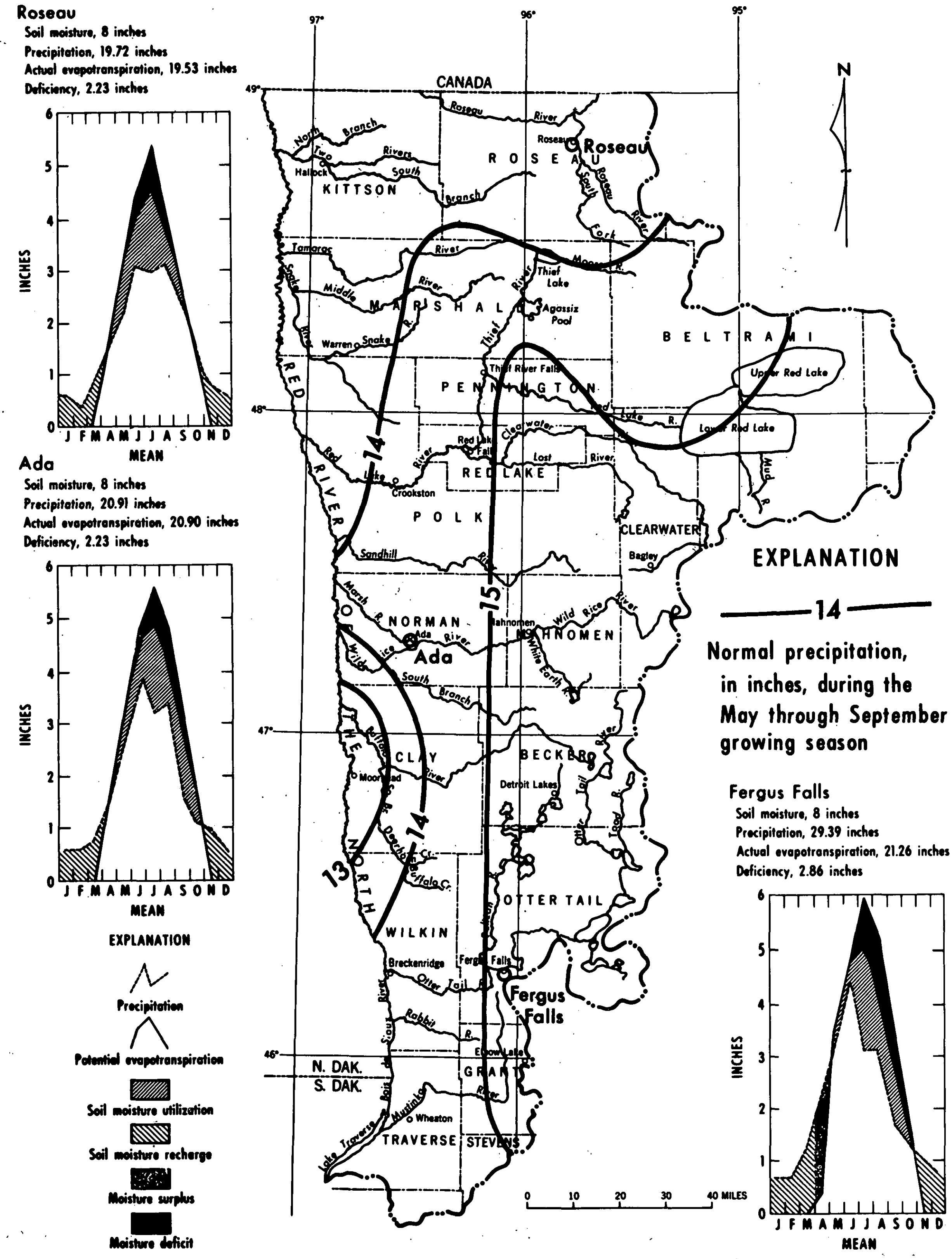


Figure 11.--Calculated values of mean moisture deficiency using the Thornthwaite method show a moisture deficit in all the physiographic regions in the basin.

slates. Because the crystalline rocks in the Red River basin are deeply buried, except locally east of the Red Lakes, very little is known about them. Granite and greenstone are probably most common crystalline rocks but other types also occur. A small deposit of iron formation was located under about 600 feet of glacial drift just east of the Red River basin in southeastern Becker and northeastern Otter Tail Counties (Anderson, 1957).

Crystalline, particularly granitic, rocks are generally considered to be impermeable to ground-water movement. Where the crystalline rocks are fractured water occurs in the open spaces but these will usually contain only a small amount of water; in many cases no more than enough for a domestic supply. Small amounts of water can also be obtained from the weathered zone of crystalline rocks.

The configuration of the Precambrian crystalline rock surface (fig. 12) is an important factor in water resource studies mainly because it defines the shape of the base of the saturated zone of the hydrologic system. It is also important to define because valleys in the basement rock commonly contain very permeable deposits of sand and gravel. The general slope is from east to west and the relief is about 1,100 feet. The highest elevations on the crystalline rock surface are in northeastern Otter Tail County and in Koochiching County. The lowest (less than 200 feet above mean sea level) is in western Kittson County. A bedrock valley extends southeast from Pennington to central Clearwater Counties and thence, southeast out of the basin. A tributary to this valley extends northeast beneath Lower Red Lake. Another fairly well defined but smaller valley occurs in the southern part of the basin extending from south-central Grant County westward into South Dakota.

Paleozoic Sedimentary Rocks

Sedimentary rocks of Paleozoic age overlie the crystalline rocks in the northwestern corner of the basin. Very little is known about these rocks in Minnesota owing to a lack of drill-hole data. Bayer (1959) described the bedrock stratigraphy of northwestern Minnesota on the basis of data derived from a few test holes, but supplemented these data with descriptions of the rocks in their area of outcrop in Manitoba.

Paleozoic rocks in this area are Ordovician in age and consist of two formations; the Winnipeg Formation and the Red River Formation. A third rock type, the Hallock Red Beds, identified and named by Bayer (1959) is either a weathered part of the Winnipeg Formation or may be an extension of the

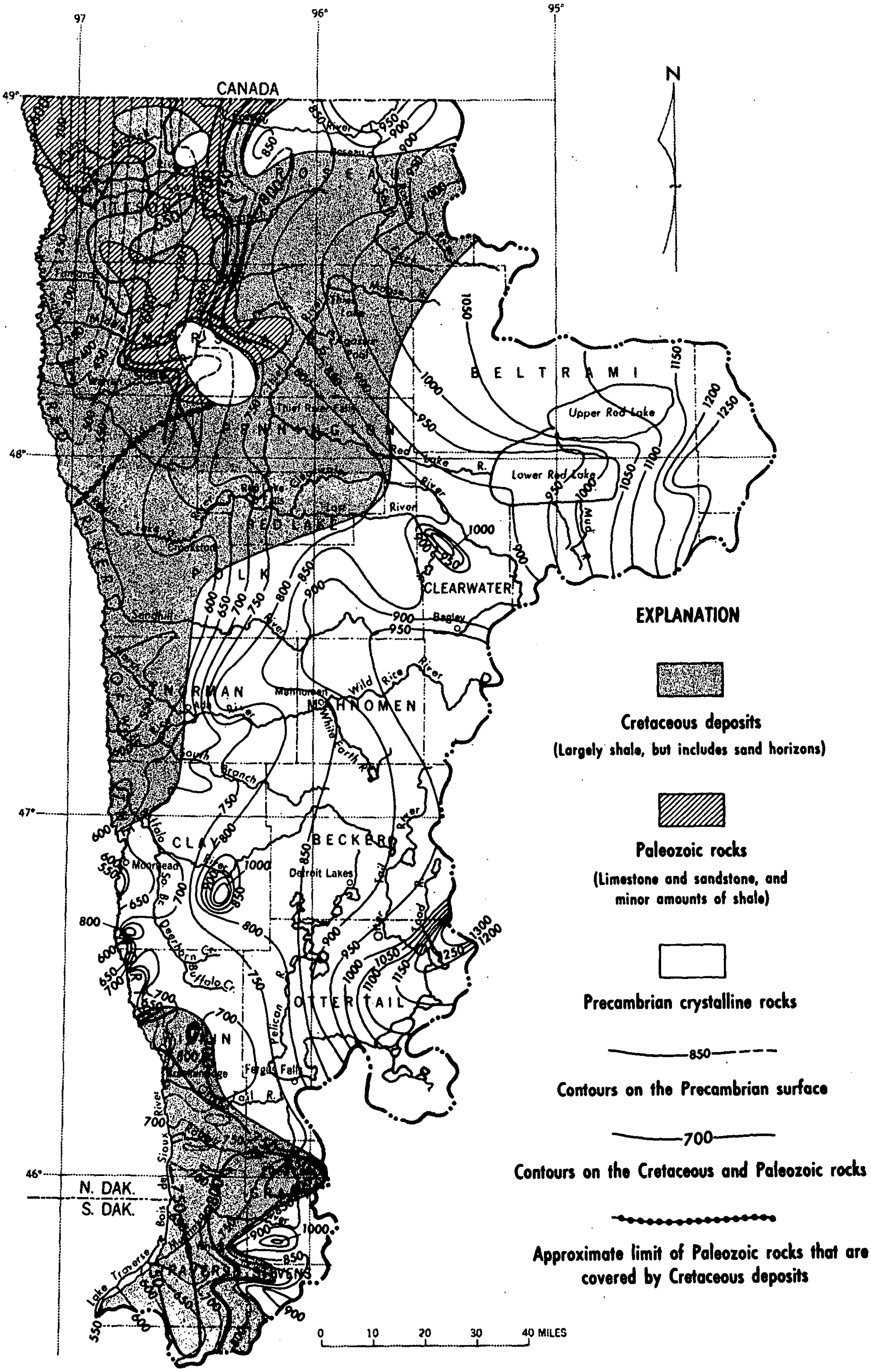


Figure 12.--Paleozoic sedimentary rocks occur in the northwest corner of the basin. Continuous Cretaceous sediments occur in the northern and southern parts. The elevation of the Precambrian surface decreases from more than 1,250 in the eastern to less than 200 feet above mean sea level in the northwestern part of the basin.

Amaranth Formation of Jurassic (?) age, which is identified north of the report area in Manitoba.

The Paleozoic sedimentary rocks lie in the depression on the Precambrian surface in the northwestern part of the basin (fig. 12). The Winnipeg Formation and the overlying Red River Formation increase in thickness from east to west. Their eastern extent is about at the Kittson-Roseau county line. The exceptions to this are near the Canadian border where they extend further eastward into Roseau County and in Marshall County where the limit swings eastward into the eastern half of the county. The rocks increase in thickness from this feather edge westward into North Dakota, where in the Williston structural basin they have a combined thickness of about 850 feet. At the Minnesota-North Dakota border in Kittson County the two formations probably reach a maximum thickness of about 400 to 500 feet. Comparison of the contours on the Precambrian surface with the supplemental contours on the Paleozoic and Cretaceous rocks (fig. 12) give a good idea of the general configuration of the sedimentary rocks. The Cretaceous rocks are thin, generally less than 25 feet, so most of the sedimentary rock thickness consists of Paleozoic rocks.

The Winnipeg Formation is separated into two general units in Kittson County. About 8 miles northwest of Hallock the lower unit consists of about 95 feet of gray, red, purple, and green mottled and variegated shale and mudstone containing minor beds of limestone. A thin sandstone unit, generally less than 10 feet thick, occurs at the base of the shale sequence. The upper unit consists of about 70 feet of white, well-sorted, medium grained, friable sandstone. Thin beds of shale as well as some well-cemented sand beds occur in the sandstone.

The Red River Formation is separated into two units, best described in a log of a test hole about 8 miles northwest of Hallock. The upper unit consists of 135 feet of slightly dolomitic yellow and tan limestones. The upper 40 feet of this unit has many small open solution holes and large irregular cavities. The texture of this unit is granular. Tan chert fragments also occur throughout this unit. The lower unit of the Red River Formation consists of 100 feet of dark gray to purple limestone that is slightly more dolomitic than the upper unit. This unit is also decidedly more silty and argillaceous than the upper unit and has a very fine grained to dense texture. Traces of pyrite and iron oxide stain also occur in this unit. The Red River Formation thins to the east and south. It is 45 feet thick at a well 27 miles south of Hallock.

The Hallock Red Beds is a name assigned by Bayer (1959) to a section of rock in a test hole drilled at Hallock, Minn. The unit is 105 feet thick and consists largely of pastel reddish-brown dolomitic mudstones. A chert and limestone unit 15 feet thick forms a prominent bed near the top of the section, and sandy zones several feet thick are common. This formation was not identified in any other test holes in Minnesota so its extent is unknown. However, a similar unit is described in a log of a hole nearby in North Dakota. Bayer (1959) presents and favors the hypothesis that it is a weathered portion of the underlying Winnipeg Formation, but he does not rule out the possibility that it is an extension of the Jurassic (?) Amaranth Formation found in adjacent parts of Canada.

Cretaceous Sedimentary Rocks

Cretaceous sedimentary rocks are found mainly in the northern and southern parts of the Red River of the North basin in Minnesota. These rocks generally are thin and discontinuous in other parts of the basin. They consist largely of dark gray, soft, argillaceous shale that contains small nodules and lenses of iron sulfide. Thin lenses of sand occur within the shale sequence. The map showing Cretaceous rocks (see fig. 12) is based on drill log information where Cretaceous has been identified and where quality of the water is a distinctive type characteristic of Cretaceous rocks. Within the area mapped as Cretaceous rocks are probably places where these rocks are absent; however, the data indicates that the Cretaceous rocks are fairly continuous within the mapped area. Conversely, the areas not mapped as Cretaceous probably have small scattered patches of these rocks underlying the glacial drift. Lithologic characteristics of the Cretaceous rocks are very much like the overlying glacial drift and, therefore, it is difficult to distinguish between the two units. Isolated areas where probable Cretaceous rocks occur are in the Mahnomen area, where there is possibly 25 feet of Cretaceous, and near the Otter Tail-Becker county line in the eastern part of the county just outside the Red River basin. In this area test drilling into basement rock by the Hanna Mining Company shows a type of rock that could possibly be Cretaceous overlying the Precambrian (Anderson, 1957). Sloan (1964) shows much of the central part of the basin covered by Cretaceous. However, on figure 12 we separated the areas of rather continuous Cretaceous rocks from areas where they may only be in scattered isolated patches, since this separation is most significant hydrologically. Carlson (1969) shows discrepancies in interpretation, especially along the State line in the northern end of the basin. His map does not show Cretaceous rocks occurring in North Dakota adjacent to Marshall and northern Polk Counties, but that the northern limit of the Cretaceous occurs perhaps 10 miles south of Grand Forks. Indications from well information in Minnesota, however, show that Cretaceous probably does occur in the western parts of these counties although there are no good drilling data to support this.

Thickness of the Cretaceous rocks in Minnesota is generally less than 50 feet and in much of the area is probably less than 25 feet. This includes the area mapped as Cretaceous and the isolated patches that may occur in the area shows no Cretaceous. The only part of the basin where a thickness greater than 50 feet occurs is in the southern part where it ranges from zero to greater than 400 feet near Browns Valley (Hall, Meinzer, and Fuller, 1911). Contours on the surface of the Cretaceous rocks in the southern part of the Red River basin are shown in figure 12. Comparison of these contours with the contours on the Precambrian rocks on the same map give an indication of the general thickness of Cretaceous rocks in this area. According to Allison (1932) the same units within the Cretaceous sediments generally occur at the base of these rocks. Very little information is available, but the sand is generally only a few inches to a few feet thick, probably no more than 15 feet. The sand is generally fine- to coarse-grained and commonly contains lignite. Where the Cretaceous is shown on figure 12 it is probably continuous into North Dakota, and is connected hydrologically to the Cretaceous sandstones there.

Quaternary Glacial Deposits

Glacial deposits form the most extensive and massive geologic unit in the Red River drainage basin in Minnesota. These deposits are the result of continental glaciers which moved into northwestern Minnesota during the past million years. Glacial moraines, which are deposited directly by glaciers form extensive, linear, rather rugged topography in the southeastern part of the drainage basin. Many of the lakes that occur in this area are the result of ice blocks having been deposited with the glacial material. These later melted out causing the material to collapse into a basin-like depression which was then filled with water. The remainder of the Red River basin, that is the western and northern parts, were covered by a large glacial lake - Glacial Lake Agassiz - which occurred in this area after the melting of the last glaciers, about 12 thousand years ago. Sediments associated with the lake include long sandy beach ridges in the eastern part, deep-water deposits of clay in the central part of the Red River Valley, and linear sand and gravel deposits buried in the subsurface of Glacial Lake Agassiz (Winter, 1967).

The most recent summary of the history of Lake Agassiz is by Elson (1967). The most recent summary of the glacial history of the entire basin is by Wright and Ruhe (1965). Zoltai (1967), and Matsch and Wright (1967) authored the most recent reports on the outlets of Lake Agassiz. Tamplin (1967) prepared a very informative summary of studies of Glacial Lake Agassiz up to 1967 that includes the earliest reports of the 1800's.

Glacial drift is made up largely of till which is a heterogeneous mixture of clay, silt, sand and gravel (fig. 13). However, there are many other types of deposits that are included in glacial drift such as outwash and ice-contact deposits. Glacial till also contains numerous buried lenses of stratified sands, gravels, silts, and clays, that are deposited simultaneously with the till, often along the margin of the glacier or in the general vicinity of the glacier. Some buried sand and gravel could be buried outwash plains. The buried sand units range from a few inches in thickness to many feet and can cover many square miles.

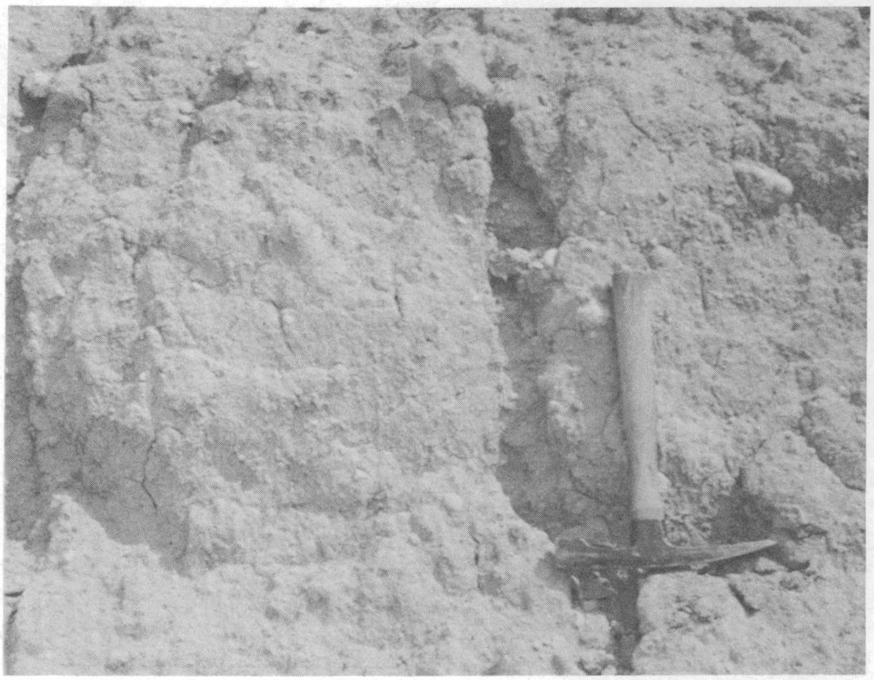


Figure 13.--Closeup view of glacial till near Clearbrook shows rocks ranging to cobble size in a matrix of silt and clay. Note the shrinkage cracks typical of this type of till.

Thickness of the glacial drift in the Red River basin ranges from less than 50 feet to more than 600 feet (fig. 14). In most of the area the drift is between 200 and 400 feet thick. The thickest sections of drift occur in the morainal area in Clearwater and Becker Counties. The glacial drift is thinnest in an area near Herman in Grant County where it is less than 100 feet thick and east of the Red Lakes in Beltrami and Koochiching Counties where it is less than 50 feet thick. Bedrock outcrops at a point near Kelliher. The isopach lines on this map represent the thickness of the glacial drift plus the Cretaceous rocks in much of the basin. They do not include Cretaceous rocks in an area in the northwestern part of the basin and the southern part of the basin where the supplemental bedrock contours were drawn on the geologic map (fig. 12).

Inclusion of the Cretaceous rocks in the total drift thickness is necessary because of the lack of data for separating the Cretaceous rock from the drift in most drill holes. Where the Cretaceous can be identified, it is generally less than 50 feet and in most of the area less than 25 feet thick. Therefore, we believe the isopach lines would not change significantly, even if the Cretaceous were separated. Inclusion is justified, also, because in the areas where the Cretaceous is thin and is not connected to the Cretaceous rocks in North Dakota the Cretaceous is essentially part of the ground-water flow system in the glacial drift.

Glacial drift in the morainal area in the east-central part of the basin is generally sandier than the till in the upper part of the moraine in the western part of the area and in the portions of the basin underlying Lake Agassiz sediments. This latter glacial till generally has a silty matrix. Rock fragments in the drift are largely limestone, dolomite, granitic rocks, and other igneous and metamorphic rocks. All the tills generally are calcareous except in their upper weathered portions.

Lake Agassiz sediments have a significant effect on the hydrologic system in the Red River basin because they are extremely fine-grained, thick, and widespread. Sand deposits that occur immediately west of the beach ridges generally are very fine to fine grained and have a thickness of no more than 10 to 15 feet. The silts and clays which lie in the westernmost part of the Lake Agassiz basin within Minnesota range in thickness from less than 1 foot to more than 140 feet. The clays tend to be thickest in the westernmost part of the area. Lake Agassiz clays contain some silt lenses that have a slightly greater permeability than the clay deposits. According to investigators in North Dakota (for example, Dennis, Akin, and Worts, 1949), the glacial lake clay can be separated into two

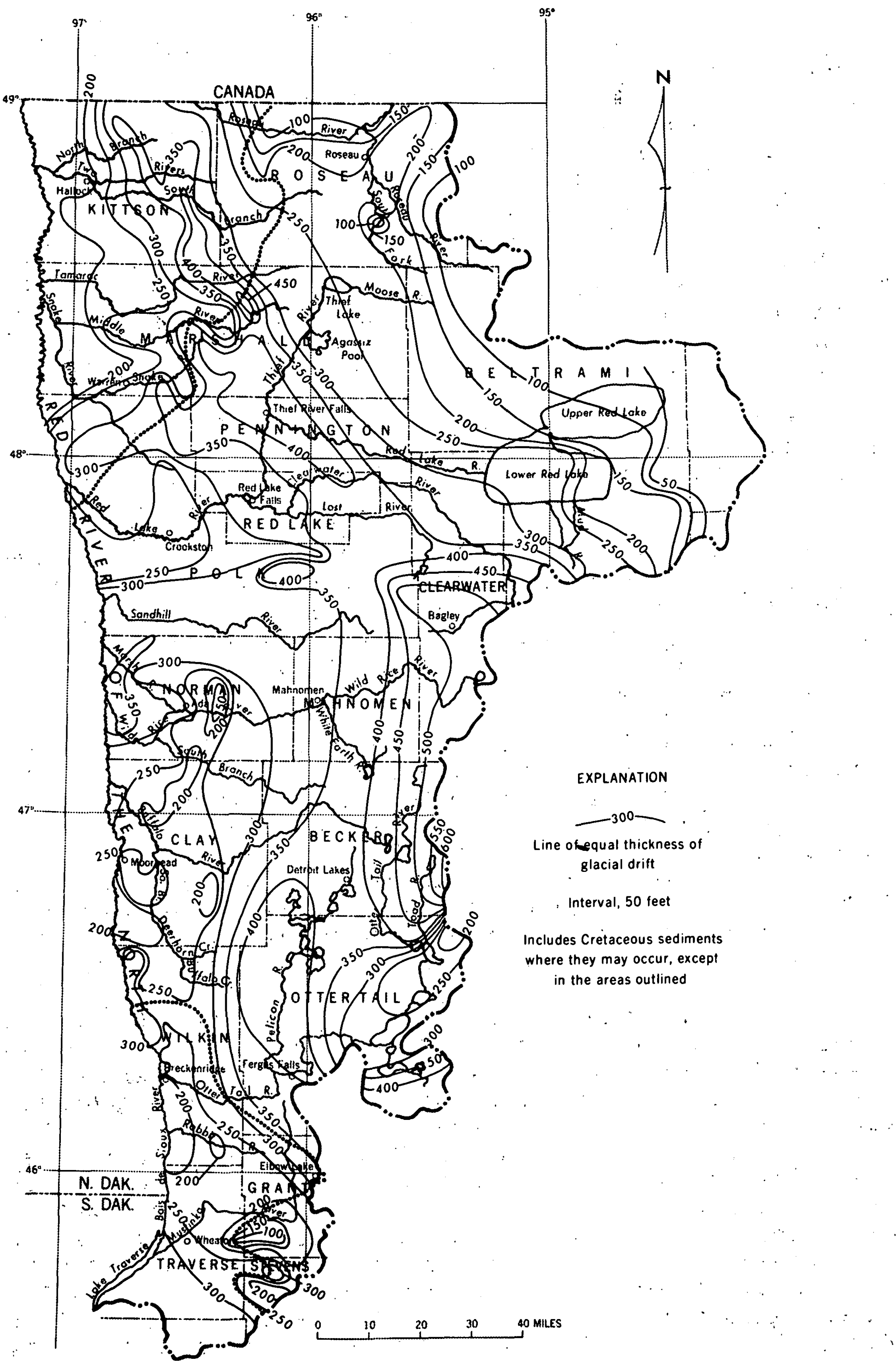


Figure 14.--Thickness of the glacial drift ranges from about 600 feet in eastern Becker County to less than 50 feet east of the Red Lakes.

units--a lower clay unit and an upper silt unit. The upper unit ranges in thickness from 10 to 30 feet (Manz, 1956). Clays below about 5 feet consist largely of montmorillonite.

Since the glacial drift is the main source of ground water and forms the bulk of the ground-water reservoir, individual types of geologic units that are significant aquifers are discussed in greater detail in figure 15. These include sand lenses within till, ice-contact deposits (fig. 16), outwash deposits, beach ridges (fig. 17), and buried linear deposits (figs. 18 and 19).

Hydrography

Hydrographic features in the Red River drainage basin include natural rivers, ditches, lakes, and wetlands. The morphological characteristics of each is controlled largely by geology and topography. Because the characteristics of rivers (including ditches) are markedly different from lakes and wetlands, each will be treated separately. The description of the hydrography is intended to give a general picture of the surface waters of the basin. Streamflow characteristics are treated much more intensively in the following sections of the report.

Rivers

River systems in the Red River of the North basin vary in size and shape depending on the geology and topography; therefore, this discussion will focus on the characteristics of rivers of different size in the three physiographic regions. The morphological characteristics considered of major importance to hydrologic analysis are channel characteristics such as type of banks, channel capacity, and channel slope.

For purposes of this report, the streams considered to be major tributaries are Mustinka, Otter Tail, Pelican, Buffalo, Wild Rice, Sand Hill, Red Lake, Thief, Clearwater, Snake, Middle, Tamarac, Two, and Roseau Rivers (see fig. 20). All other streams are considered to be minor tributaries.

Minor streams

In the morainal area, these small streams generally begin as small rivulets that form from overland flow. Often they do not have well-defined banks and flow along only low depressions in the land surface. In places the streams have eroded the land surface to where banks a few feet high have been developed (fig. 20 D and H). Minor streams are commonly characterized by

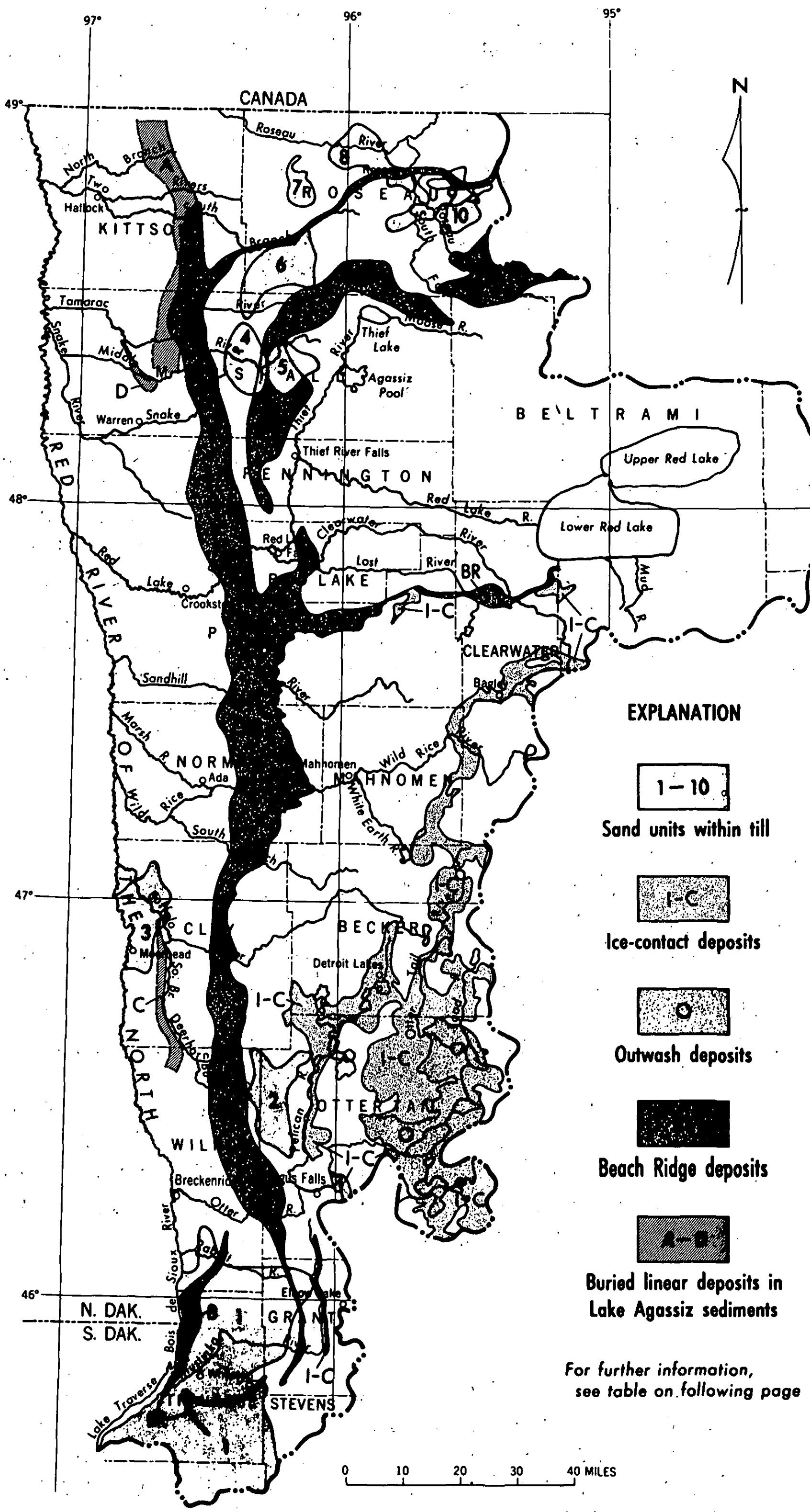


Figure 15.--Large amounts of ground water are available from some of the known aquifers such as the ice-contact and outwash sand and gravel.

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EXPLANATION (for fig. 15)

Water Resources of the Red River of the North Drainage Basin in Minnesota

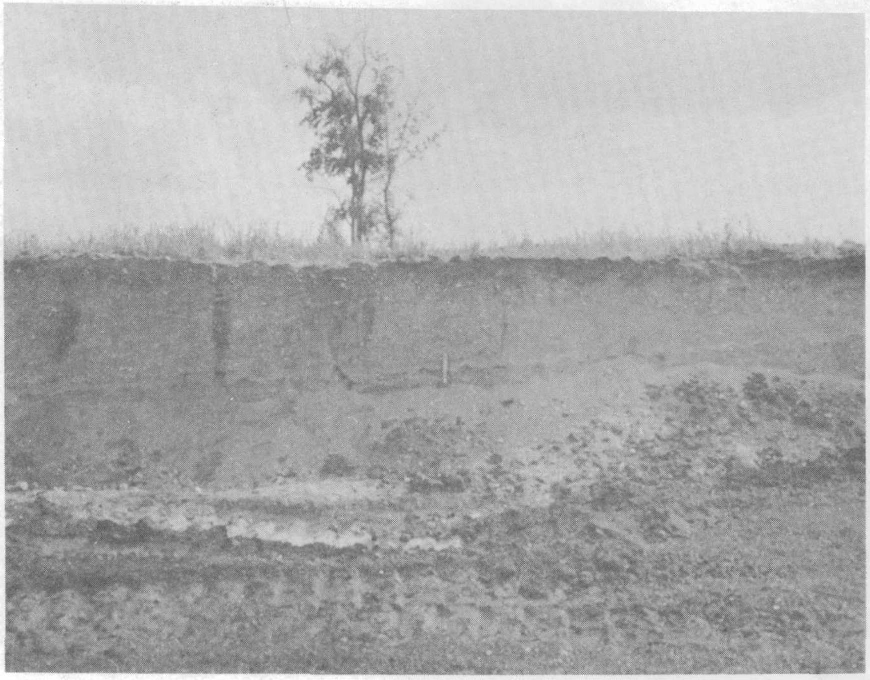
Aquifer	Lithologic characteristics	Thickness	Water-bearing characteristics	Transmissivity	Potential for future development
	Sand units within till				
1	Sand, fine, to gravel. Coarser in southern and eastern parts.	< 30'	Reported yields range from less than 10 gpm for farm wells to 300 gpm for municipal wells.	15,000 (estimated)	Good. Currently supplies water to most municipalities within its area.
2	Sand, medium, containing much coarse sand to fine gravel.	> 100'	No high-yield wells reported in area. Yields of several hundred gpm could be expected.	100,000 (estimated)	Excellent. Currently undeveloped.
3	Sand and gravel (detailed description not available).	--	Yields of several hundred gpm were obtained in the Moorhead area, but this pumpage exceeded recharge. Probably could yield up to 100 gpm on a sustained basis.	--	Fair. Aquifer was overpumped in the Moorhead area.
4	Sand, fine to medium, contains lenses of gravel in eastern half.	up to 100'	Yields of several hundred gpm could be expected, locally.	10,000 (calculated). Could be as high as 30,000 (estimated)	Good. Currently undeveloped.
5	Sand overlain by silt in eastern part. Silt in western part.	20'-50'	Yields of about 40 gpm reported. Yields up to 100 gpm could be expected, locally.	Up to 10,000 (estimated), locally	Fair. Currently undeveloped.
6	Sand and gravel containing silt layers. Sandier in northwestern part than in southeastern part where large amounts of clay occur in the aquifer.	40'-45'	Yields of about 40 gpm reported. Yields up to 100 gpm could be expected, locally.	Up to 10,000 (estimated), locally	Fair. Currently undeveloped.
7	Sand and gravel.	< 20'	Yields of about 40 gpm reported. Yields up to 100 gpm could be expected, locally.	Up to 10,000 (estimated), locally	Fair. Currently undeveloped.
8	Sand and gravel.	5'-30'	Yields of several hundred gpm are obtained at Roseau and can be expected at other places also.	25,000 (calculated)	Good. Relatively undeveloped.
9	Sand and gravel.	Up to 50'	Yields up to 60 gpm reported. Yields of 100 to 150 gpm could be expected, locally.	Up to 20,000 (estimated), locally	Good. Currently undeveloped.
10	Sand and gravel.	Up to 50'	Yields up to 60 gpm reported. Yields of 100 to 150 gpm could be expected, locally.	Up to 20,000 (estimated), locally	Good. Currently undeveloped.
	Ice-contact deposits				
I-C	Sand and gravel. Predominantly medium sand to medium gravel, stratified, well sorted (see fig. 16). Commonly contains layers of till, clay and silt. Grades laterally into sandy till along much of its boundary.	Largely 50'-100'	Yields greater than 500 gpm have been reported. Yields greater than 1000 gpm could be expected locally.	50,000-100,000 (estimated)	Excellent. Relatively undeveloped.
	Outwash deposits				
O	Sand and gravel. Predominantly fine to medium sand containing much coarse sand to medium gravel, well sorted. Lenses of silt occur locally. Boundary is indefinite along much of west and south edges where it grades into ice-contact sand and gravel.	Largely 20'-80', > 100' locally	Yields from irrigation wells generally range from 300-800 gpm. Yields greater than 1000 gpm could be expected locally. For a more detailed appraisal of aquifer see Reeder (1970).	20,000-80,000. Up to 200,000, locally, south of Rush Lake and west of Little Pine Lake.	Excellent. Use for irrigation supplies is increasing rapidly.
	Beach Ridge deposits				
BR	Sand, fine to coarse, including lenses of fine to medium gravel, well sorted (see fig. 17). The area outlined shows the beach ridge zone. Individual ridges within the zone range from less than one to tens of miles in length and in width from a few hundred feet to more than a mile where several occur close together.	Only a few feet at edges to 30'-35' at thickest part.	Yields range from about 5 to 20 gpm. Yields of not more than 30 gpm could be expected. The smaller beach ridges do not yield dependable supplies to wells. The aquifers are under water-table conditions and (about) only their lower half is saturated.	5000-15,000 (estimated) in the thickest saturated sections	Fair. Relatively undeveloped.
	Buried linear deposits in Lake Agassiz sediments				
A	Sand and gravel, contains many interbeds of silt and clay. Lateral and vertical variations in grain size are great. Coarsest sediments are in the Halma-Lake Bronson area (described in Schiner, 1963) and in the central axial part of the aquifer elsewhere. Configuration of deposit is shown on figure 18.	20'-100', 150' locally	Yields greater than 1000 gpm have been obtained south of Lake Bronson. Yields of several hundred gpm could be obtained in the better parts of the aquifer in other areas.	50,000-90,000 (calculated) in Halma-Lake Bronson area. Less than 50,000 elsewhere.	Excellent. Relatively undeveloped.
B	Sand, fine to medium containing coarse sand locally in central axial part, grades to very fine sand and silt toward lateral boundaries.	> 100' in thickest parts	No large yield wells in aquifer. Could yield several hundred gpm to wells in best parts of aquifer.	Up to 20,000 locally (estimated)	Excellent. Undeveloped.
C	Sand, fine, to gravel. East part of aquifer consists of medium to coarse sand and occurs in the axial and lower part. Sand grades to very fine sand, silt, and clay toward lateral boundaries. Much of deposit overlain by several feet of lacustrine clay. (See fig. 19).	> 100' in thickest parts	Yields of 350 gpm reported. Could probably yield this amount in axial part throughout much of its length.	300,000 (calculated near Dilworth. Probably less than 100,000 in other parts.	Excellent. Relatively undeveloped. Currently serves as supplemental source for Moorhead.
D	Sand, fine to coarse, contains much gravel near Argyle. Central axial part of aquifer contains coarsest sand. Deposit described in greater detail by Maclay and Schiner (1962). Much of deposit overlain by several feet of lacustrine clay.	70' in thickest part	Yields less than 50 gpm could be developed except near Argyle where greater yields could be developed.	6,000 to 8,000 (calculated) near Stephen, to 10,000 (estimated) near Argyle.	Fair. Currently developed for Argyle supply.

A

B

Figure 16.--The stratified (photo A) and coarse-grained material (photo B) typical of ice-contact deposits is clearly shown in a gravel pit south of Perham.

A



B

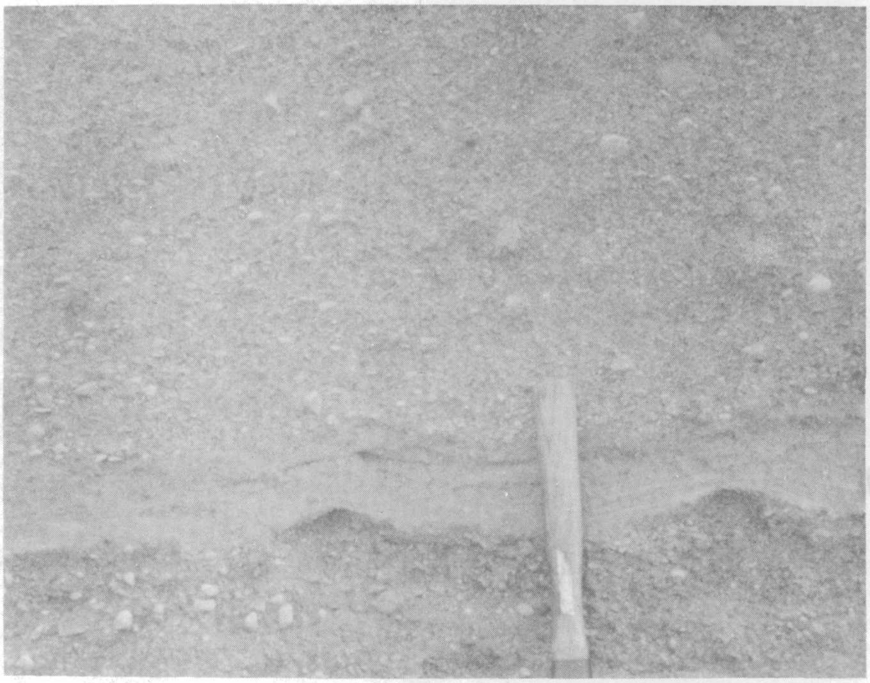


Figure 17.--The stratification (photo A) and grain size (photo B) are typical of beach ridge deposits. Photos taken in a gravel pit near Gonvick.

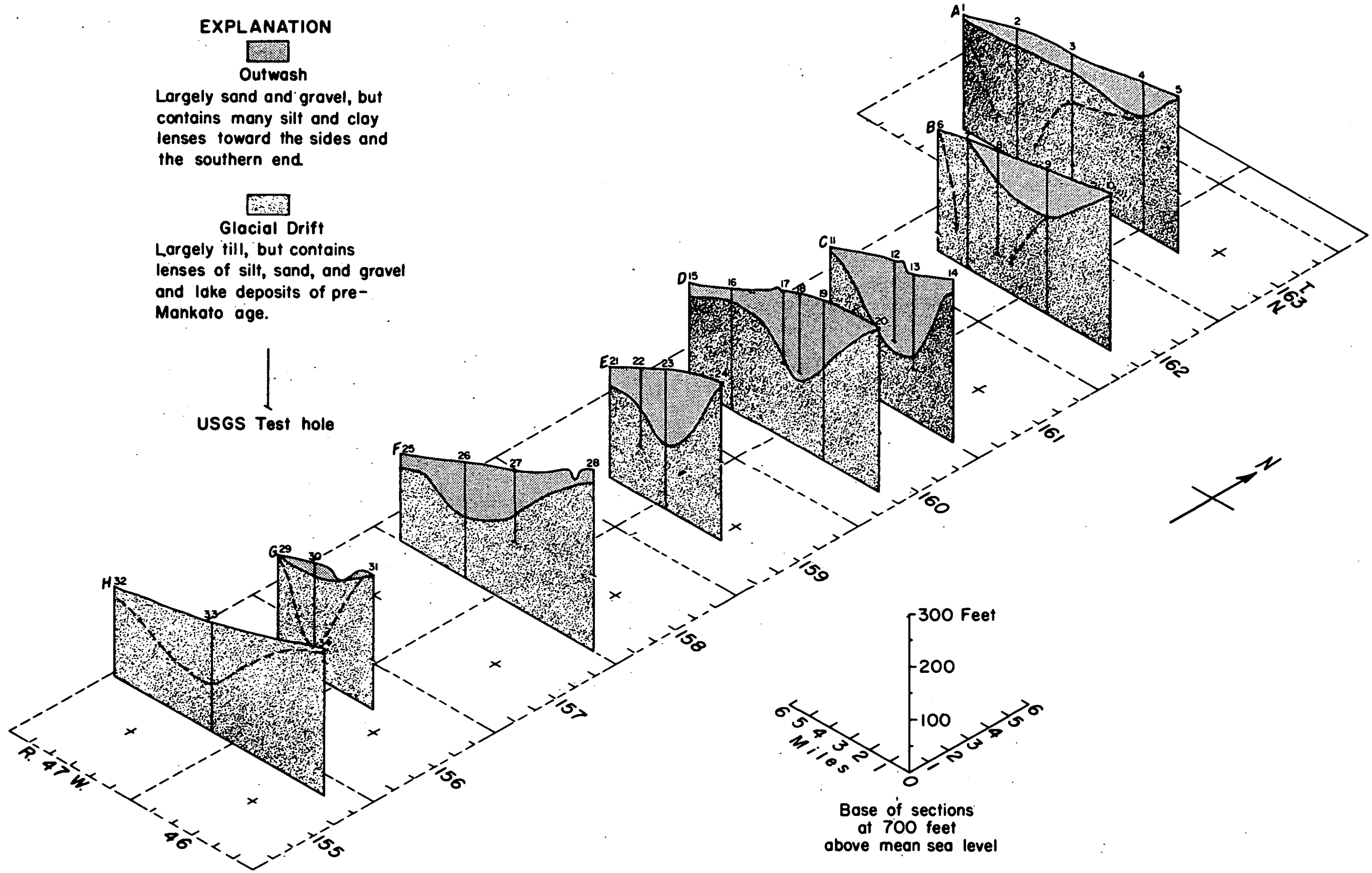


Figure 18.--Unit A, a linear sand and gravel deposit within Lake Agassiz sediments, extends from near the Canadian border southward into the central part of Marshall County. The thickest sections of outwash, which also contain the coarsest sand and gravel, occur in the Halma-Lake Bronson area (sections C and D). The dashed line on several sections shows an alternate shape the outwash deposits could be if certain thin sections of till are considered part of the outwash deposits.

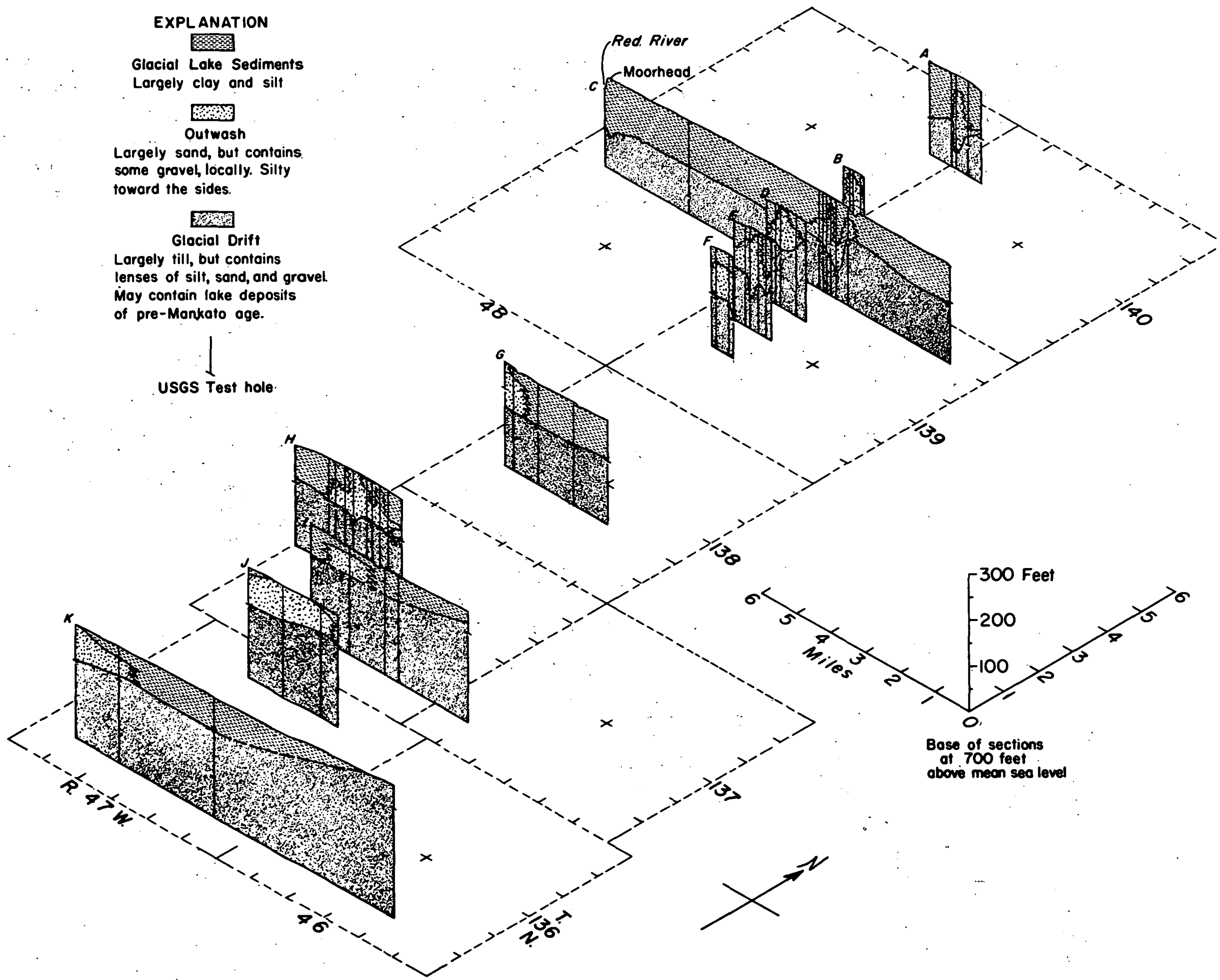


Figure 19.--Unit C, a linear sand and gravel deposit within Lake Agassiz sediments, is a narrow ridge of sand generally less than a mile wide and over 30 miles long. The sand contains much gravel in the area east of Moorhead (T.139 N.).

steep slopes in their uppermost reaches, particularly in the morainal area, before they enter lakes and wetlands. The lower reaches commonly are short channels connecting the lakes and swamps--sometimes rushing quite rapidly to the next lake and other times winding slowly through marshy wetlands.

Ditches are a special type of minor stream. They are most common in the western part of the morainal area and in the area of Glacial Lake Agassiz, where, according to Hochbaum (1967) "Now there is no region in the world where agricultural drainage is so intensive as within the prairie watershed of Glacial Lake Agassiz." In the morainal area ditches were dug mainly to drain small depressions and prairie potholes, which are small lakes that hold water all or part of the year, and generally are ringed by a marshy border. Pothole drainage probably reaches a maximum in Minnesota in Mahnomen County, where about 50 percent, or possibly more, of the potholes have been drained (Hochbaum, 1967). The ditches themselves are usually shallow and have moderately sloping banks. In most cases the channel slopes are quite flat, but, occasionally a ditch is seen that has a steep channel slope, and the channel is actually being eroded.

In the lake plain and lake-washed till plain the need for ditching was recognized by the first settlers to the area. Particularly in the region near the Red River, broad shallow lakes were formed in wet years along many of the tributary streams. Flooding was extremely common in the vast, flat retion and the water would stand for long periods of time. The extremely dense network of ditches was established to make this fertile area suitable for farming. The ditches range in size from the very broad, shallow, grass-lined ditches, which are found in nearly every field, to the large Judicial ditches which extend for many miles. The main arteries formed by the Judicial ditches (ditches established by district courts) could almost be considered major tributaries in some cases. Many are up to 10 feet deep with well defined banks and channels. Some are choked with vegetation and are relatively ineffective. The ditches in the vast peatlands in the lake-washed till plain often were dug without regard to the subtle watershed divides in this area and are essentially useless. Where the ditches cross the area of steep land slopes at the eastern edge of the lake plain active erosion of the channel occurs.

Major tributaries

Tributaries that head in the morainal area commonly flow from lake to lake in their uppermost reaches. The channel sizes in the reaches throughout the morainal area vary considerably. They commonly change quite abruptly from shallow

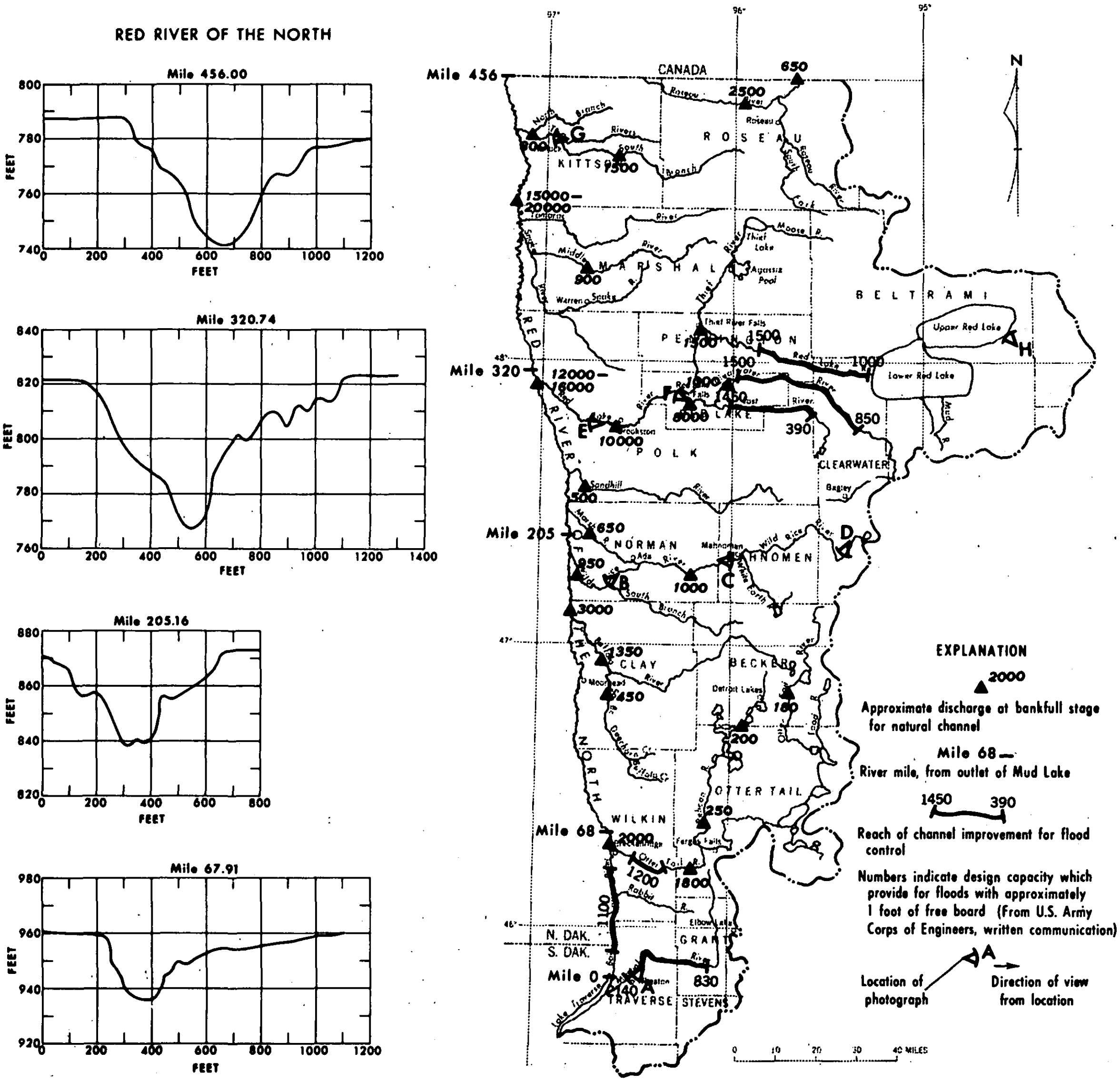
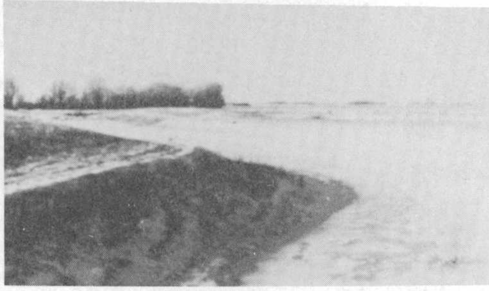
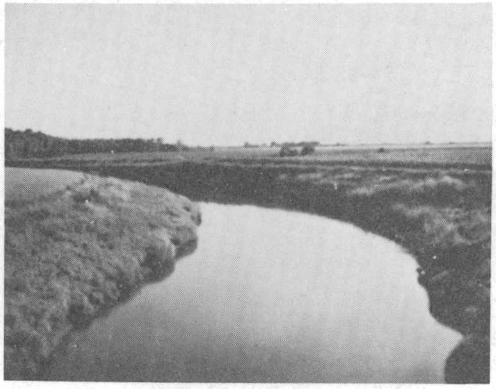


Figure 20.--Channel characteristics of the Red River and major tributaries vary considerably as the streams traverse the area from the morainal uplands to the flat lake plain. A) Mustinka River near Wheaton; G) Two Rivers near Hallock; D) Wild Rice River near headwaters in moraine (near Zerkel); C) Wild Rice River near edge of morainal area (near Twin Valley); B) Wild Rice River in lake plain (near Ada); H) Shotley Brook near Upper Red Lake; F) Clearwater River at Red Lake Falls; E) Red Lake River near Crookston.



A



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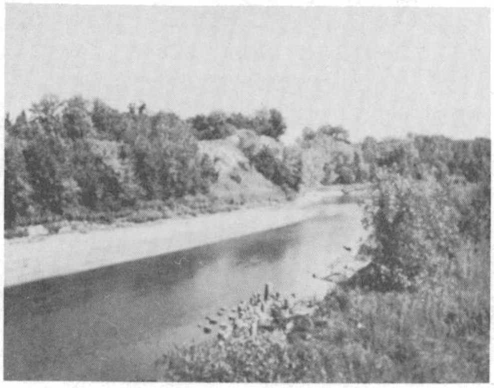

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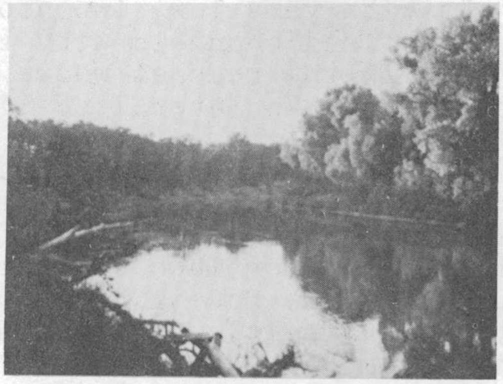

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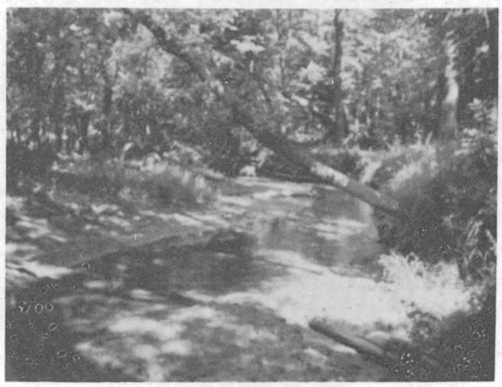


H

channels with very low, inconspicuous banks in the swampy areas to well-defined channels with low to high banks in the other reaches. In the reaches where the streams are contained by conspicuous banks lateral cutting is common.

The streams that head in and flow across the lake-washed till plain generally are contained by low banks. Some of these streams have had man-made modifications, principally channel straightening, for much of their length (see fig. 20). The exception is the Roseau River which has surprisingly well-developed channels upstream from Roseau where it decends quite sharply from Beltrami Island.

Where streams cross the eastern edge of the lake plain they flow in well-defined channels, and are actively eroding. Striking examples of well-defined channels are along the Red Lake River and Clearwater River near Red Lake Falls, where they are bound by banks about 100 feet high (fig. 20F).

In the lake plain nearly all the tributaries flow within well-developed channels with low banks. Although slumping banks and other evidences of erosion are seen, in general, the tributary streams are not severely eroding in this area. As is typical of streams flowing in areas of low slope, nearly all of these tend to meander. Many of the streams have had some type of land modification by man along part of their reach in the lake plain. The photographs keyed to the map in figure 20 show the changing character of selected streams in the Red River basin.

Longitudinal profiles of the Red Lake River (fig. 21) and the Wild Rice River (fig. 22) were constructed to compare a major stream heading in the lake-washed till plain with one heading in the moraine. The profile of Red Lake River shows the flatness of the lake-washed till plain separated from the flatness of the lake plain by a steep slope between mile 90 and 100, near Red Lake Falls. The profile for the Wild Rice River shows the sharp drop in elevation where it traverses the end moraine in its upper reaches above Mahnomen. From Mahnomen to the edge of Glacial Lake Agassiz the river flows across ground moraine and the slope flattens considerably. The river then flows across the eastern edge of the lake plain--the beach ridge area--and the slope increases again to near Ada. Westward from Ada the river crosses the very flat central part of the lake plain. The length, slope, and other pertinent data on some of the major tributaries within the Red River basin are shown in table 1.

Channel capacities for selected points on the tributaries are shown on figure 20. These range from less than 200 cfs in

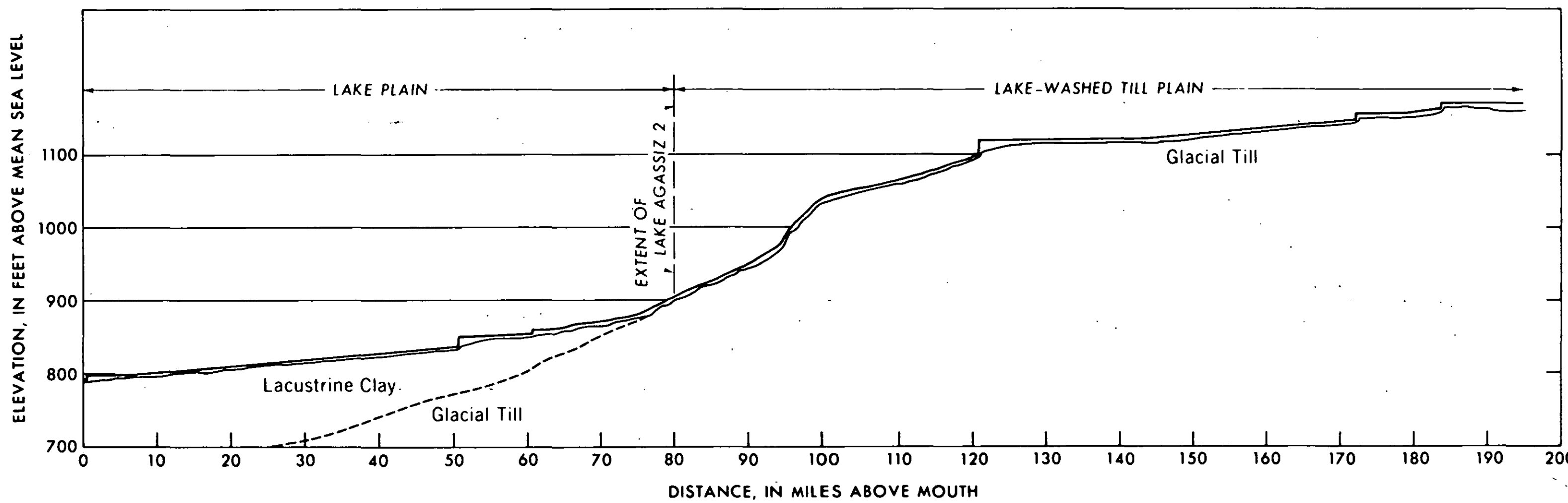


Figure 21.--The profile of the Red Lake River is characteristic of streams that traverse the lake-washed till plain and the lake plain. Note the sharp increase in slope where the lake plain and lake-washed till plain meet.

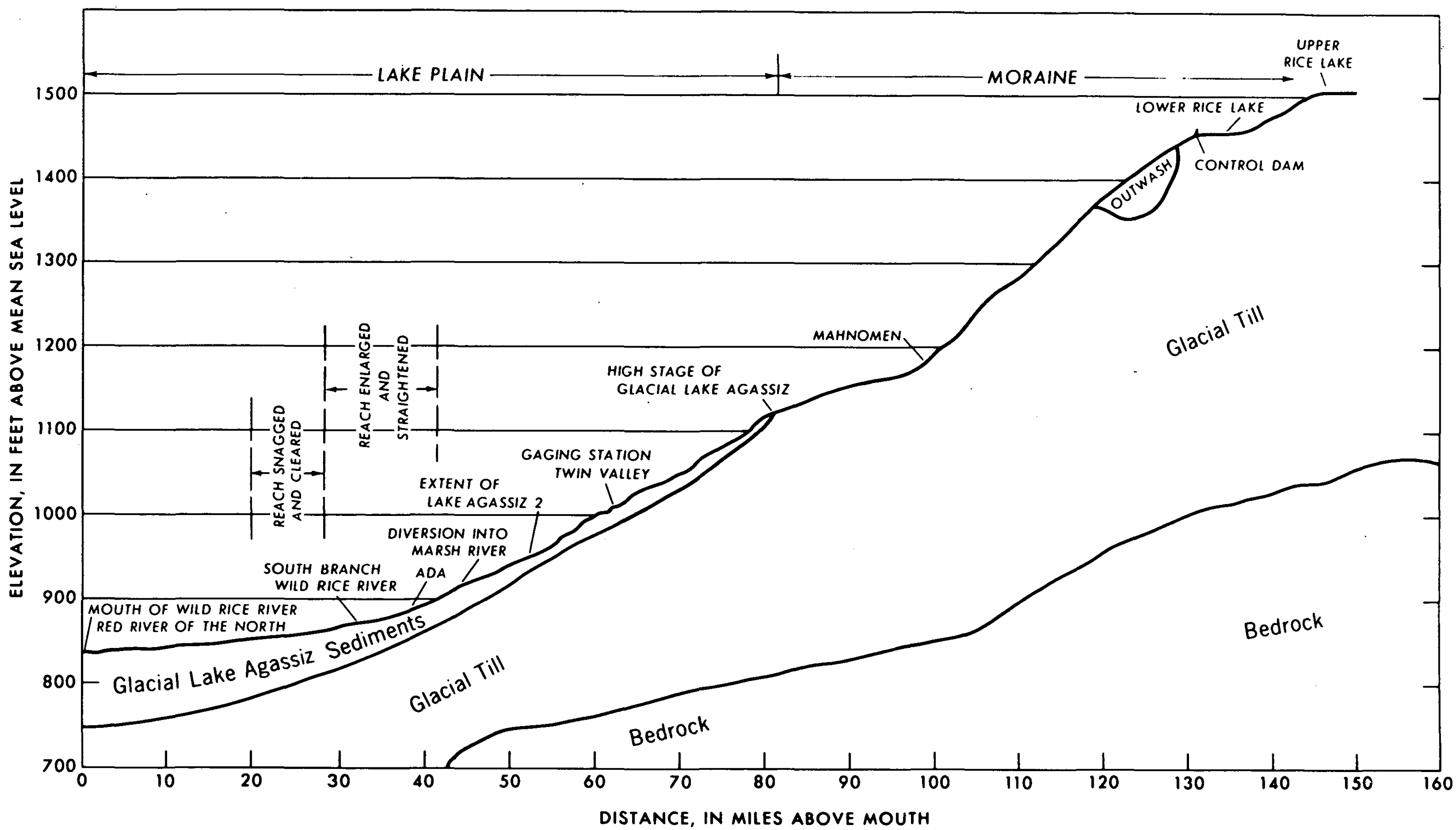


Figure 22.--The profile of the Wild Rice River is characteristic of streams that traverse the morainal area and lake plain.

Table 1.--Physical data on the major tributaries to the Red River of the North in Minnesota

River	Drainage Area (sq mi)	Approx. Length (mi)	Elev. at Source (ft above msl)	Elev. at Mouth (ft above msl)	Fall (ft)	Mean Slope (ft/mi)
Mustinka	869	68	1,135	976	159	2.34
Rabbit	321	26	1,060	955	105	4.04
Otter Tail	2,043	200	1,510	947	563	2.82
Buffalo	1,143	88	1,400	851	549	6.24
Wild Rice	1,653	193	1,500	832	768	3.46
Marsh	300	46	919	815	115	2.26
Sand Hill	480	104	1,300	804	496	4.77
Red Lake	5,711	196	1,174	794	380	1.94
Snake	760	60	1,085	769	316	5.27
Tamarac	365	47	1,050	766	284	6.04
Two	1,067	76	1,074	755	319	4.20
Roseau	2,060	180				
Red (headwaters to international boundary)	40,200	394	947	750	197	0.50

some streams in the morainal area to over 10,000 cfs in the lower reach of the Red Lake River. In most areas, capacities increase downstream, but in the Red River basin there are many exceptions, such as the Roseau River. At Ross, the Roseau River has a bankfull capacity of 2,500 cfs, but in the swamplands below this site the capacity decreases to about 700 cfs. In order to provide for flood flow, channel capacities have been increased on most of the rivers in the lake plain area. Generally, the modified channels are designed to have a capacity which will provide for flood flows having a 10-year recurrence interval with 1 foot of freeboard.

Red River of the North

The Red River of the North begins at the confluence of Otter Tail and Bois de Sioux Rivers near Breckenridge, Minn. The river flows in a natural channel throughout its entire length to the Canadian Border except for local leveeing at Breckenridge, Moorhead, and East Grand Forks. The very low slope and nearly homogeneous, fine-grained material across which the Red River flows cause it to be almost a classic example of a meandering river. The river flows about 395 miles from Breckenridge to Canada--a direct line distance of about 190 miles. Slumping banks, cutoff channels and scour and fill are evidence that the river is actively eroding its banks and modifying its channel throughout its length. Cross sections of the channel of the Red River of the North show the general deepening and widening of its channel between Breckenridge and the Canadian border (fig. 20). Bankfull capacity of the Red River ranges from about 2,000 cfs at Breckenridge to more than 20,000 cfs below its confluence with the Red Lake River.

Lakes and Wetlands

Distribution of lakes and wetlands in the Red River basin is related very closely to physiography. For example, lakes are very common in the morainal area but almost nonexistent in the Glacial Lake Agassiz region. The notable exceptions to this are the reservoir lakes such as the Upper and Lower Red Lakes, Lake Traverse, and Lake Bronson.

Potholes and wetlands are very abundant in the morainal area. Wetlands are also common in the low areas between beach ridges. The extremely large area of peat in the lake-washed till plain is a special type of wetland and is part of one of the most extensive peatlands in the United States.

Lakes

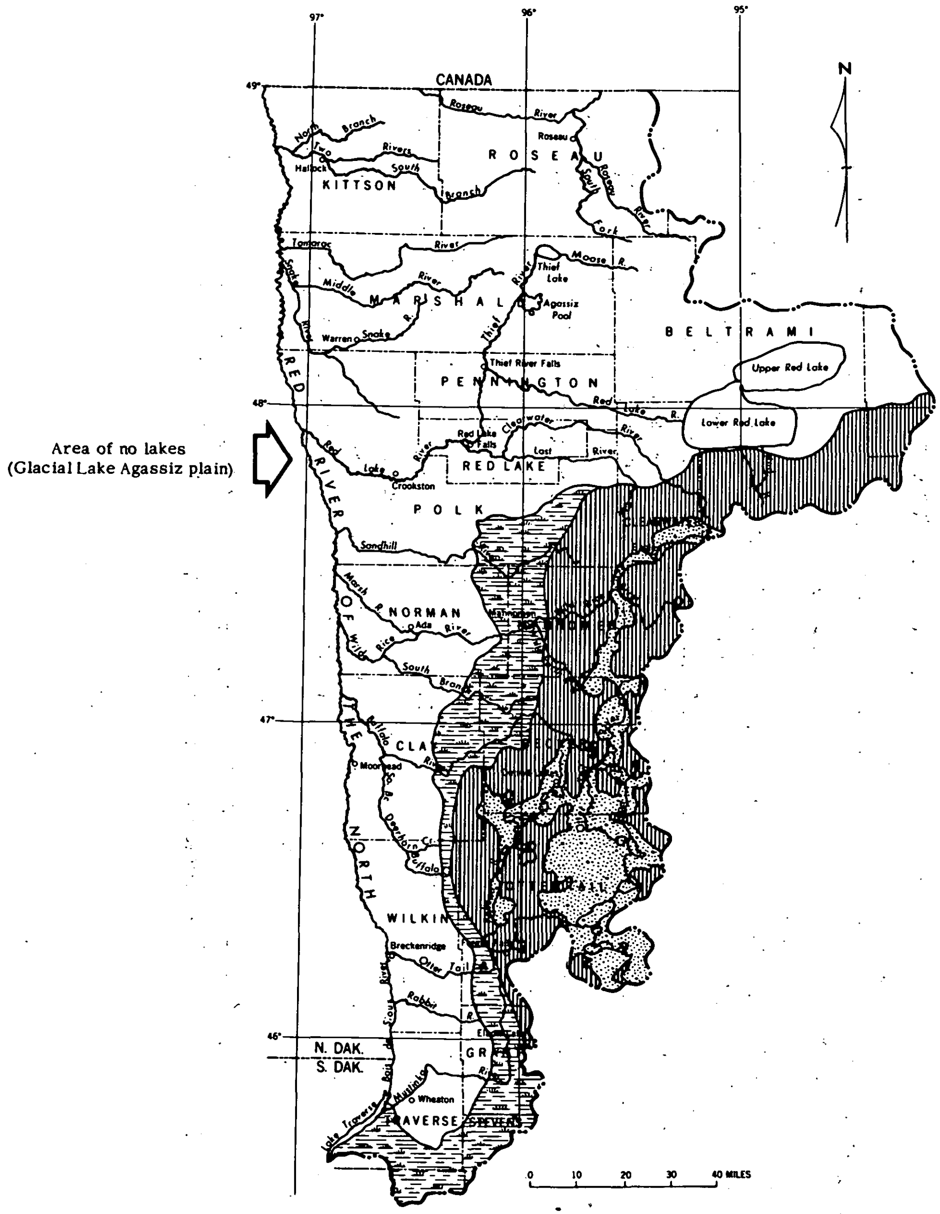
Upper and Lower Red Lakes, covering 288,800 acres, comprise the largest body of water lying entirely within Minnesota. Their stages are currently controlled at the outlet of Lower Red Lake, but even at the natural level the lakes covered nearly this area.

The morainal area of the Red River basin contains one of the largest concentrations of natural lakes in Minnesota. Throughout most of the morainal area the concentration is greater than 21 lakes per township. The lakes range in size from 10 acres--the smallest body of water included in the Department of Conservation's Inventory of Lakes--to 13,854 acres--Otter Tail Lake (Minnesota Department of Conservation, Division of Waters, Soils, and Minerals, 1968).

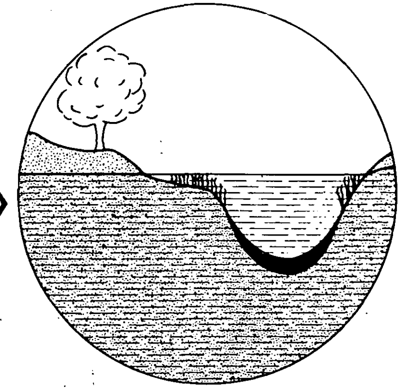
Shorelines of the lakes are highly variable even around individual lakes. They range from flat, swampy peatlands to wave-cut cliffs or sharp steep banks formed in glacial till, that have local relief up to 100 feet. Depths of lakes vary considerably depending upon local topography. Generally, the deeper lakes with the more rugged shorelines are in the most hummocky part of the morainal area. The smaller lakes in the western part of the morainal area, commonly referred to as potholes, are shallow lakes with gently sloping shorelines. These are often ringed by a zone of rooted aquatic plants and willow and boxelder trees. Wetlands in the morainal area have much the same hydrologic characteristics as lakes. The major difference between the two is that sediment accumulation in the wetlands has filled in the lake basin.

To bring some semblance of order to the widely varying factors affecting lakes it is necessary to classify them into natural groupings. Zumberge (1952) classified the lakes of Minnesota according to their geologic origin but did not attempt to delineate the areas of various lake types on a map. Moyle (1956) and Bright (1968) classified the lakes of Minnesota into very general categories based on water chemistry. These are very useful classifications but none are based on the total environment of the lakes. Because of the wide variations in each of the factors affecting lakes and the great amount of study needed on all of them, the ideal classification will probably take some time to develop. Of the major factors such as climate, geology, topography, and drainage area, for a general classification for hydrologic purposes, geology and topography are of primary importance.

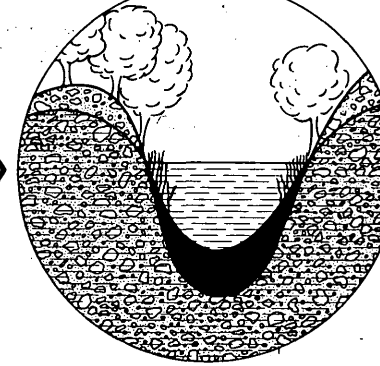
The lakes in the morainal area are grouped into three basic types (fig. 23): 1) Lakes in the very hummocky morainal area



Area of lakes in glacial ice-contact or outwash areas underlain by sand and gravel - lakes are usually quite deep, but have a lesser amount of sediment on the bottom than the lakes underlain by till. Productivity is high, but not as high as in lakes underlain by till and aquatic plants are usually less abundant. The water table in the land surrounding the lake is usually fairly flat because of the high transmissibility of the sand and gravel. Lakes in this setting are usually clear and have a good interconnection with the ground-water system.



Area of lakes in very hilly, glacial moraine underlain by glacial till - lakes are usually deep and have a thick accumulation of sediment on the bottom. Productivity (the total living organisms) in this type of lake is high and aquatic plants are usually abundant. The water table gradient is generally quite steep in the hills surrounding the lake because of the tightness of the till. This causes high potential but slow ground-water movement to the lake and is the reason for the occurrence of many springs surrounding these lakes.



Area of lakes in gently rolling glacial moraine underlain by glacial till (prairie potholes) - lakes and marshes are usually shallow and have a relatively large accumulation of sediment on the bottom. Productivity is extremely high and aquatic plants usually cover the entire lake area. The water table gradient in the surrounding land is not steep and at certain times of the year might actually be lower away from the lake than in the lake, indicating potential recharge to the ground-water system. However, the impermeability of the bottom sediments probably allows only a small amount of water to move into or out of the ground water system.

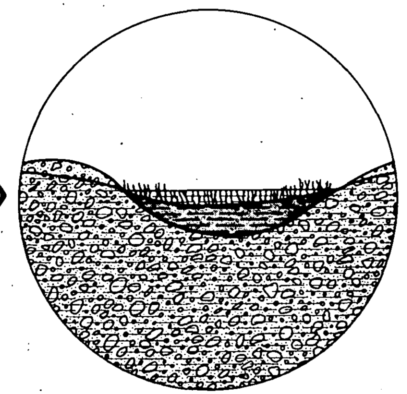


Figure 23.--Lakes in the Red River basin are classified according to their geologic and topographic setting into 3 types.

underlain by till. This lake type is characterized by highly variable slopes of the bottom and surrounding hillsides that range up to several tens of feet in local relief. They are generally the deeper lakes and sediment accumulation can be tens of feet thick. 2) Lakes in areas of outwash and ice-contact deposits underlain by sand and gravel. This type is also characterized by highly variable shoreline relief and deep water in the ice-contact areas, but fairly low shoreline relief and shallow water in the outwash areas. Sediment accumulation generally is less in these lakes than in the other two types. 3) Lakes in the gently rolling glacial moraine underlain by till. This type of lake is usually shallow with low sloping shorelines. Sediment accumulation is relatively rapid and many have aquatic plants growing over the entire bottom.

Wetlands

This section of the report is concerned only with the wetlands in the basin of Glacial Lake Agassiz (wetlands in the morainal area were discussed in the section on lakes). The wetlands in the areas between beach ridges are fairly continuous but do not cover a large area. In general, they are fed by seepage from the precipitation that infiltrates into the sandy beach ridges. Peat accumulation is not great, probably no more than a few feet.

The wetlands in the lake-washed till plain are a part of a vast peatland that covers much of north-central Minnesota. Peat accumulation is more than 10 feet thick in places. Much of the peat is nearly completely saturated, but attempts to drain the entire wetland beginning in the 1920's has met with little success. The ditches, dug at mile intervals across most of the area, crossed watershed divides and little water actually drained from the area. Vegetation patterns that occur in this area (see Heinselman, 1963), which are probably related to natural water movement in the peat, were essentially unaffected by the ditches. Much of the land along the margins of the wetland that was drained for farming has since been abandoned and is reverting to wetland.

WATER RESOURCE MANAGEMENT

As clean water becomes increasingly important to people and their activities, management of the water in the best interest of all becomes essential. It is important not only to solve the present water problems wisely, but to anticipate what the future holds. A seemingly adequate solution might be very temporary in duration and might actually aggravate a future problem.

In the past water management in the region has been largely for flooding, drainage, and water supply. The Garrison diversion unit is planned to divert 8,850 cfs (cubic feet per second) from the Missouri River drainage at Garrison Reservoir to the Red River, the Souris and the James River drainages for irrigation and municipal-industrial uses. Also included as part of the Garrison diversion plan are measures for flood control, drainage of non-irrigable lands, and pollution abatement. Much of the water management prior to 1967 has included major flood-control projects, local flood protection projects, watershed protection projects, fish and wildlife developments, land drainage, and some irrigation. A considerable number of man-made reservoirs, large and small, have been constructed particularly in North Dakota. The largest of these is Lake Ashtabula on the Sheyenne River, which holds about 69,000 acre-feet of usable storage.

In the Red River basin many water problems currently exist (fig. 24). It is a region of water scarcity in some places and overabundance in others. Some of the water is very pure and some is unusable for many purposes. Some areas flood annually and other rarely flood. The principal concerns of the people in the Red River basin regarding water are water supply, floods, pollution, drainage, and recreation.

Water Supply

Sources of Water for Supplies

Primary considerations in the management of water supply are: 1) Location and amount of the supply. 2) Accessibility--can it be brought to the user? 3) Dependability--can the supply be relied on for a long period of time and under adverse climatic conditions? 4) Quality--is the natural quality of the water suitable for the intended use? Table 2 shows the advantages and disadvantages of ground water and surface water in regard to the four considerations above.

In the following section of this report location, amount, and dependability of water sources and the natural quality of the water is discussed. Accessibility is not treated in detail because this depends largely on the location of the intended user and engineering aspects of carrying water.

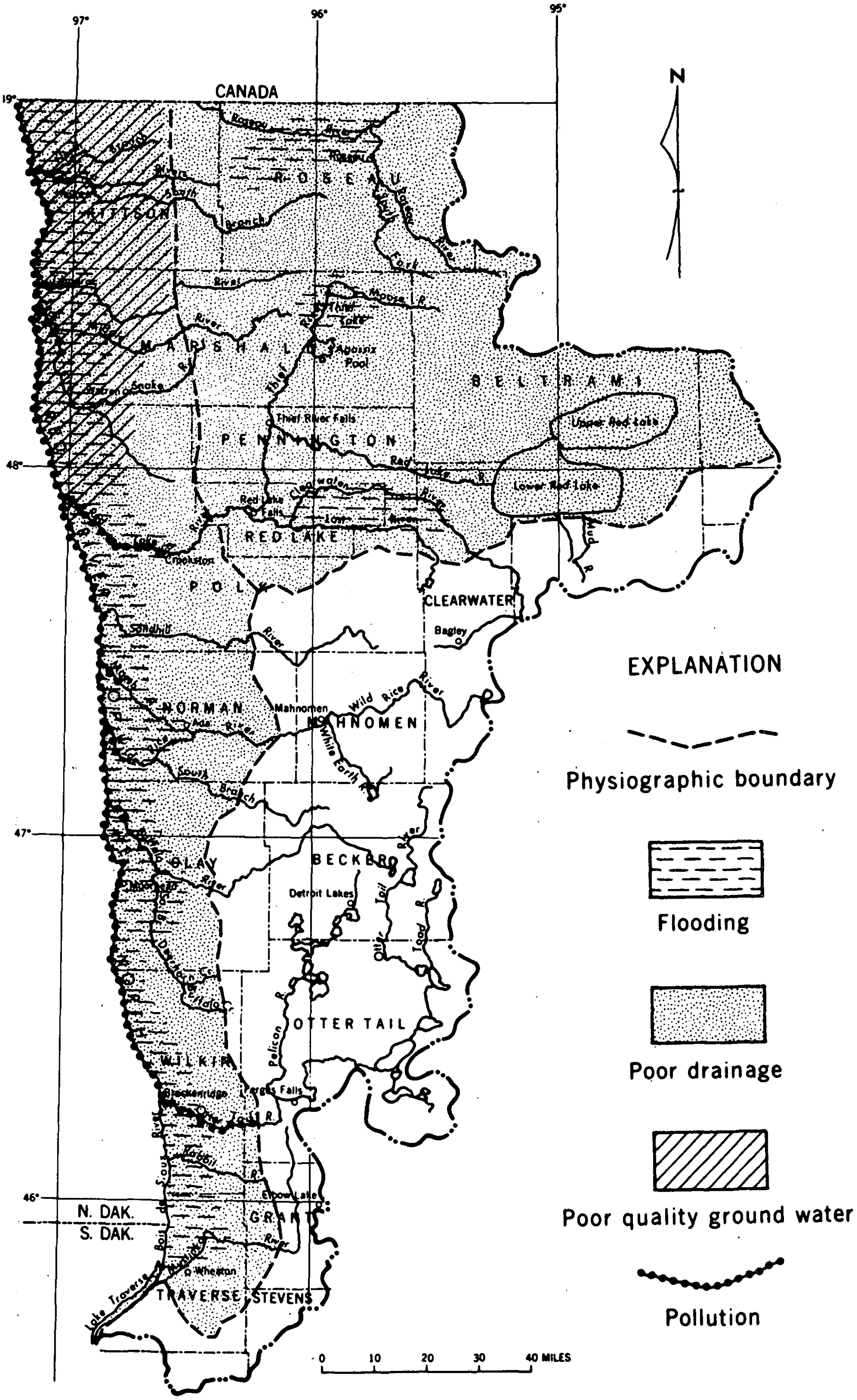


Figure 24.--Most major water problems occur in the lake plain and lake-washed till plain.

Table 2.--Advantages and disadvantages of ground water and surface water as sources of water supply

	SURFACE WATER	GROUND WATER
Location and amount	Surface water is easily located.	Ground water can be easily located where surficial deposits indicate a good possibility of being water-bearing.
	Amount of surface water is not large in some areas, even with storage.	In most places exploration by test drilling or other methods is usually necessary to locate sources capable of supplying high-yield wells. This is true even for surficial aquifers. Locally, even obtaining a small supply is sometimes difficult.
Accessibility	Surface water is readily accessible to riparian land owners.	With or without exploration, ground water is generally accessible to most people regardless of where they live.
	For the large number of people not living along streams and lakes, surface water is generally not available. Even if they had the right to take water, the cost of physically transporting water is an important economic factor.	Locally, an aquifer capable of supplying high-yield wells may not be in the immediate vicinity and a municipality may have to go several miles to obtain a supply.

Dependability	Because streamflow can be observed and measured it is possible to calculate the amount of water that will probably be available for any length of time. Data is already available at some locations on many of the streams.	Ground-water sources are usually very dependable. If discharge does not exceed natural recharge they can normally be used for long periods of time including during extended droughts.
	Streamflow is highly variable in most streams in the basin. Dependable water supplies of almost any size require storage reservoirs.	Determining the safe yield of an aquifer is difficult and cannot be done with the same precision and accuracy as for a surface-water source. Ordinarily the data is not available and it is costly to obtain. Shallow surficial aquifers are generally not dependable during drought years.
Quality	Surface water is generally low in total dissolved solids and is fairly uniform over the entire Red River basin.	Ground water is generally of good quality for most uses. The quality varies over the basin but generally does not vary at any location with time. Temperature is very constant throughout the year and color and organic pollution generally is not a problem.
	Treatment is generally necessary to remove suspended sediments and organic matter that is hazardous to health. Temperature and color varies widely over the year at any location along the river.	Certain chemical constituents such as hardness and iron are high in many places and treatment is usually necessary. In some areas, such as the northwestern corner of the basin, ground water is unacceptable for domestic consumption.

Surface water

Approximately $0.7x10^6$ million gallons of water per year are available for management from streams or from aquifers within the watershed assuming no reuse of water. The availability of surface water as streamflow throughout the Red River of the North basin is shown on figure 25. The diagram shows the theoretical maximum quantity of streamflow that could be developed for a water supply. Since storage of high flows would be required to approach complete utilization of the average flow, consideration must be given to storage and transmission losses and evaporation. The significant variations in average streamflow are related to the differences in land characteristics such as the geology and topography and variation in the regional precipitation pattern.

Variations in basin characteristics are complex within the Red River of the North basin in Minnesota because of the contrasting physiography in the moraine, lake plain, and lake-washed till plain. In the morainal area streams generally yield a higher average flow per square mile than those in the lake plain. The Otter Tail, Wild Rice, and Red Lake Rivers, all of which head in the morainal area, have the largest average annual flow although many smaller streams within the moraine have equally as large yields per square mile. Examples of streams having low yields (basins are mostly within the lake plain) are the Mustinka, South Branch Buffalo, Middle River, and Two Rivers. Streams within the lake-washed till plain generally have greater yield than those in the lake plain but less than the streams in the moraine. The exception to this is the Roseau River which has a yield comparable to those streams in the morainal area. The high yield is probably caused by the presence of two large sandy areas that lie partially within its watershed. The integrated effect on the areal variability is the average flow in the Red River of the North. The tributaries from Minnesota contribute heavily to the average flow of the Red River of the North and, interestingly, the Otter Tail and Red Lake Rivers contribute one-half the average flow to the main stem at Breckenridge and East Grand Forks, Minn., respectively, where each joins the Red River. The average annual flow from the tributaries in Minnesota is equivalent to 1.7 inches of water over the entire basin and is the residual from an average annual precipitation of 21 inches on the basin as a whole.

The annual mean discharge varies from year to year and is dependent upon the vagary of weather and the antecedent moisture conditions within the basin. The frequency characteristics of annual mean discharges at the 10-year recurrence interval for 26 selected sites in the basin are shown on figure 26.

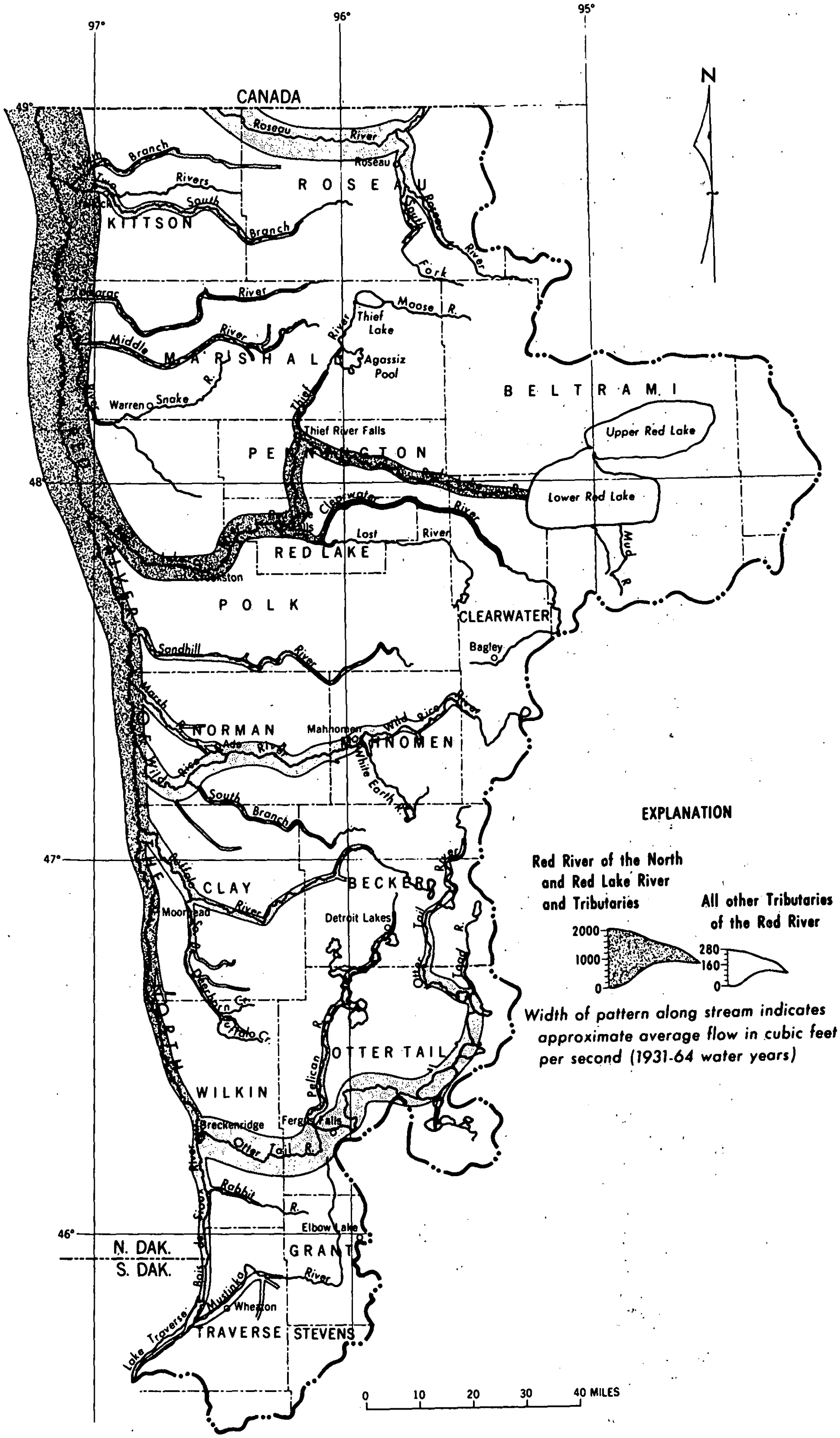


Figure 25.--The average flow is the theoretical maximum quantity of streamflow that could be developed for a water supply. Losses of water which would occur through seepage and evaporation while in storage and during transmission from reservoir to user must be considered.

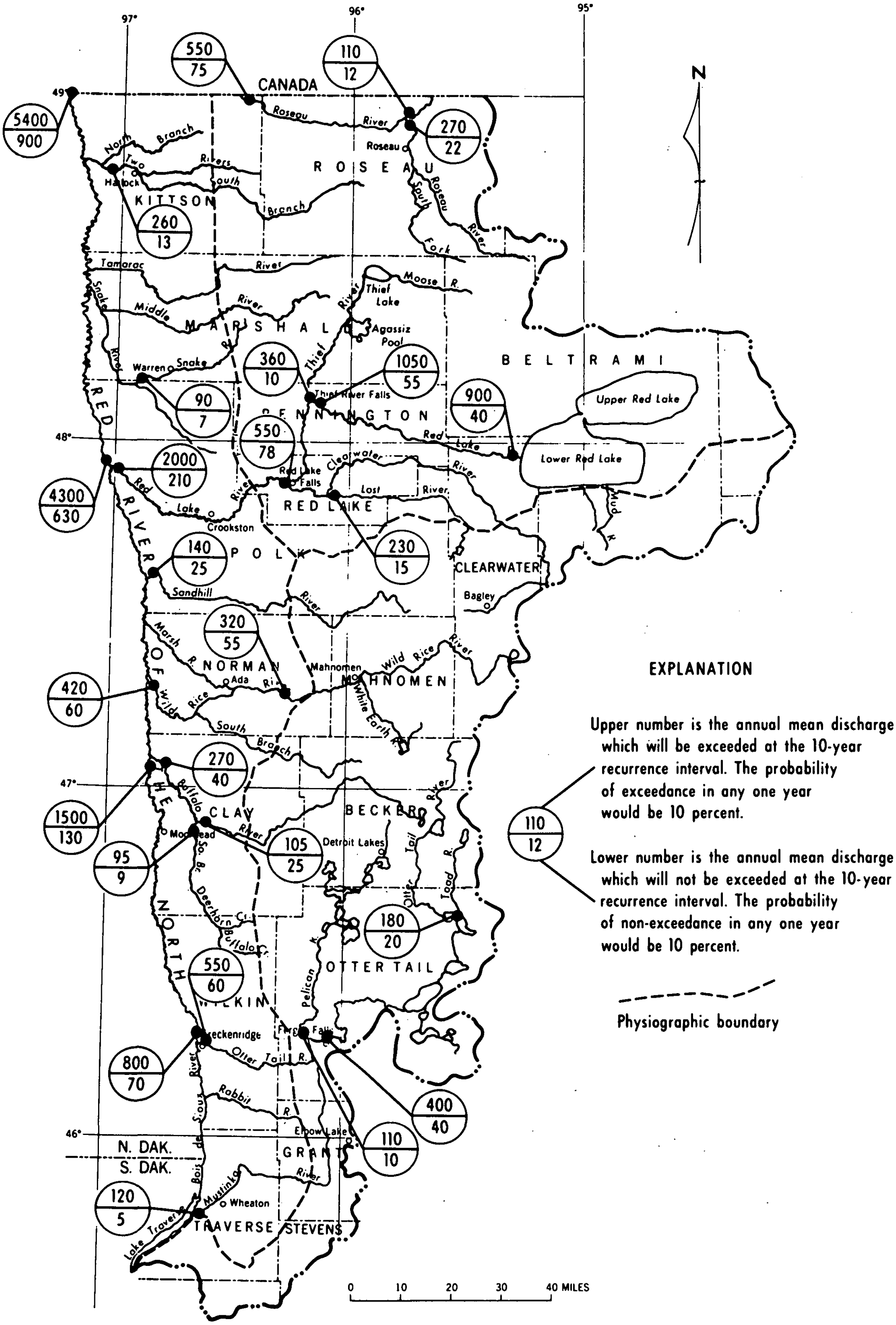


Figure 26.--Ten-year high and low annual mean discharge is shown for selected sites in the basin to facilitate regional comparison.

The annual mean discharge at the sites will be greater than the higher figure and less than the lower figure on an average of once in 10 years. The probability of exceedance of the higher figure or nonexceedance of the lower figure in any one year would be 10 percent.

A knowledge of the probability of recurrence of extremes of annual mean discharge is useful in understanding the hydrology and characteristics of surface runoff of a basin. A preliminary analysis of streamflow might entail a consideration of the usefulness of a stream for a surface supply with or without storage. The suitability of such a supply and the acceptable cost-benefit ratio might be weighted against the 10-year low annual mean discharge. The ratio of the high to low 10-year annual mean discharge is an indication of the yearly variability of a stream and the figures on the map can be used for comparing one stream with another, and in delineating general areal surface water availability. A large ratio indicates areas which do not have a large yearly carryover or residual surface and ground-water storage.

The daily mean flow is subject to seasonal variations, and dependable supplies are governed by low flows in the late summer, fall, and winter when streams have receded to their minimum because of evapotranspirative demands and reduced ground-water inflow during the winter freezeup. The average low flows of streams within the Red River basin within Minnesota are shown on table 3. The table shows various low-flow parameters computed for 17 gaging stations. These sites have been selected because the data shown describes the low-flow characteristics of the major streams throughout the basin.

The 7-day average low flow, the low 10-year annual mean discharge, and the streamflow that is exceeded 90 percent of the time are of particular significance in hydrologic studies relating to water supply and waste disposal in streams. A more complete discussion of the mean 7-day low flow (that which occurs on the average once every 2 years) is found in the section on the hydrologic system. Streams in small drainage basins will have different low-flow characteristics than those shown in the table and many cease to flow nearly every year. Most streams receive little dry weather flow in the lake plain and the lake-washed till plain; but exceptions are streams receiving substantial discharge from springs in ground-water discharge areas, and those flowing through deposits of sand and gravel.

Since all streams in the Red River of the North basin are characterized by variability in discharge and if the anticipated demand is greater than the natural supply either an alternate supply must be provided, such as ground water, or

Table 3.--Low-flow data for streams in the Red River of the North basin in Minnesota

Map Key (fig. 29)	Gaging Station	Period of record (water years)	7-day average minimum discharge for indicated recurrence intervals		Low 10-year annual mean discharge (cfs)	Daily discharge at 90 percent flow duration (cfs)
			2-year (cfs)	10 year (cfs)		
1	Mustinka River above Wheaton	1916-17, 1919-24, 1931-58	0	0	5	no flow
2	Otter Tail River below Orwell Dam, near Fergus Falls	1931-64	68	8	50	23
3	Pelican River near Fergus Falls	1910-12, 1943-65	16	0	30 4*	7
4	Red River of the North at Fargo, N. Dak.	1902-65	74	9	92	105
5	Buffalo River near Dilworth	1932-65	8.5	.4	33	14
6	Wild Rice River at Twin Valley	1910-17, 1931-65	16	3.8	55	13
7	Wild Rice River at Hendrum	1945-65	15≠	3≠	60≠	20≠
8	Sandhill River at Climax	1944-65	6	3	23	8
9	Red Lake River at Crookston	1902-65	200	18	210	80
10	Clearwater River at Red Lake Falls	1910-17, 1935-65	35	12	78	33
11	Thief River near Thief River Falls	1910-17, 1921, 1923-24, 1929-65	0	0	9	no flow
12	Middle River at Argyle	1945, 1951-63	0	0	7	no flow
13	Red River of the North at Grand Forks, N. Dak.	1882-1961	400	88	630	195
14	Two Rivers below Hallock	1945-55	0	0	13	.3
15	Red River of the North at Emerson, Manitoba, Canada	1911-65	430	91	900	180
16	Roseau River at Ross	1929-61	6.5	1.5	56	8
17	Roseau River below South Fork near Malung	1947-65	1	.1	15	8

* Estimated for 1931-64.

≠ Adjusted for breakthrough (south of Ada) to Marsh River, 1948-52, and extended to period of record of gage at Twin Valley.

facilities developed for storing high flow for later release during droughts. The storage required to maintain specified rates of flow in six tributary basins of the Red River is shown in figure 27. All curves are based on low flow of 10-year recurrence interval or 1 year out of 10 on the average the storage will be deficient to maintain the specified draft rates. Draft storage relationships for other recurrence intervals are shown in the Hydrologic Atlas series except for the Mustinka and Middle River watersheds where low streamflow and scarcity of reservoir sites make draft storage analyses impractical.

Ground water

Most water that occurs in geologic materials beneath the surface of the earth is ground water. The upper surface of the ground-water system is the water table. Beneath this surface ground water completely fills all the available open space, or pore space, between the rock and mineral grains. The characteristics of rocks that describe the total pore space is termed porosity. Differences in hydraulic potentials within the ground-water system either natural or caused by man through pumping wells or ditching, etc. causes ground water to move within the ground-water system. The rate of water movement is controlled by the differences in hydraulic potential and the size and interconnection of pore spaces within the rocks. The interconnected pore spaces provide the avenues through which the water moves and is termed hydraulic conductivity (permeability). Hydraulic conductivity, K, is defined as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°F (Ferris and others, 1962, p. 72).

Geologic materials within the Red River basin, particularly the drift, contain a wide range of hydraulic conductivity which depends on grain size and sorting. Sorting is a characteristic of sediment that describes how uniform or clean it is. Well-sorted material has uniform grain size and, hence, uniform porosity which generally provides better hydraulic conductivity. In poorly sorted material, even though it might contain a large percentage of large particles, the pore spaces are filled in with finer particles and causes the overall hydraulic conductivity to be low. Glacial till is an example of this type of material. For this reason wells completed in till do not yield much water and are generally termed "dry holes" even though the till is completely saturated. A well must be completed in sand, sand and gravel, or gravel units, which are usually well-sorted and have a good hydraulic conductivity before adequate supplies of water are obtained. The

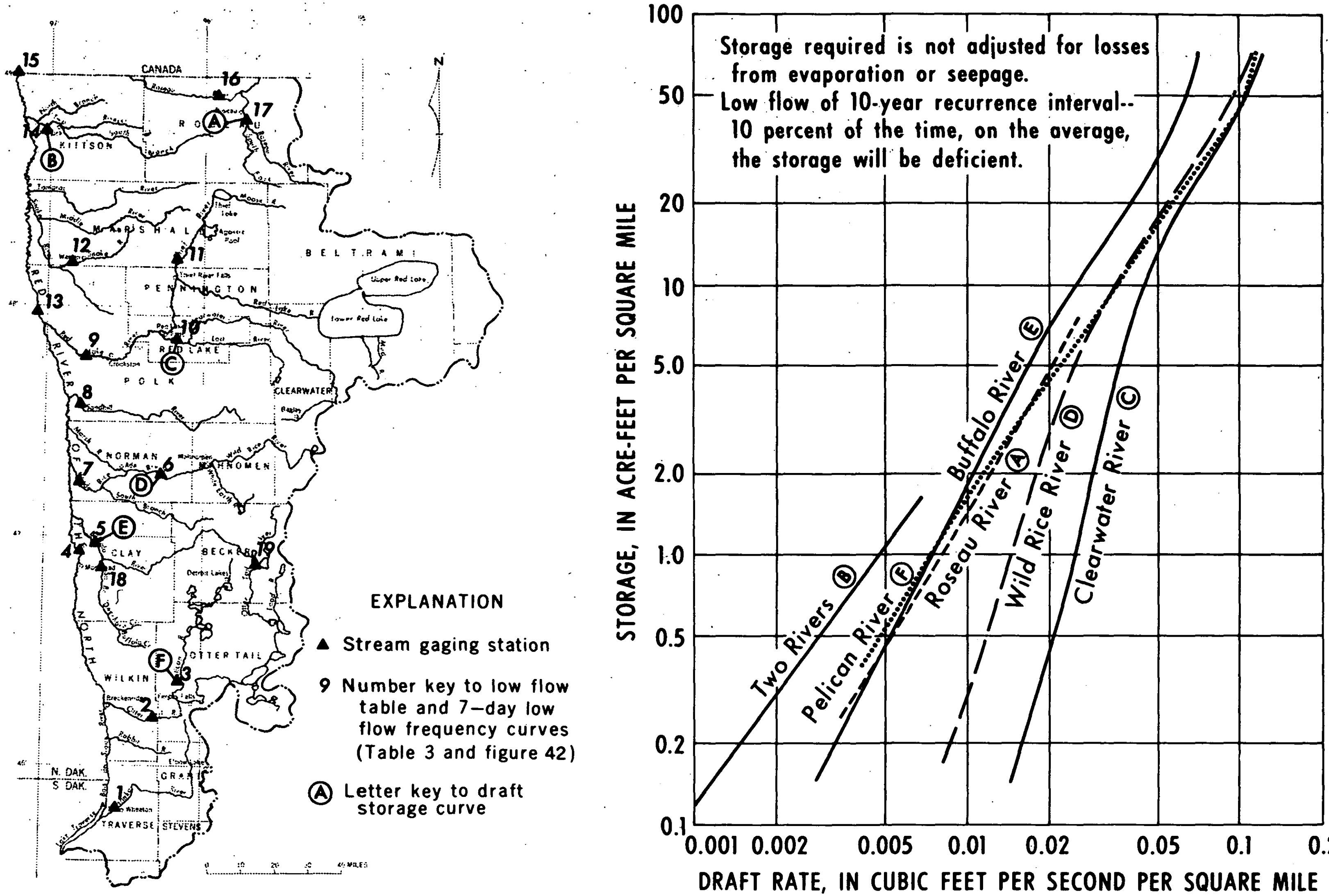


Figure 27.--Draft storage curves for selected rivers in the basin show that less storage is required to maintain a specified draft rate in streams in the morainal area than in the Glacial Lake Agassiz region.

term aquifer is applied to rock units that yield water readily in sufficient quantity that it can be considered a source of supply.

For most domestic and stock needs it is possible to encounter a sand and gravel unit that will yield enough water (about 10 gpm, or less) nearly everywhere in the Red River basin. These units can be almost any size and occur at any depth. Most well drillers will test or examine each sand unit as drilling progresses and usually will complete the well in the first adequate sand unit encountered. If a well eventually becomes inadequate often times it is necessary only to drill a little deeper to penetrate another sand unit which may satisfy the need. For this reason well depths have a very wide range in areas of glacial drift.

Where high yield wells are needed the problem of finding an adequate sand and gravel unit is generally much more difficult. Test drilling is generally necessary to locate sand and gravel units that will yield more than 50 gpm (gallons per minute) to individual wells. It is likely that supplies of this magnitude can be found in most townships if adequate test drilling is done.

In describing the aquifers it is necessary to know the meaning of several terms called aquifer constants; these are transmissivity and storage coefficient. Transmissivity is generally used in field practice as a means of expressing flow rates through the entire saturated thickness of the aquifer and is equal to the hydraulic conductivity multiplied by the saturated thickness. It is a regional spatial average and may not be representative of any particular section of material. Transmissivity, T, is defined as the rate of flow of water at the prevailing water temperature in gallons per day, through a vertical strip of the aquifer, 1 foot wide and extending the full saturated height of the aquifer, under a hydraulic gradient of 100 percent. Total storage within an aquifer varies as the water level fluctuates. The storage coefficient, S, of an aquifer is defined as the volume of water it releases from, or takes into, storage per unit surface area of the aquifer per unit change in component of head normal to that surface.

For all the aquifers described in this report in which high yield wells are completed an attempt was made to obtain pumping test information so the aquifer constants could be determined. Knowledge of aquifer constants is important because they are essential in calculating the potential development of the aquifer. Of primary importance in estimating ground-water potential is to determine the "safe yield," that is, the amount of water that can be removed on a sustained basis without seriously dewatering the aquifer.

Paleozoic sedimentary rocks

The sandstones and limestones that comprise the bulk of the Paleozoic rocks in the Red River basin are untested with respect to their water yielding capacity. Because of the highly saline water that occurs in these rocks the aquifers have never been used. Test holes that have penetrated the Paleozoic rocks have yielded flows up to 60 gpm under very great hydraulic pressure. Controlled pumping tests were never run on the rock units so aquifer constants are not known. The greatest potential of obtaining water is probably from the upper zone in the dolomitic limestone of the Red River Formation and the upper sandstone unit of the Winnipeg Formation. From the meager data available it appears that the Paleozoic rocks have great potential for yielding water if a need for saline water should develop.

Cretaceous sedimentary rocks

Water from Cretaceous aquifers is not widely used in the Red River basin. Most use is for farm supplies so pumping rates usually do not exceed 10 gpm. Cretaceous aquifers are tapped most commonly for large yields in the southern end of the basin where the Cretaceous sediments are relatively thick. The few large-yield wells that were constructed in this part of the basin were very difficult to develop and most attempts have failed. Pumping test, grain size, and thickness data are inadequate for determining hydraulic constants of the aquifer.

Recharge to the Cretaceous sand units is largely from leakage through confining shale beds. The very low vertical hydraulic conductivity of the shale is one of the most critical restrictions on water availability from Cretaceous sand units.

The potential for development of large municipal and industrial water supplies from Cretaceous aquifers is poor. Where the sand is more than 10 feet thick and widespread it might be possible to develop wells that yield up to 100 gpm, or slightly more. If the sand is only several feet thick, yields less than 50 gpm should be expected.

Quaternary glacial deposits

The drift is the most significant source of ground water in the Red River basin. The most important aquifers in the clacial drift include ice-contact sand and gravel, outwash sand and gravel, linear sand and gravel deposits in the subsurface of Glacial Lake Agassiz, and sand lenses in till.

The availability of ground water for development from these aquifers is discussed in figure 15. Other aquifers within the till undoubtedly also exist, but they are as yet undefined.

Quality of water

Chemical quality of some water in the Red River basin imposes serious limitations on its use. Described in this section of the report are the physical and chemical characteristics of water that have a significant effect on its use.

Physical properties of water of importance to most users are temperature, color, and sediment concentration. Generally, ground water is very uniform in temperature--roughly equivalent to the average annual air temperature, is colorless, and is free of sediment. Surface water varies widely in temperature throughout the year; from freezing in the winter to almost 90°F in summer on some of the smaller streams. Surface water can be highly colored in some areas, particularly in peatlands and in streams draining them. Sediment concentration varies considerably in streams both areally and with time. Sediment concentration and loads are not great in the forested areas of the Red River basin. Where farming is intense and in areas where active erosion occurs along stream valleys, sediment concentrations increase. Sediment concentration and load are generally much greater during high flows in spring and after thunderstorms than in other times of the year. Sediment concentration can also include suspended pollutants which are common in some reaches of the tributaries and in the Red River itself.

Chemical constituents and properties of water of importance to most users include total dissolved solids, hardness, chloride, sulfate, iron, fluoride, nitrate, boron, sodium, and pH. Chemical properties of surface water vary with time. In the spring of the year and after thunderstorms the concentration of dissolved chemical constituents in streams is low. At times of low flow, when water in streams is largely ground-water seepage, the quality strongly reflects the quality of water in the upper part of the ground-water system.

Wide variations in chemical characteristics of ground water, areally and with depth, are common particularly in the areas where the glacial drift is underlain by Cretaceous or Paleozoic sedimentary rocks. To illustrate the areal variations, maps showing lines of equal concentration of selected chemical constituents were drawn. Because of vertical variation in some areas, only water analyses from wells finished in the glacial drift that were between 50 and 200 feet in depth were used. This excludes shallow wells that draw water from the upper part of the ground-water system which are more likely to show effects of pollution, and it excludes the deeper wells that are in rocks beneath the glacial drift or in the part of the drift that may contain water that closely reflects the quality of water in the sedimentary rocks. In some areas, particularly in the northwestern part of the basin, even in the interval selected, the influence of water moving upward from the Paleozoic rocks is clearly seen. Vertical variation of water types is not discussed in detail because only the general water quality situation is of interest here. A detailed discussion of vertical variation of water quality is included in the section on hydrochemistry later in the report.

Total dissolved solids--The parameter reported as total dissolved solids (the residue after evaporation) consists primarily of the dissolved mineral constituents, but it also includes organic matter. Water containing less than 500 mg/l (milligrams per liter) of dissolved solids is considered generally adequate for domestic and many industrial purposes. However, in parts of the Red River basin, water of much higher concentration is used either as raw water or as treated water. Water with more than 1,000 mg/l dissolved solids is likely to be unsuitable for many purposes. The map of dissolved solids concentration within the Red River basin (fig. 28) shows a wide variation of dissolved solids from about 300 mg/l in the eastern part to more than 2,000 mg/l in the northwestern and southern parts. In most of the basin the concentration is between 300 and 600 mg/l.

Hardness--Hardness is a measure of the soap-consuming capacity of water. Soap is precipitated by metallic ions, principally calcium and magnesium. Among the industries requiring soft water are laundries, some food processing plants, and manufacturers of certain grades of paper. The hardness of ground water in the Red River basin ranges from less than 100 to more than 1,000 mg/l, but water in most of the basin is between 200 and 400 mg/l (fig. 29). Hardness standards generally recognized are as follows:

Hardness (mg/l)	Rating	Suitability
0-60	soft	Suitable for most uses without further softening
61-120	moderately hard	Usable except in some industrial applications
121-180	hard	Softening required by laundries and some other industries
181+	very hard	Requires softening for many uses

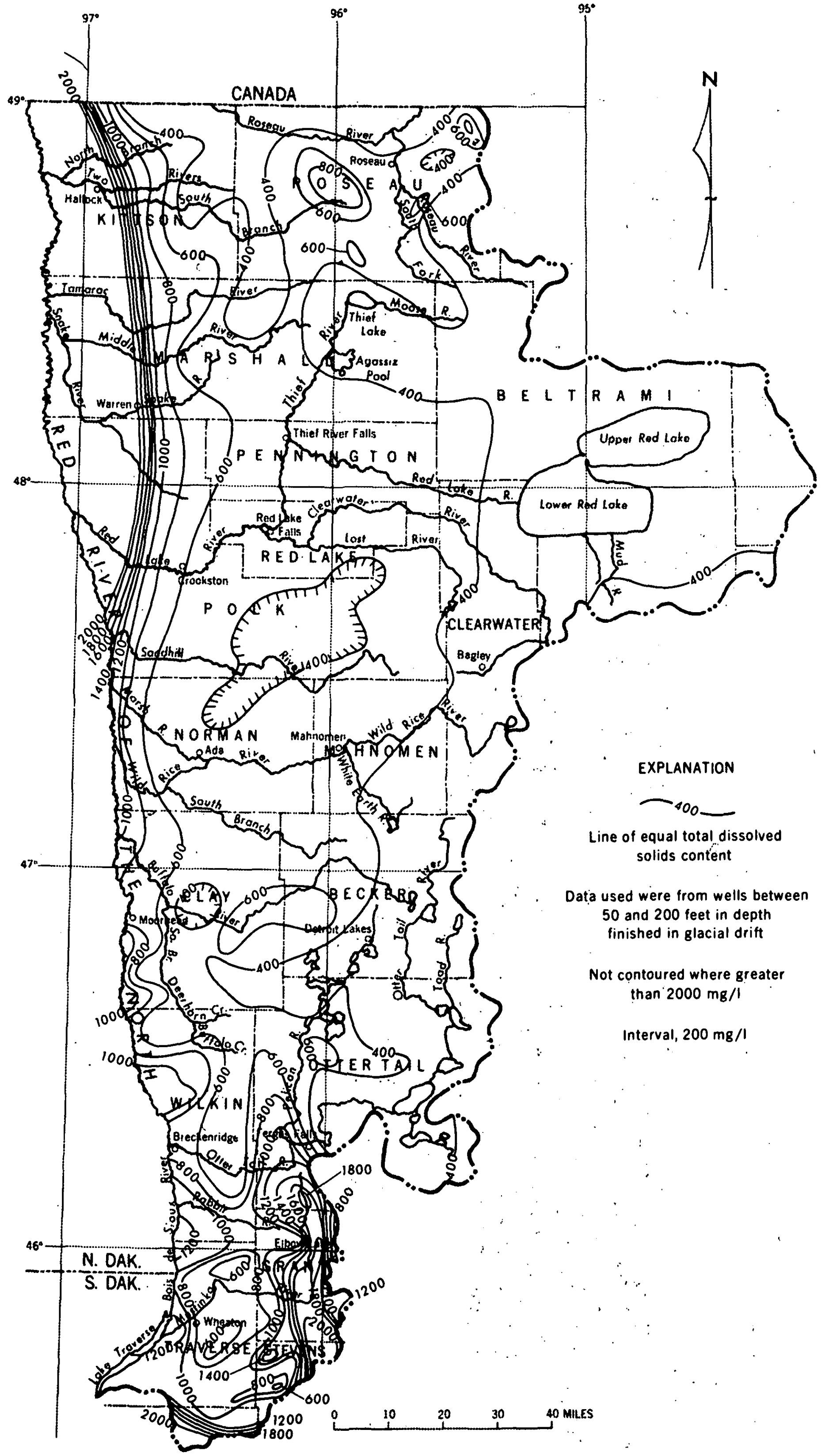


Figure 28.--Total dissolved solids content of water in the drift ranges from less than 400 to more than 2,000 mg/l. The effect of the poor quality water moving upward into the drift can be seen in the northwestern part of the basin.

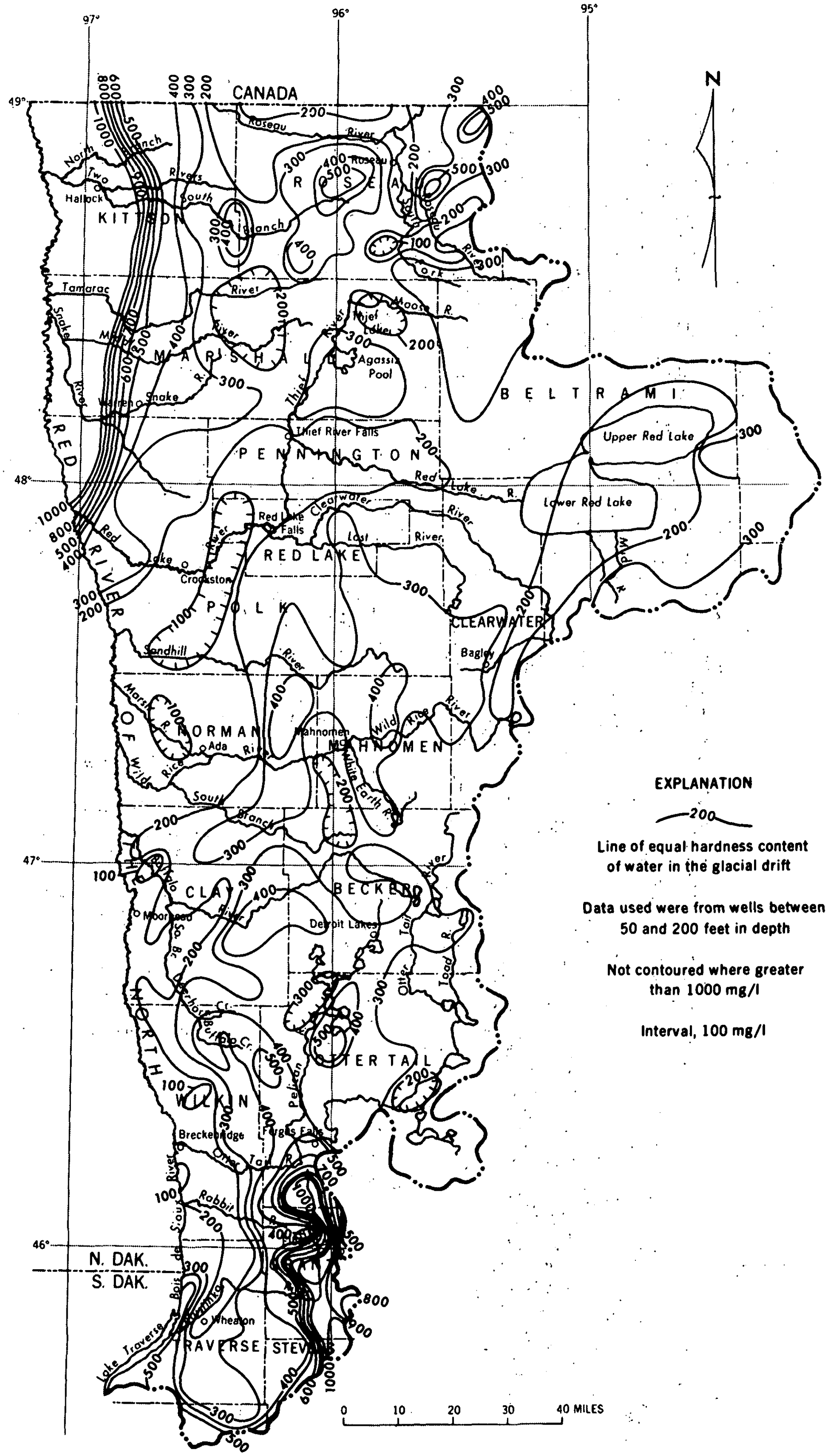


Figure 29.--Hardness of water in the drift is less than 200 mg/1 in much of the lake plain area.

Chloride--Chloride is dissolved from rocks and soils and tends to stay in solution longer than most ions as water moves through the ground-water reservoir. Locally, ground water may contain chloride derived from pollution. Small quantities of chloride, generally less than 250 mg/l have little effect on the use of water for domestic and municipal uses. Large quantities, in water that also contains considerable calcium or magnesium, increases the corrosiveness of the water. Sodium chloride gives the characteristic salty taste to water that is detectable generally, when the chloride content exceeds about 250 mg/l. However, it was observed that in parts of the Red River basin most well owners did not describe the water as "salty" until the concentration of chloride was 500 to 750 mg/l. The chloride concentration of ground water in the glacial drift in the Red River basin is shown on figure 30. Most water in the basin contains less than 50 mg/l of chloride. In general, where the chloride concentration is greater than 750 milligrams per liter water is not used for domestic purposes. At many places in the northwestern part of the area chloride concentrations of 2,000 mg/l or more were determined in waters from wells less than 100 feet deep.

Sulfate--Sulfate is dissolved from the unweathered glacial drift which contains iron sulfide minerals, gypsum, and anhydrite. Sulfates of most of the common metallic elements are readily soluble in water. The sulfate ion, once formed, is chemically stable in most of the environments to which natural waters are subjected. Because of these two facts, the areas of high concentration of sulfate shown on figure 31 are believed to be largely in waters that have moved through the ground-water system for a considerable distance. However, high sulfate concentrations might also be caused by local geologic conditions. Sulfate in waters within the Red River basin is generally not a problem as most of the water has a sulfate concentration less than 300 mg/l. In areas where the sulfate concentration is greater than 1,000 mg/l ground water could have a laxative effect and an unpleasant taste.

Iron--High concentrations of iron are common in ground water within the Red River basin and are usually excessive for many uses. Iron is objectionable because of the aesthetic considerations and taste when its concentration exceeds about 0.3 mg/l and because it causes a reddish-brown stain on porcelain and enamelware at higher concentrations. It is also troublesome in water used for many industrial purposes, including the manufacture of food, carbonated beverages, high grade paper, and ice. The occurrence of iron is highly variable and it is difficult to map any patterns. It is generally greater than 1 mg/l throughout most of the watershed and in local areas it exceeds 5 mg/l. Iron may be removed by appropriate treatment of the water.

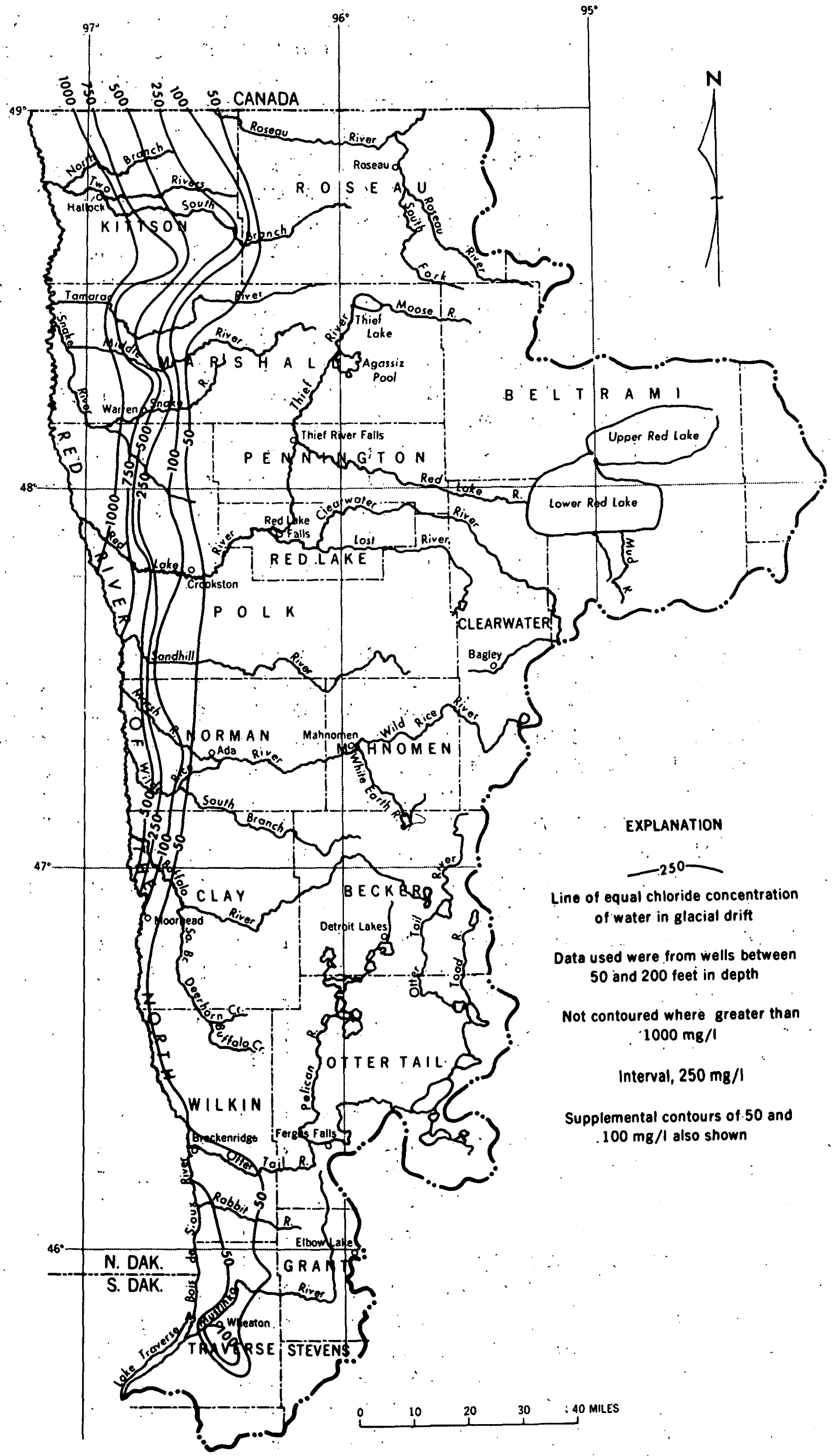


Figure 30.--Chloride concentration of water in the drift is less than 50 mg/l throughout most of the basin.

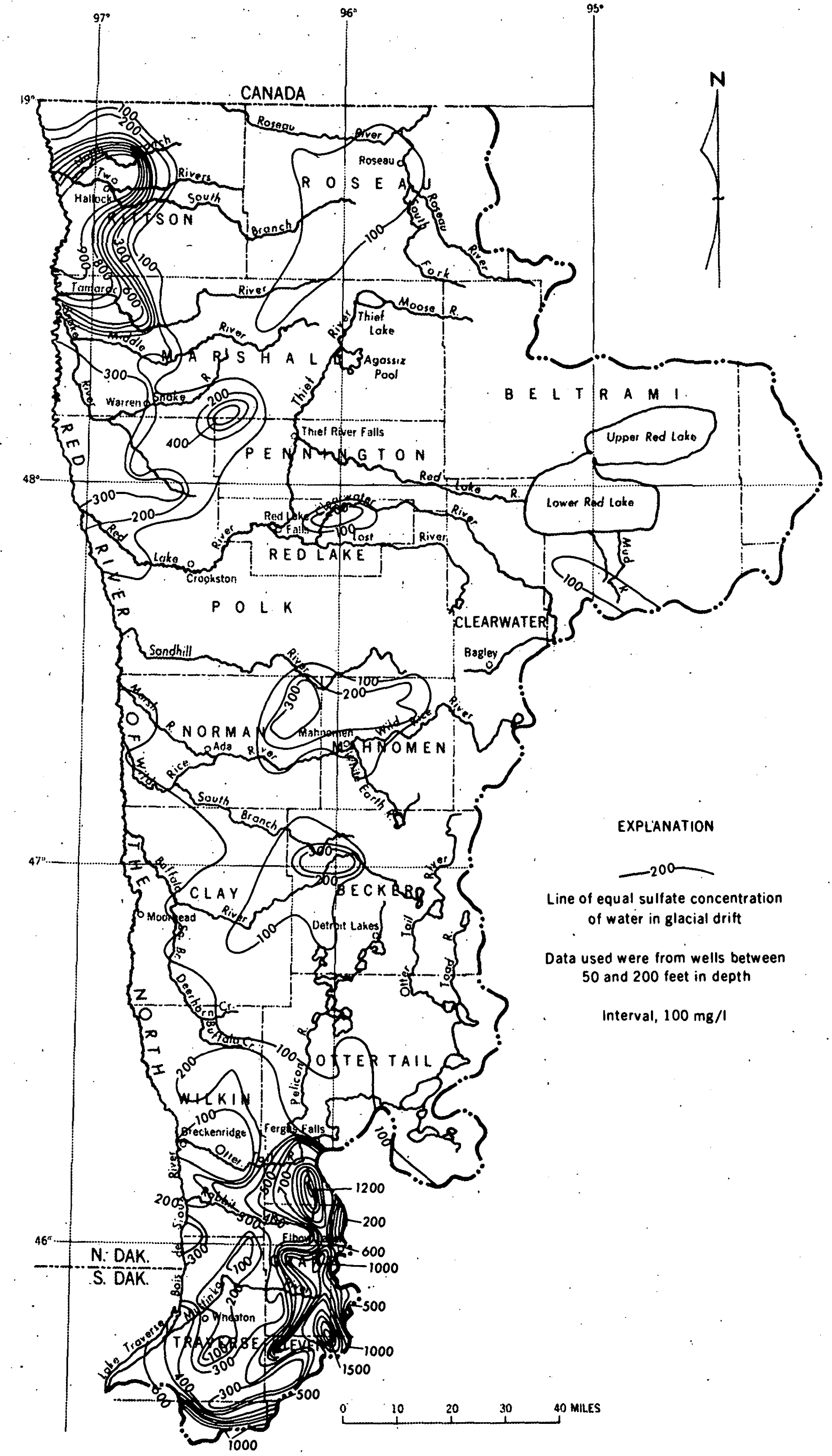


Figure 31.--Sulfate concentration of water in the drift is less than 300 mg/l in most of the basin, but increases to more than 900 mg/l in the southern and northwestern parts.

Fluoride--Fluoride is present in most waters in the glacial drift but largely in concentrations of less than 1 mg/l. At a few places water in the deeper part of the drift or the underlying Cretaceous rocks has fluoride concentrations of 1.5 or more mg/l. Fluoride concentrations of about 1.0 mg/l in drinking water may be beneficial in reducing dental decay, especially among children. At higher concentrations, it can cause mottling of teeth and other harmful effects. In the southern part of the watershed, near Graceville, some wells tapping Cretaceous deposits and deeper drift deposits have been abandoned because of detrimental effects of the water on the appearance of teeth.

Nitrate--Much of the nitrate in the ground waters of the Red River basin probably is of organic origin. Some plants in the area contribute nitrogen compounds to the soil; in addition, the leaching of fertilizers, animal excreta, and sewage effluent add nitrate to the waters of the region. The concentrations of nitrate in shallow sandy aquifers in some areas are as high as 5 mg/l. Some shallow dug wells contain waters with nitrate nitrogen in excess of 50 mg/l. Waters containing 50 mg/l of nitrate are harmful to infants. However, most ground waters have a nitrate concentration of less than 1 mg/l. Waters of the streams generally are much higher in nitrate concentration than ground water.

Boron--Boron is a necessary element for normal plant growth but may be toxic to plants when in excess of 0.5 mg/l. Boron concentration in the glacial drift is generally less than 1 mg/l except locally in the southern part of the watershed. Ground water from rocks of Cretaceous and Paleozoic ages generally contain more than 1 mg/l of boron and where these waters are moving upward the boron concentrations are locally higher in the drift.

Sodium--The relation of sodium to calcium plus magnesium concentration is significant to the use of water for irrigation. When sodium is present in irrigation water in relatively higher concentration than calcium and magnesium, it may replace the calcium and magnesium ions adsorbed on the soil colloids and deflocculate the soil. Calcium and magnesium, when adsorbed on soil particles, tend to aggregate the soil particles; flocculation is the first step in the formation of stable soil aggregates and in the development of soil having good tilling ability. The sodium-adsorption ratio of water is directly related to the adsorption of sodium by soil and thus is a criterion for determining the suitability of an irrigation supply. In general, those waters occurring within the Cretaceous deposits or in the deeper drift deposits near the Red River of the North tend to have high sodium adsorption ratios, and therefore, in some cases make the water unsuitable for irrigation purposes.

Present and Potential Water Supply Development

The need for municipal, industrial, or rural water supplies has resulted in a certain amount of development of ground- and surface-water sources. Municipal water use and source of supply in the Red River basin is shown on figure 32. The water use data were collected over a period of 5 years, 1963 to 1968. It is difficult to separate municipal from industrial use in many cases because some industries buy water from the municipalities. For this reason the use figures are very general and should be used with caution. They are presented only to give relative orders of magnitude.

The larger water users--Moorhead, East Grand Forks, Fergus Falls, Breckenridge, Thief River Falls, and Crookston--and two smaller users--Hallock and Stephen--obtain their water from surface-water sources. All but Moorhead and East Grand Forks have constructed reservoirs to store water to assure that supplies are adequate during periods of low flow. The reservoirs are near town in most places but several communities, such as Hallock, are quite distant from the reservoir and water losses during transmission from the reservoir to community are significant. All other communities in the Red River basin use ground water. Municipal wells are generally 6 to 12 inches in diameter, screened, and some are gravel packed. Most communities have a central distribution system so there are few communities where a large concentration of domestic wells are clustered in a small area.

The amount of water used for industrial purposes is not as well known as for municipal. In some communities the industrial use is included in the totals shown on figure 32. Where the industrial use is known and is an unusually large part of total use it is noted on the map. The greatest amount of water for industrial purposes is used for dairy product processing; agricultural product processing, such as potato washing and potato product industries; sugar beet processing; and water power. Most of these uses are nonconsumptive and most of the water is returned to streams. In creamery, potato washing, and power generation the water quality is affected very little. However, in potato and sugar beet processing, although much of the water returns to the system, the quality is more seriously affected.

Most creameries use ground-water sources because of its low temperature. Construction of industrial wells is much the same as for municipal wells. The potato and beet processing industries use surface water more than ground water and storage in surface reservoirs is usually necessary.

Water used for rural purposes is either for irrigation supplies or for rural domestic and stock supplies. Irrigation

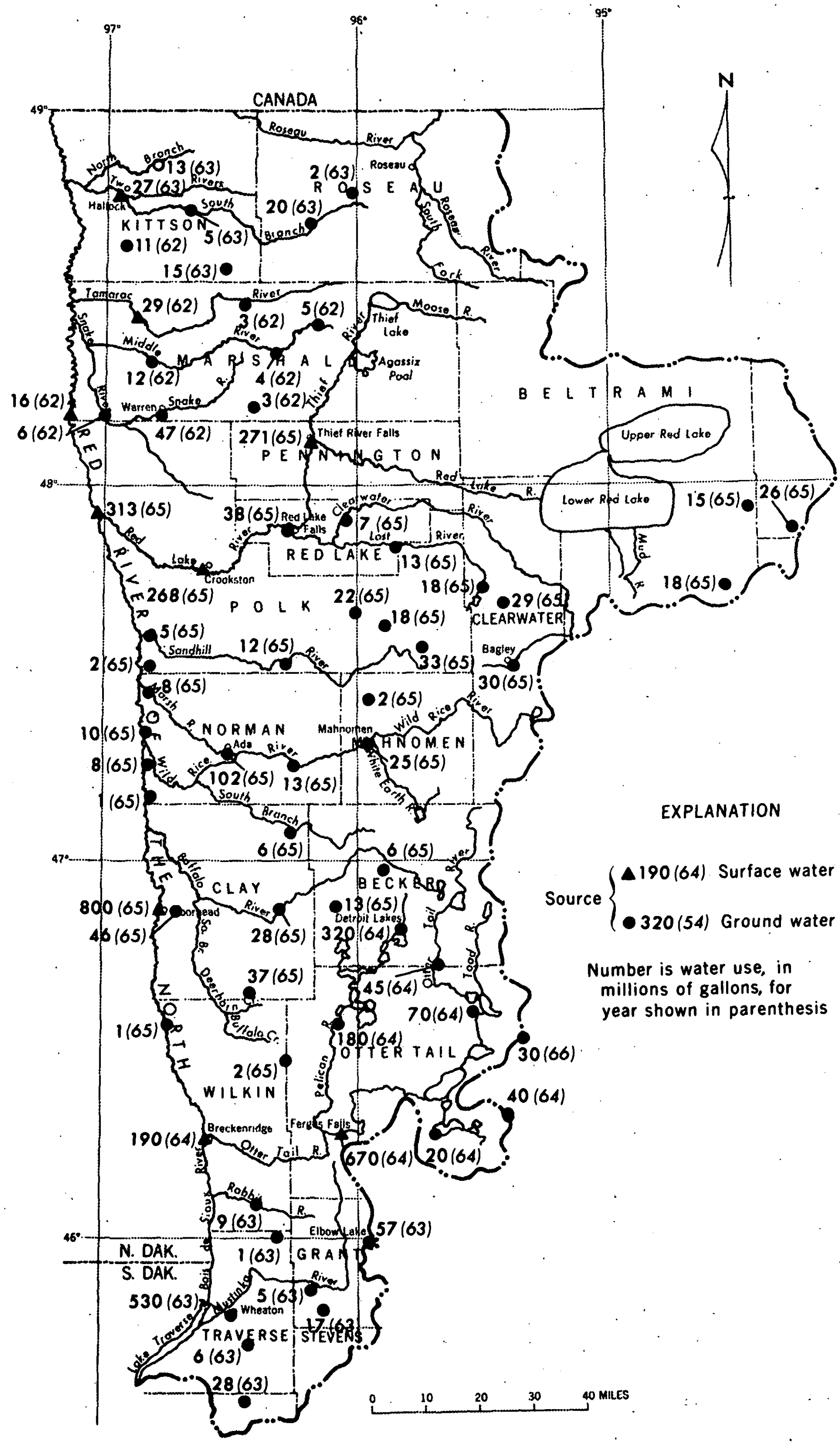


Figure 32.--Most municipalities obtain their water from ground-water sources. However, the largest users have surface-water sources.

is not widely practiced in the Red River basin. The only areas where it is currently practiced is east of Moorhead, where several irrigators draw supplies largely from the Buffalo and South Branch Buffalo Rivers, and the area of outwash sand and gravel in the southeastern part of the basin. In the outwash area irrigators obtain supplies from both surface- and ground-water sources. Surface-water supplies are drawn from both rivers and lakes. Ground water is obtained by large diameter screened wells.

Rural, domestic, and stock supplies are obtained from both surface- and ground-water sources also. Domestic supplies are entirely from wells, and for stock most farmers use a combination of both sources. The small yield wells, which are adequate for most farm needs, have in the past been mostly open-hole wells or screens fashioned on the spot simply by slotting the pipe. Use of screens has increased in recent years.

The concentration of wells in the basin is directly related to population distribution. In the heavily farmed areas such as the clay and silt areas of the Red River Valley, in the gently rolling western part of the morainal area, and in the area of outwash, well density is 1 to 3 per square mile. In the beach ridge area and in the western part of the lake-washed till plain the density is less--from less than 1 to 1 per square mile. In the less peaty parts of the lake-washed till plain well density is about the same as in the Red River Valley, but in the peat areas there are no wells at all. In the rugged part of the morainal area well density is very low overall, but there are concentrations of wells used by cabin owners around many of the lakes.

From the discussion of water sources and present water use a general idea of the potential for water supply development can be derived. The ground-water resources are relatively undeveloped except locally, such as near Moorhead. Much surface water is already being stored in existing reservoirs. Locations that would be adequate for small amounts of surface-water storage still exist in the basin, but sites for storing large volumes of water are generally lacking. Therefore, future development of surface water through storage in reservoirs would probably involve small reservoirs.

Management Alternatives for Water Supply

Many alternatives for managing water are available; some of which could be applied to water problems in the Red River basin. Some of these are operational and others are currently undergoing research. Many of them require research every time they are used so they can be adapted to each local situation.

Surface-water management: Many factors must be considered if reservoirs are to be constructed. Reservoirs generally serve many purposes such as water supply, flood control, pollution abatement, and recreation. Often, operation of the reservoir for one purpose is not always in the best interest of another purpose; for flood control it is desirable to have the reservoir level as low as possible in later winter so maximum storage of spring runoff water is possible. This is often undesirable for people living adjacent to the reservoir because it causes unsightly shorelines, affects wildlife, and inhibits recreation. Also, care must be taken so enough water of good quality remains for water supply throughout the winter. In years of low streamflow, release of water may be necessary for pollution abatement, which again will have an affect on recreation and water supply.

It might be desirable, if water must be transmitted for long distances from reservoirs, to use a series of small reservoirs in the lake plain area rather than a large reservoir in the morainal area. Another important consideration in surface-water storage is that annually about 2 feet of water is lost from the water surface through evaporation--a significant loss of water. It may be desirable to study the feasibility of using evaporation suppressants on water stored in surface-water reservoirs to reduce water loss.

Ground-water management: Research into better methods of locating ground-water supplies is greatly needed. This would assure that the best and closest possible source is being used. Better methods of well drilling and construction could lead to better development of water supplies in some of the small aquifers in the Red River basin. Special uses of saline or other poor quality water could be beneficial in part of the Red River basin where this type of water is abundant. Desalinization might be considered for these areas when it becomes economical. Pumping water from the lower-yielding aquifers by using several low-yield wells rather than one high-yield well might be desirable. This is particularly applicable to beach ridge aquifers.

Joint management of both sources: Joint use of ground and surface water also offers many management possibilities particularly in the lake plain. Mixing of good quality water with poor quality water often results in an intermediate type which is acceptable for a particular use. This might be considered in areas again where poor quality water is abundant. The storage capacity of aquifers should be studied because of the possibility of storing surface water in them. Ground-water pumpage could greatly exceed natural recharge if surface water at high flow could be injected into ground-water reservoirs. This technique could probably be used near Moorhead where high flows from the Buffalo River could be injected into

Aquifer C (fig. 15) and pumped out later in the year. Storage in the ground has several advantages to surface storage: 1) the sand and gravel would have a filtering effect on the water; 2) the water would be cool; and 3) there would be no evaporative loss. Care should be taken in an operation like this, however, so the underground system is not contaminated or ruined physically. For example, waters must be chemically compatible or precipitates will form that reduce hydraulic conductivity. Suspended solids must be removed before injection and contamination by bacteria must be prevented.

Delivery systems: Development of better and less costly methods are needed for carrying water by pipelines, or other methods, both from source to central distribution system, and from this system to individual users. Better metering and more realistic water billing in some of the communities in the Red River basin would reduce water demands.

In summary, many future alternatives to the management of water for water supplies are possible. The selection of any one or several of these methods depends upon the economic and hydrologic feasibility. In selecting any one or set of these alternatives it should always be remembered that the development of a water resource should be considered a part of the hydrologic system, and that any change in the hydrology in one place will have consequent changes at other places within the system. These consequent changes could have beneficial or nonbeneficial side effects.

Pollution of Water Resources

Pollution of natural water bodies is the introduction into the water of substances which alter its natural quality so as to impair its usefulness or render it offensive to sight, taste, or smell. Water supply and waste disposal are closely interrelated activities that are of major concern to a water manager. Naturally clean water can be drawn only from an unpolluted source. Water managers, therefore, should be thoroughly familiar with the catchment area of their supply in the case of large streams and lakes, and with the ground-water system within the vicinity of the source.

Pollution Problems

Water pollution problems occur at several places in the basin, but the most serious are in the Red Lake River and the Red River of the North. Sources of pollutants are municipal, industrial, and agricultural wastes.

Most municipalities and industries discharge wastes into nearby streams, ditches, or lakes (Minnesota Pollution Control Agency, 1968). In most cases the wastes receive primary or secondary treatment but a few installations still discharge untreated sewage. Even with secondary treatment the waste is not entirely of desirable quality. The waste commonly contains an abundance of nutrients such as nitrate and phosphate that lead to prolific eutrophication. In an area like the Red River basin, where streams are generally small and subject to wide variations in flow, the buildup of waste sometimes becomes critical. This is particularly common during the period of low or no flow in the minor streams in late fall and winter.

The most serious pollution in the Red River basin has been caused by municipal and industrial wastes in several localized areas in the main stem of the Red River of the North (U.S. Public Health Service, 1965).

Pollution from agricultural sources can result from accelerated rates of erosion and excessive use of fertilizers such as nitrogen and phosphorous compounds. These products are dissolved and carried to lakes and streams or move downward to the ground-water system. Areas where large numbers of animals are kept, such as feedlots, can have a harmful effect on water resources. Runoff of animal waste into streams during rainfalls is common. Where the waste products are heavily concentrated it is also common to find shallow ground-water supplies contaminated.

When surveying contamination of underground water, the major problem is identifying the pollution and predicting the areal extent of the contaminated zones that result from dispersion of the contaminant in the ground. Many changes involving oxidation, adsorption, and complexing within the zone of aeration determine whether the pollutants are reduced to harmless proportions before they reach the ground-water systems. The degree of dilution of the polluted water at given distances from the waste injection site is also an important consideration.

Management for Pollution Control

Streams tend to purify themselves naturally. Water managers must recognize that the capacity of a stream to dilute waste and purify itself is an important economic factor to be used. It is necessary, therefore, for the water manager to be able to recognize and be familiar with the symptoms of pollution and the methods for prevention or cure that the natural forces exert for self purification. He must be able to 1) identify the origins and intensity of pollution; 2) measure and estimate the magnitudes of the forces of natural purification; 3) recognize the limitations of these forces; and 4) prescribe either a regimen that will bring about a spontaneous cure or one in which sufficient external remedial aid is given to insure recovery.

Rapid lake eutrophication, as commonly indicated by algal blooms and prolific weed growth, occurs in many smaller lakes and a few of the larger lakes within the Red River basin. The water quality of these lakes may deteriorate to such a degree that the economic use of the waters for water supply, recreation, aquatic life, and agriculture is affected. Lakes undergo eutrophication, which is the natural aging process, however, this process can be greatly accelerated by man who may knowingly or unknowingly increase the nutrient content of the water. Nitrogen and phosphorous are two of the major macronutrients that greatly affect the eutrophication process. These two nutrients occur at high concentrations in effluents from secondary sewage treatment plants and when these effluents are discharged into lakes, even though the other organic materials have been removed, may result in accelerated lake eutrophication.

The aqueous environment chemistry is directly influenced by the relative abundance of elements involved. It is a system that involves interchanges of gases, nutrients, and energy between the living organisms and the elements and materials held in suspension and solution. Gas exchanges indicate the activity of plants and animals in photosynthesis and respiration. The exchange of nutrients describe the recycling processes. Energy exchanges occur in the form of some life as well as organic material which may include pollution. Optimum water quality management requires an understanding of the complexities of this system.

Management practices used to alleviate or control eutrophication involve the control of the principle nutrients, nitrates and phosphates. The most obvious method of nutrient control involves the diversion of sources of nutrients away from the lake. If this is not feasible, other methods for nutrient control may include: 1) removal of nitrogen and phosphorous by tertiary treatment of sewage effluent; 2) harvesting of weeds in the lake; 3) harvesting of fish decreases the nutrients slightly; and 4) removal of lake sediments that may be a source of nutrients or a site of nutrient storage.

In the Red River basin local waste disposal practices include surface dumping, sanitary land fills, septic tanks and cesspools, and sewage stabilization ponds. Since most wastes are released at the ground surface or at a slight distance below, the water table is accessible to contamination by waste, however, up to the present no extensive pollution of the ground-water reservoir is known to occur within the Red River basin. Proper management of these facilities will result in little or no pollution. Hydrologic characteristics which are important in the selection of sites for disposal of wastes are the permeability and sorptive capacities of the materials both in the ground-water reservoir and in the zone of aeration. The zone of aeration is especially effective in attenuating most contaminants and thus a considerable depth to the water table is considered favorable in waste disposal practices. Proper surface drainage of disposal sites can materially lessen pollution hazard by the prevention of leaching. Within the zone of saturation most contaminants are dispersed. Dispersion and dilution may be desirable practices in pollution control. In order to safely manage land disposal waste the water manager should be cognizant of hydrologic conditions as well as the type of waste being disposed. With this information the water resources can be adequately protected for future use.

In conclusion, the water manager needs to have adequate hydrologic information as well as adequate planning to solve any problems regarding the contamination of the water resources. Some problems involving surface streams are best solved on a regional scale, whereas, other problems including solid waste disposal may be handled adequately at the local level.

To manage and alleviate pollution, the classification for water use and the standards of quality and purity have been established by the Minnesota Water Pollution Control Commission (1967) for the Red River of the North from its origin at the confluence of the Bois de Sioux and Otter Tail Rivers to the Canadian boundary; the lower Otter Tail River from Fergus Falls to Breckenridge, and the Red Lake River from Crookston to the mouth in East Grand Forks. The standards were set to maintain water quality so the water may be used for domestic consumption, fisheries and recreation, industrial consumption, agriculture and wildlife, and waste disposal.

Flooding

Flood Problems

Floods of the Red River of the North and its tributaries are typically sporadic, for, although generally occurring in early to late spring, their dates and magnitude are subject to much variation. Most of these floods are caused by rain falling on melting snow or by intense rainfall on land already sodden by antecedent conditions. Although the summer floods occur less frequently than those in the spring, they cause high agricultural losses from soil erosion and crop damage. At Grand Forks, the time distribution of annual flood crests are shown on figure 33. The floods of April-June 1950 in the lower part of the Red River of the North basin in Minnesota were the largest that had occurred in several decades and caused the greatest damage that the area had ever sustained up to that time. Damages along the main stem (both sides) and the tributaries in Minnesota totaled about 18.5 million dollars (U.S. Geol. Survey, 1954, p. 153). The areal extent and discharge of the 1950 flood together with the maximum flood known and year of occurrence at selected sites is shown on figure 34. Locally, the 1950 flood has been exceeded.

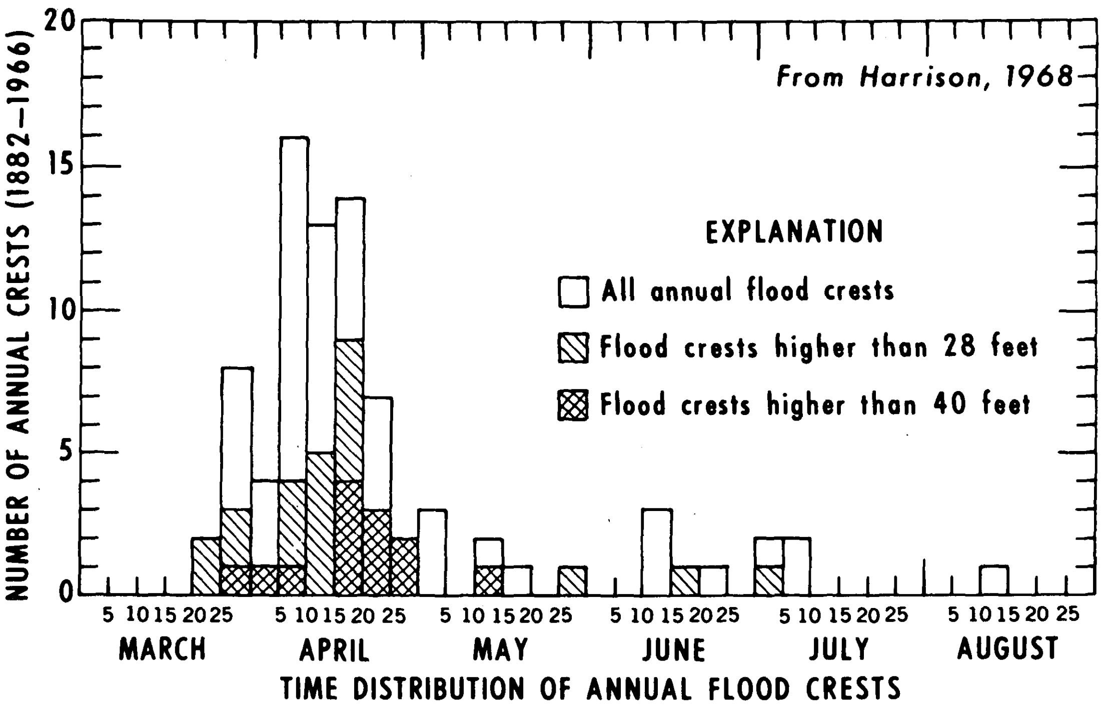


Figure 33.--Time distribution of annual flood crests on the Red River at Grand Forks, N. Dak. indicates mid-April is the time of the most frequent and severe floods.

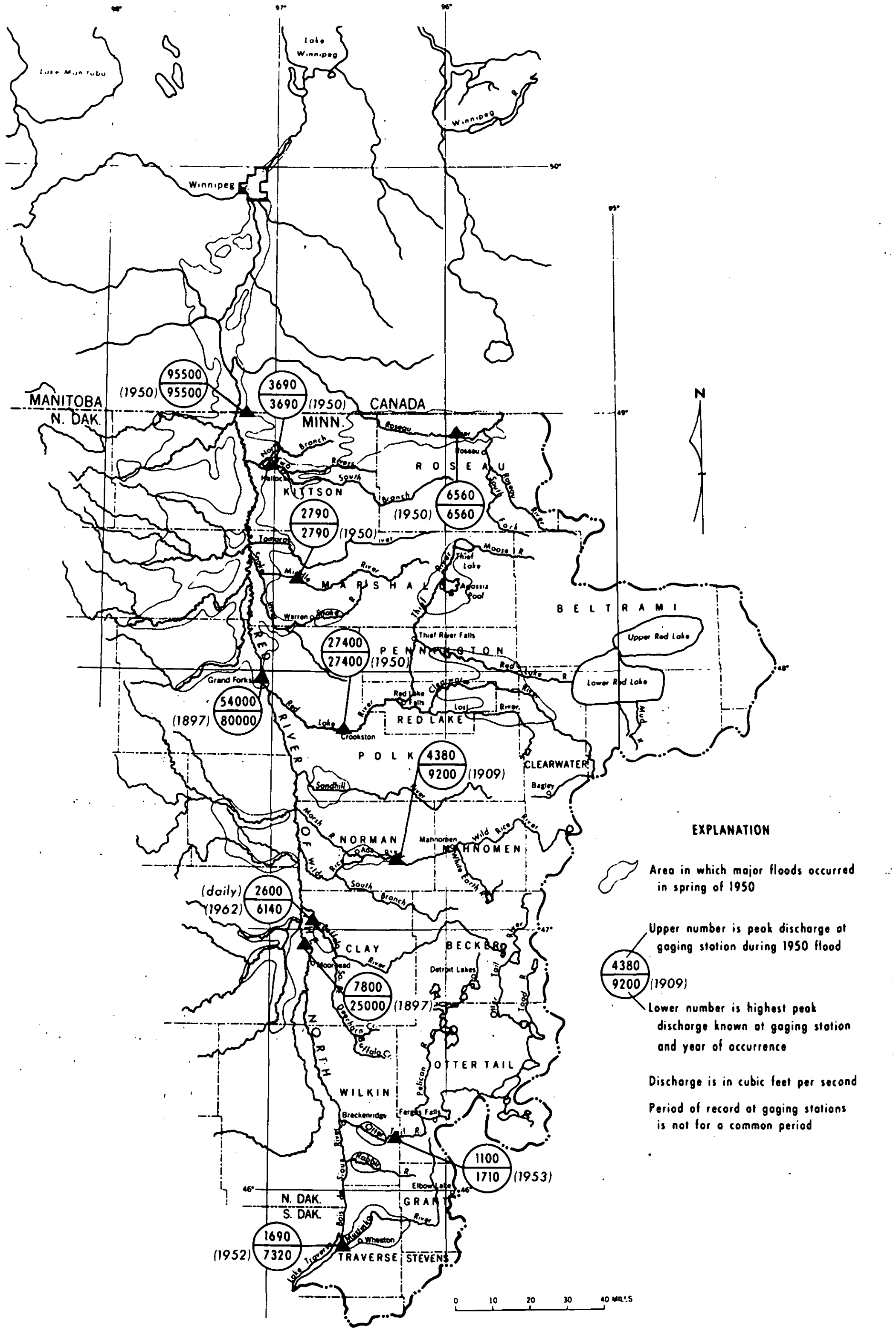


Figure 34.--Area inundated by the 1950 flood was greatest along the Red River north of Grand Forks, N. Dak.

Floods on the Red River of the North and its tributaries above (south of) Fargo, N. Dak. in April 1952 were the greatest since 1897. Flood damages were heaviest in the urban area of Fargo-Moorhead. The spring flood of 1965 produced near record stages and discharge in many areas of the Red River of the North basin. Moorhead, East Grand Forks, and Oslo on the main stem, and Crookston and Roseau on tributaries suffered considerable damage. Agricultural and transportation losses were high. Again in 1966 spring floods on the Red River of the North and its tributaries approached or exceeded record flood stages at many points in the basin. The total flood damages in 1966 were only one quarter as large as the 1950 flood damages, due mainly to the construction of flood control projects over the intervening years, issuance of advance warnings by the U.S. Weather Bureau and the U.S. Army Corps of Engineers, and the extensive flood fight waged by affected communities. In the 1966 flood the greatest damages were agricultural, of which almost one-half occurred in the Red River basin (U.S. Army, Corps of Engineers, written commun., 1966).[1]

Major floods have occurred along the tributary streams to the Red River of the North in Minnesota. The village of Roseau and other communities along the course of the Roseau River have been sporadically subjected to severe flooding. Planning and flood control measures are now being considered in order that these losses may be decreased.

Local flooding on small drainage areas is caused by heavy intense thunderstorm rainfall. Although these floods are of local extent they occur with high frequency. Damages from these local floods is increased by inadequate drainage and capacity of some of the ditches and streams within the area.

[1] *A major flood occurred in the Red River basin again in 1969. Peak stages and discharges exceeded previous known maxima on parts of most major tributaries of the Red River of the North (Anderson and Schwob, 1970).*

Management for Flood Alleviation

As the size of the tributary channels increase through modification, the Red River channel itself becomes less adequate to carry flood discharge. An enlargement of the river channel, principally by deepening or clearing in order to increase its discharge capacity, is usually precluded by the cost and in some cases by the large amounts of sediment that would be deposited within the channel when floods subside. Such enlargement has been done along several reaches of the Red River. The discharge efficiency of a river within the limits of its banks depends largely on the fall and the cross section of the channel. The only way to increase the fall is to reduce the length of the channel by straightening. In the case of large rivers in flat terrane it is difficult to maintain straight channels because of the natural tendency to meander. Straightening of channels has been accomplished within the Red River basin, particularly on the Mustinka River, Clearwater River, Ruffy Brook, Red Lake River, Wild Rice River, Sandhill River, and several others.

Another flood control practice is the restriction of the river to its channel by building embankments along its course. This practice was carried out in the vicinity of Breckenridge, Moorhead, East Grand Forks, and Crookston. These are largely local measures and have no effect in lowering flood peaks further downstream.

The most effective way to reduce flood peaks is to provide storage during periods of high flow. This may be done by either diverting water into a natural low-lying depression, such as is proposed for Roseau Lake (drained lake depression near Roseau) or by creating artificial storage through construction of a dam as has been done on Otter Tail River and is proposed on the Wild Rice River. By use of storage, flood peaks can be materially decreased, and for floods of shorter recurrence interval, even lowered to such a point that flooding will not occur downstream from the reservoir.

Flood damages can be materially reduced by nonstructural measures such as preparedness action resulting from advance warning, improved land use practices, and flood-plain zoning.

Flood-prone area maps are now being made for communities along the Red River and its tributaries that are subject to flooding. By forecasting the probable frequency in areas of flooding, builders in these flooded areas can anticipate necessary measures to prevent high damages. In some cases the flood area maps will result in restricting land use in the areas subject to frequent flooding.

As it has been so aptly stated, "The flood plain is nature's safety valve," and is needed to carry waters above bankfull stage. Proper management and restriction in the use of flood plains must be considered in all areas concerned with flood prevention problems. Flood plain zoning goes hand-in-hand with the other common flood control and damage prevention measures and should be a part of the integrated plan for flood control and damage reduction in a river basin.

In summary, flooding is one of the major problems of the Red River basin. Much work has been done in the area of improvement of channel capacity and construction of structural measures to alleviate flood damages. In the future more effort will be directed toward nonstructural measures to control floods. By knowing the natural regimen of streams, man can adapt his land management practices to alleviate or materially decrease flood damages.

Drainage

Drainage in the Red River basin has been extensive, particularly in the Glacial Lake Agassiz region. The richness of the clayey and silty soils in the lake plain is due partly to the wetness of the area. Before settlement the areas were somewhat marshy for part of the year and the soil that developed was deep and rich in organic matter. The very factors that caused the rich soil to form were drawbacks to farmers who could not farm such wet lands. Drainage seemed to be the best solution and the extent that drainage was accomplished is shown on figure 35. In 1950 the percentage of land in drainage in the Red River basin ranged from less than 10 percent in the eastern part of the morainal area to over 80 percent in the Glacial Lake Agassiz area in Marshall County.

In the lake plain the flatness of the land and inadequate outlets for spring or storm runoff contributed to poor drainage. Water remained on the land surface for long periods of time and was discharged largely by evapotranspiration. Drainage ditches had to form almost a complete drainage system from small ditches in nearly every field to larger collector ditches to still larger collector ditches, which approach major tributaries in importance. Even with the construction of the drainage system in its present form, backwater from full or plugged ditches continues to flood fields. More than 50 percent of the land is in drainage throughout most of the lake-plain area, and in the western part of the lake-washed till plain.

In the eastern part of the lake-washed till plain, the peat is not only a depression-fill type but is also partly upland peat. Minor topographic features exist in this vast peatland that form watershed divides. The extensive drainage program of the early 20th century often ignored these divides and consequently did not succeed entirely; only in a few areas were the ditches effective. In many places where the peat did drain, extensive fires that burned for many years occurred in the marshes. Much of the land that was farmed as a result of this drainage has been abandoned and the land is slowly reverting to its natural condition.

In the morainal area, drainage activity is nearly all related to local marshes and potholes. As a result 10 to 30 percent of the land in the western part of the morainal area was in drainage by 1950 (fig. 35).

Land drainage is one of the primary concerns of water managers in the Red River basin. Drainage is a very useful water management practice if done in the best interest of the entire watershed. It is a challenge to water planners and water managers to keep to a minimum the undesirable side-effects that are caused by the conflicting methods of the many and varied water users and manipulators.

Water Recreation

The morainal area of the Red River basin is outstanding in terms of water recreation. Although some water-based activity is available on the Red River and on reservoirs on the major tributaries, the vast majority of recreation activity centers on the many lakes in the morainal area. In this case, tourism is a major factor in the economy.

The water-oriented activity of most vacationers is fishing, swimming, and water skiing. Nearly every lake in the basin is used for one or more of these purposes, but not all with the same intensity. The lakes most intensively used are the larger lakes in Otter Tail and Becker Counties, especially near the towns of Detroit Lakes, Perham, and Battle Lake.

Water-fowl hunting is a major attraction in the Red River basin in the fall of the year. This activity again draws a large number of people to the area. Hunting centers around the prairie pothole region in the western part of the morainal area, but is also common in the eastern part.

Canoeing is not a primary activity of vacationers in this basin, but several rivers have good potential for this sport. The Red Lake, Wild Rice, and Otter Tail Rivers all are large enough for canoeing, and offer a wide variety of canoeing experiences. A report by Ropes, Brown, and Wheat (1969) describes the recreation values for the Red Lake River. This

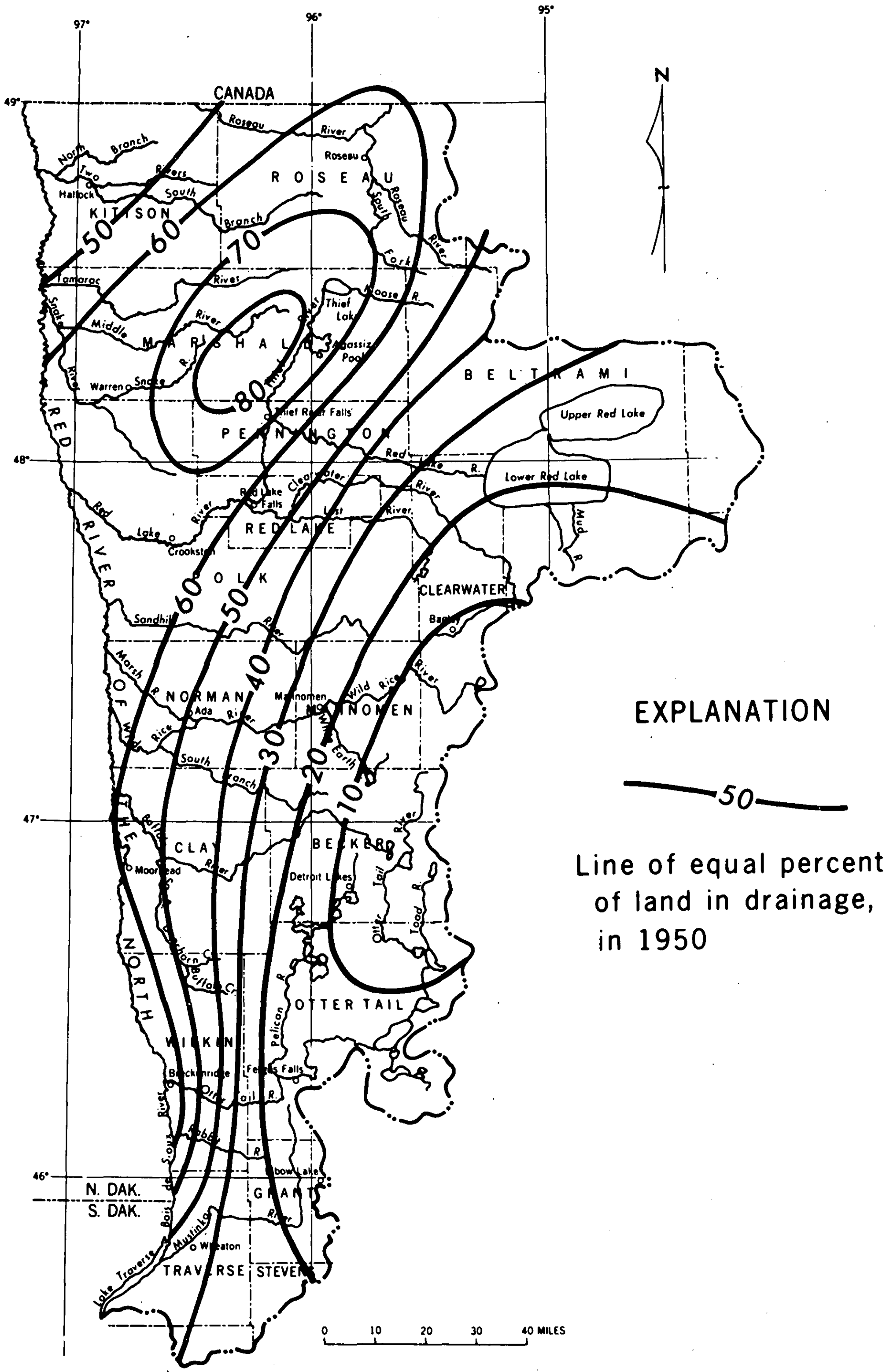


Figure 35.--More than 40 percent of the land in most of the Glacial Lake Agassiz region is in drainage.

river is also included in a book published by the Minnesota Department of Conservation, Division of Parks and Recreation (1968). Canoeing on the Otter Tail River is discussed very briefly in HA-296.

Pleasure driving is also a very common activity with vacationers, and clean unpolluted lakes are an important factor in the aesthetic value of an area.

Tourism is good for the economy of the area, but the concentration of people also creates problems. Many power boats on shallow lakes tend to stir up the lake and make the water dirty and unpleasant for swimming. Where many power boats are docked the water often has a layer of oil. Where many cabins surround a lake, by-products of human waste eventually get into the lake waters and create an excess of nutrients. This creates profuse growth of algae and other aquatic life which, in turn, causes accelerated eutrophication and build-up of organic sediment.

With the growing numbers and leisure time of people, water managers must be concerned with the water needs for tourism, especially if it is a major factor in the economy of an area. The need for clean and pleasant rivers and lakes is essential to the Red River basin, and land and water resource planners and managers must assure that the attractiveness of the morainal area is maintained.

THE HYDROLOGIC SYSTEM

This section of the report is a more technical discussion of the hydrologic system than the section on water management, which covers the more practical aspects of water resources. It should provide a deeper understanding of the water resources in the basin for water scientists, planners, and managers who wish to model all or parts of the hydrologic system.

Water Balance

The steady state conceptual model or water balance equation applied to the Red River of the North area in Minnesota is: $P=R+ET$, where P is the mean annual precipitation (inflow); R is the runoff (outflow); and ET is the mean evapotranspiration (water loss). The model states that inflow equals outflow plus water loss (largely evapotranspiration), and that on a long-term basis there is no change in storage within the hydrologic system. Storage changes do occur within the hydrologic system from season to season and from year to year, however, these changes are generally compensating on a long-range basis.

Therefore, to quantify this model, mean values for both precipitation (inflow) and runoff (outflow) were used.

Mean annual precipitation in the Red River basin is 21 inches (weighted on the basis of the percent of the total area within each contour interval of precipitation, fig. 7). Ground-water inflow was considered negligible. This consideration is based on the low transmissivity and low hydraulic gradients within the ground-water reservoir, and the fact that the regional surface water divide and ground-water divide approximately coincide in most areas. It is known that in some places underflow enters the Red River basin and in other places it leaves the basin, but these inter-basin transfers are relatively small and are assumed to be compensating. Locally, underflow would be a significant factor in the hydrologic balance of a small area.

Runoff, or water yield, from the Red River basin in Minnesota is 2 inches. Runoff is one of the more readily measurable variables within the hydrologic equation. Therefore, it is one of the more reliable factors in computing the water balance. The estimate of water yield for the Red River basin in Minnesota is based upon streamflow records which vary in period from a few years to as much as 85 years. It represents the water available for man's use. However, it should be realized water may be reused several times before leaving the basin.

Water loss represents the difference between water input and water output if no change in water storage occurs. It is that water returned to the atmosphere by evaporation and transpiration. Evapotranspiration is the water used in natural cycling which sustains plant growth and moderates and controls atmospheric and land surface temperature. Therefore, it is not a loss in the sense of performing essential hydrologic and biologic function, but does decrease the amount of water available for man's use. It is the largest variable in the hydrologic equation that removes water from the land and also is effective in decreasing precipitation before reaching the land surface. The mean annual water loss for the Red River basin is estimated to be 19 inches; the difference between precipitation and runoff.

Evapotranspiration was computed for several locations within the Red River basin on the method described by Thornthwaite and Mather (1957), (fig. 11).

Potential evapotranspiration is the evapotranspiration that theoretically would occur if water is always available to satisfy all evapotranspirative processes. By allowing for changes in soil moisture storage the computed values of evapotranspiration based on Thornthwaite's equation was generally greater but agreed within 10 percent of those calculated as the difference between precipitation and runoff. Because of the uncertainties involved in estimating soil moisture capacity it was interpreted that the evapotranspiration calculated as a difference to be more representative of natural conditions.

In order to show the annual variation in the components of the hydrologic equation, analyses were made for several subbasins within the Red River of the North drainage in Minnesota (fig. 36). The assumption that no storage change occurs is not entirely met and storage change may be as much as 1 inch for some areas in the moraine. As indicated by the variation in the runoff, water availability for use is not uniform areally or with time, fluctuating widely from year to year.

In conclusion, climatic conditions are the most significant factors controlling the annual water yield. Because of the low transmissivity and the essentially full condition of the ground-water reservoir, variation in annual water yield cannot be explained by variation in ground-water runoff. This above condition is particularly true for basins of drainage area greater than several hundred square miles. For smaller drainage basins the effect of ground-water storage and ground-water runoff could moderate the water yield from year to year.

On the following pages a more thorough examination is made of the surface runoff and ground-water systems--both major parts of the total hydrologic system. Because of the importance of water quality for all uses of water, a section on the hydrochemical system of the Red River basin is included also.

Surface Runoff

Surface runoff is that part of precipitation that appears in surface streams and is the natural flow unaffected by artificial diversion, storage, or other works of man. When precipitation falls many varying factors immediately start to function to determine the extent to which a part of the precipitation will appear as surface runoff. Runoff varies with time; for a storm period, a month, a season, or a year. Before runoff can occur, the demands of evapotranspiration, infiltration, and surface and channel storage must be satisfied. Intensity and duration of storms, areal distribution of storms, antecedent conditions of the land surface, temperature, velocity and duration of winds, and surface storage are the variable factors affecting the rainfall-runoff relationship which must be considered in studying the hydrologic cycle on a short term basis.

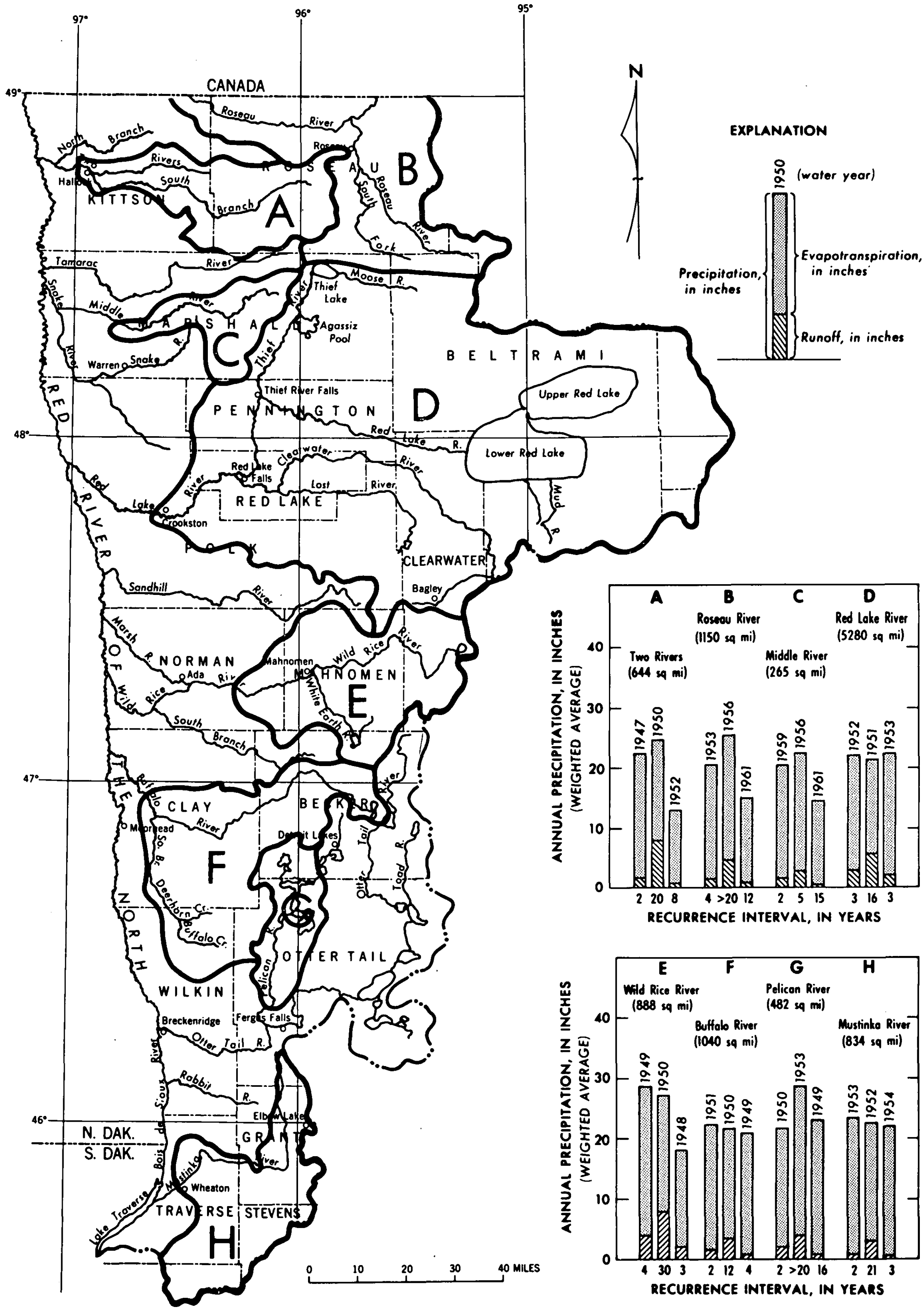


Figure 36.--Water budgets for selected sub-basins in the Red River basin show the variations in rainfall-runoff-evapotranspiration relationships between years and between the different physiographic areas.

Runoff varies from place to place and is thus related to basin characteristics of which the following are influential: 1) topography, 2) geology, 3) soils and vegetation, 4) size and shape of basin, 5) basin orientation, and 6) natural surface storage. Although total runoff increases with basin size, unit runoff generally decreases as basin size increases.

Volume and rate of runoff from a basin can be changed significantly by the works of man. Volume of runoff can be affected by developments such as storage of water in reservoirs, irrigation, ditching, and artificial recharge. Rates of runoff can be altered by use of flood control reservoirs, channel modification and diversion, changes in land use and soil cover, and changes in water use.

Areal Variation of Runoff

The amount and areal distribution of annual runoff in the Red River basin in Minnesota is shown in figure 37. Generally, the average annual runoff is lowest, less than 1 inch, in the lake plain, and increases from west to east in a pattern similar to the distribution of precipitation. The greatest average annual runoff, more than 4 inches, is in the morainal highlands south of the Red Lakes. Local minor variations will occur, especially in areas of ground-water discharge along the west edge of the moraine, in local areas of rough terrain, and in areas of poorly defined surface drainage.

Time Variation of Runoff

To understand the variations in surface runoff a knowledge of the daily, seasonal, and yearly changes in streamflow is needed. Although the average flow (fig. 25) is theoretically the maximum quantity of water in the stream that could be developed for a water supply it does not show the natural variation of unregulated streamflow in the Red River basin. Monthly, seasonal, and yearly variations in streamflow are shown by the hydrographs in figure 38.

In general, the highest runoff in the basin is in the spring and early summer, thereafter receding to the minimum for the year in late winter. The period of record used in the hydrographs (1931-65) includes the extreme drought years of the 1930's as well as the destructive and widespread spring floods of 1950 and 1965.

A comparison of the relationship between rainfall and runoff can be made from figure 38. The departure from normal of the monthly precipitation for 1931-65 for Crookston is

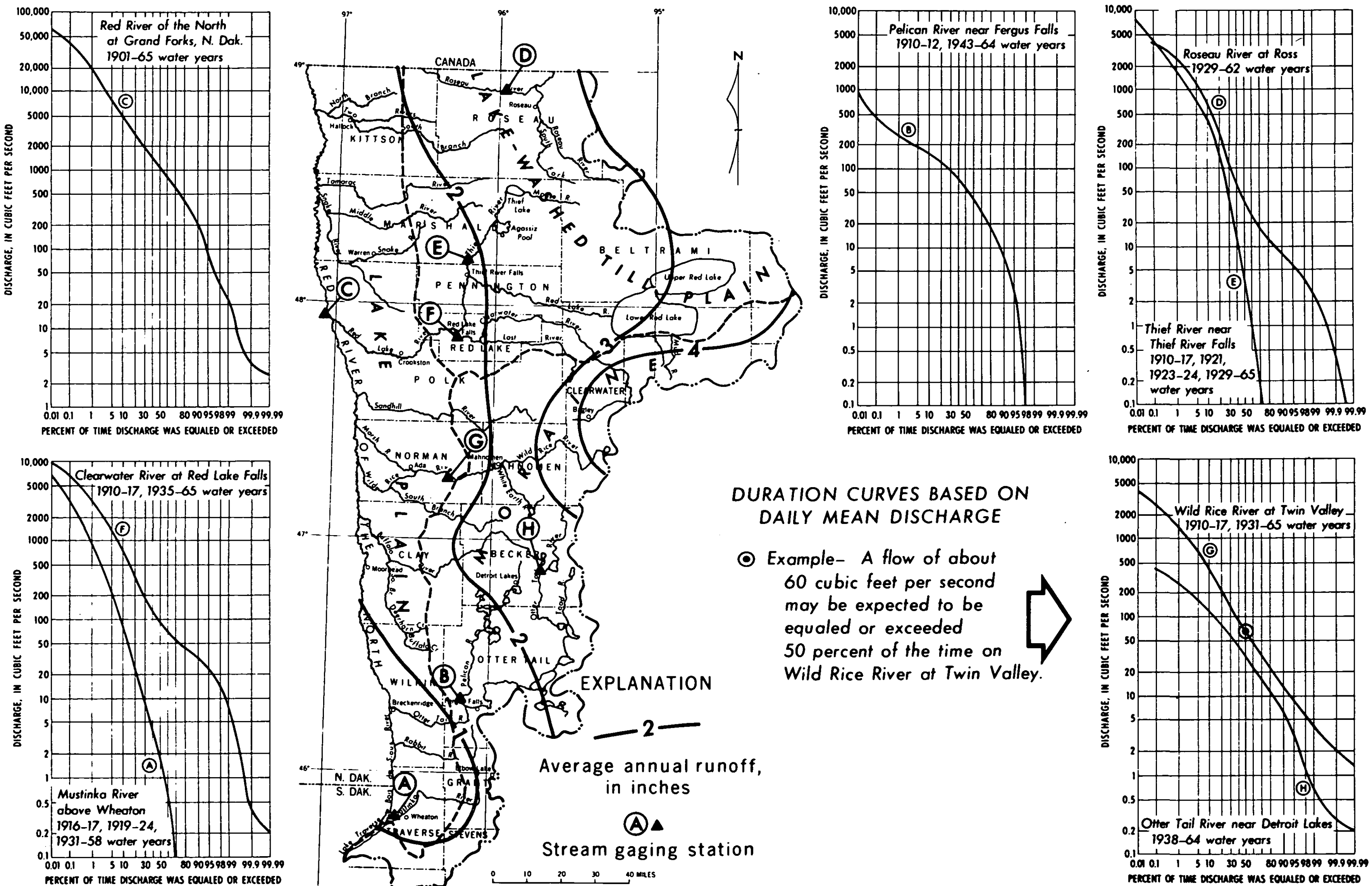


Figure 37.--Average annual runoff increases from less than 1 inch to more than 4 inches from southwest to northeast across the basin. The flow duration curves for tributary streams in the lake plain show considerably less tendency to maintain base flows than those for the morainal area.

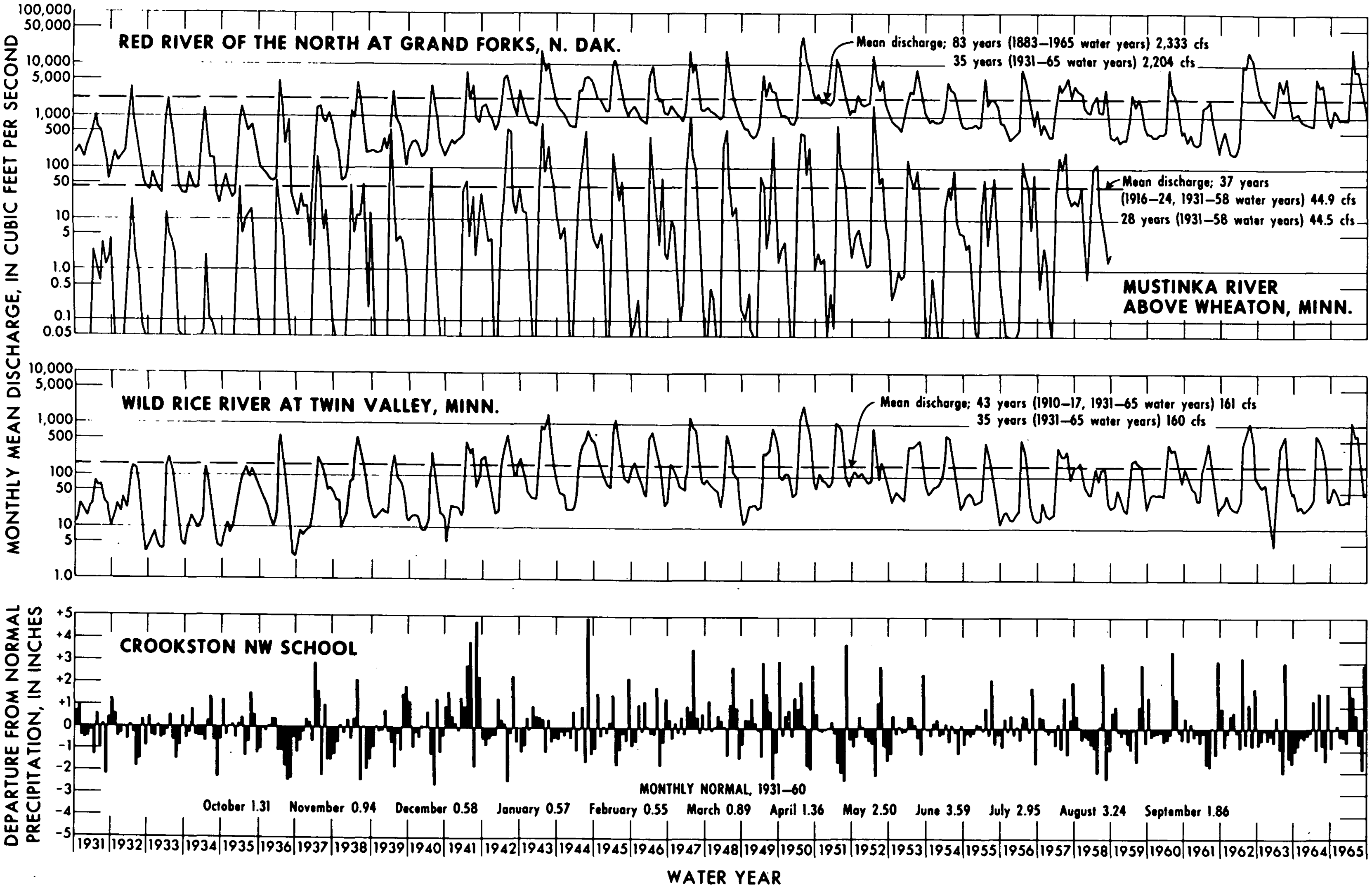


Figure 38.--Hydrograph for Mustinka River above Wheaton shows the "flashy" nature of streams in the lake plain compared to the more stable flow of the Wild Rice River at Twin Valley, which is typical of streams in the morainal area.

representative of the Red River basin in Minnesota. The below normal precipitation of 1931-40 had a marked effect on streamflow throughout the basin.

Three streams were chosen to illustrate differences in streamflow that can be expected because of location and differences in basin characteristics. The Mustinka River is typical of the streams in the lake plain, which contains few lakes or aquifers. It has long periods of no flow and wide variations of flow most years. In contrast, the Wild Rice River above the gage at Twin Valley drains the moraine with its many lakes and aquifers. The flow is more sustained during droughts, does not go dry, and has less monthly, seasonal, and yearly variation than that of the Mustinka River. The sustaining influence of the Minnesota tributaries heading in the moraine, such as the Otter Tail, Wild Rice, and Red Lake Rivers, is apparent in the hydrograph for the Red River of the North. The hydrograph shows the integrated effects of precipitation patterns, changes in geology and topography, and the regulatory effect of flow-controlling reservoirs.

Flow duration curves are useful for analyzing both the availability of streamflow and making comparative studies of many streams within a basin. The shape of the curves reflect the factors that influence streamflow in a river basin. The steepness of the curve is an indication of variability of daily discharge. A steep slope is indicative of a stream having little ground- or surface-water storage and a flat slope is indicative of high base flow from ground- or surface-water sources.

Flow duration curves for the Red River of the North and seven smaller streams in the basin are related to the average runoff and the three physiographic regions as shown in figure 37. With the exception of the Red River of the North, the seven streams have little or no artificial regulations and they were chosen because they are representative of the various regimens of flow found throughout the basin (flow duration curves for most gaging stations in the basin are found in the series of Hydrologic Atlas reports).

Roseau and Thief Rivers are both in the lake-washed till plain but the duration curves for the two rivers are dissimilar in shape. Roseau River receives much ground-water contribution from large areas of sand in part of its drainage area; whereas, the Thief River drainage basin consists largely of peat and poorly permeable glacial till, has little base flow, and goes dry most years. Clearwater River heads in the glacial moraine and flows through considerable deposits of outwash sand and gravel which contribute substantial quantities of ground water to the stream. The stream receives less ground-water contribution in the reach in the lake-washed till plain, and a duration curve for a site on the Clearwater River in the morainal area upstream would be much flatter at its lower end than the curve shown for Red Lake Falls. Wild Rice and Otter Tail Rivers drain a morainal area which includes lakes and outwash sand and gravel before flowing across the lake plain. The Pelican River heads in a lake area of the moraine which is similar to the headwaters area of the Otter Tail River, but has less ground-water contribution per unit area along the lower reaches than Otter Tail River, and it goes dry some winters. Mustinka River is typical of streams mostly within the lake plain. It is highly variable, receives little ground-water inflow, and goes dry most years. The daily flow of the Red River of the North is affected by manipulation of reservoir storage and sewage effluent as well as the natural effects of great variation in tributary discharge.

High flow

Analyses of flood peak discharge and stage and the duration of high flows are necessary to provide specific usable information on flood events. Although the duration curve shows the percentage of time a specified discharge is equaled or exceeded it does not indicate the magnitude, frequency, or duration of floods.

Most flooding on the larger streams in the Red River of the North basin has occurred in the spring and was a result of melting snow or a combination of melting snow and spring rains. Factors affecting the severity of flooding on a specific stream are 1) above-normal antecedent soil moisture; 2) unusually heavy snowfall; 3) delayed melting of snow; and 4) above-normal precipitation during the breakup period. Flooding during the snowmelt period is often aggravated by blockage of river channels and drainage ditches by snow and ice. This is especially true in the lake plain where low relief and slope of the land surface and the small capacity of natural channels result in slow runoff and overbank flooding that inundates large areas. There are also many areas in the lake plain where there is no protective tree cover to trap drifting snow, and channels often fill with snow to the level of the surrounding prairie.

Many of the larger tributaries of the Red River of the North head in the moraine where stream gradients are steep and the runoff is rapid. Flooding on the lower reaches of these streams is intensified because of the flat gradients of their channels in the lake plain. Ice jams on the main stem of the Red River of the North produce particularly damaging river stages between East Grand Forks and Canada; particularly during medium range floods. The river flows from south to north and the initial spring breakup in the headwaters is at least a week or two earlier than the ice breakup in the lower (northern) reaches of the main stem.

Because most floods occur in the spring and are coincident to breakup and ice jams, the stage of a river is not always dependent upon discharge. When there is a possibility of damage from inundation the stage-frequency relationship provides valuable data. The height of overbank flooding which occurs on the average at 5, 10, and 20 year recurrence intervals for 10 gaging stations in the basin is shown on figure 39. The sites were selected to provide an insight into the stage-frequency relationships, especially as it relates to the physiography of the basin.

Stage-frequency data for the Red River of the North at Grand Forks, N. Dak., is not related to the tributaries in Minnesota because of its north-south orientation and because of the great variety of basin factors affecting floods. The Red Lake River at Crookston also deviates from other streams in the basin because it is regulated at all stages by storage in the Red Lakes.

The stage-frequency data for the remaining 8 gaging stations are generally more characteristic of the moraine, lake plain, and lake-washed till plain areas in the basin. Sites A (Otter Tail River) and B (Buffalo River) are in the moraine and are similar, with little overbank flooding. Sites E (Clearwater River) and F (Wild Rice River) are both in the flat terrain, but on streams that head in the moraine, and have more frequent overbank flooding. Sites C (Sprague Creek), D (Middle River), G (South Branch Buffalo River), and H (Two Rivers) are within the lake plain or lake-washed till plain where overbank flooding is severe.

The stage-frequency relationship provides data for studies on flood-plain zoning and can be used in plans to reduce damages which might occur on the flood plain. Channel geometry is not constant throughout a physiographic area and a study of the topography and channel changes in an area is a necessary supplement to specific stage-frequency data for selected sites.

Records of peak discharges were analyzed by the annual-flood array method for the Red River of the North basin in conjunction with a flood-frequency study by Prior and Hess (1961). The mean annual peak discharge and the annual peak which will occur on the average once every 10 and 20 years at many sites in the basin are shown on figure 40. The flood-peak frequency data is especially applicable in the design of

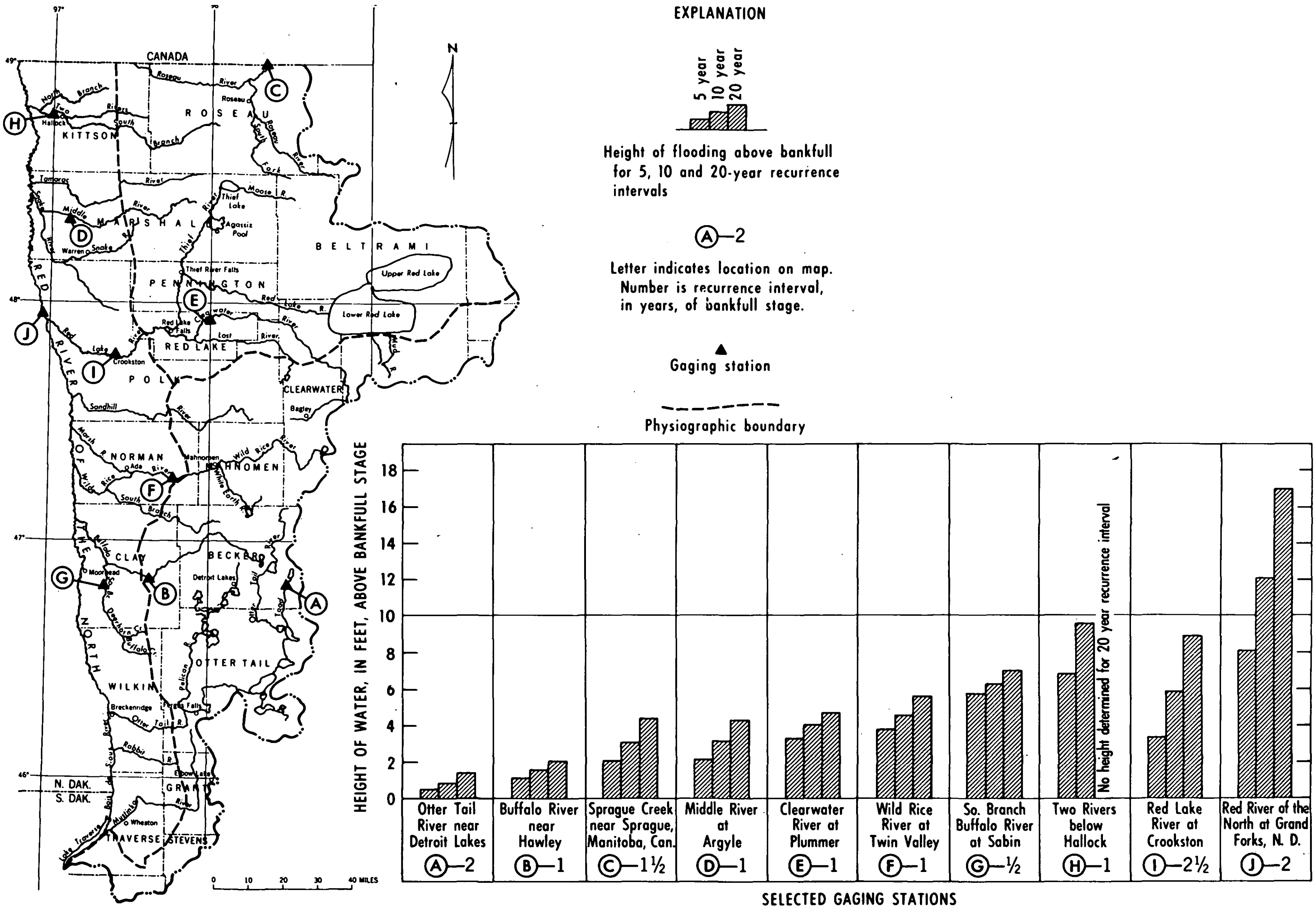


Figure 39.--Stage-frequency relationships for selected sites in the basin show little overbank flooding in the morainal area and considerable flooding on the Red River.

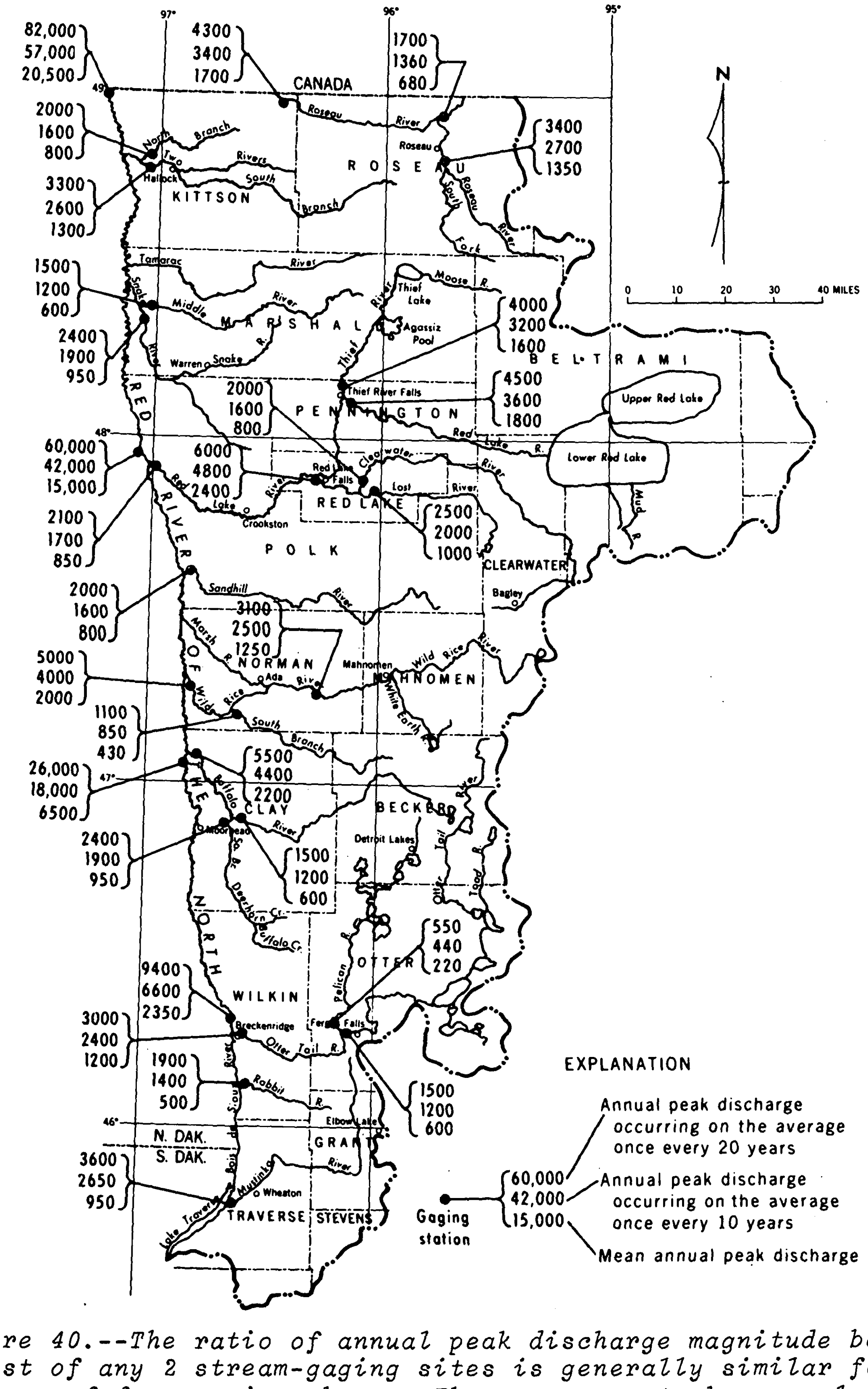


Figure 40.--The ratio of annual peak discharge magnitude between most of any 2 stream-gaging sites is generally similar for the range of frequencies shown. There appears to be no relationship to physiographic region.

bridge openings, channel improvement, and problems relating to reservoir capacity and flood routing.

The volume of water discharged is directly related to the duration of high water. The design of flood control structures is dependent upon the frequency and duration of floods. A high-flow frequency analysis has been made of the streamflow records from 5 gaging stations on the Red River of the North and 51 gaging stations on 12 large streams in the basin in Minnesota. Although there is some similarity in the shape of the high-flow frequency curves throughout the basin, differences do exist because of differences in the flood-producing factors. Seven streams were selected as representative to show the type of high-flow frequency relationships that are found throughout the basin. The data for the highest mean flows in cubic feet per second per square mile for 7 consecutive days for the 7 streams are presented in graphical form for ease in comparison (fig. 41). The curves for Red River of the North at Grand Forks and Red Lake River at Crookston illustrate the relationship for the largest streams, and include the greatest variety of basin characteristics.

Otter Tail River flows through the morainal area, has more than 13 percent of the drainage area in lakes, and has the least high mean flow per square mile. In contrast, the drainage area of the Wild Rice River at Twin Valley is also in the moraine but has only 3 to 4 percent in lakes, and maximum flows are higher. The Middle River and South Branch Buffalo River are entirely within the lake plain and show the highest maximum mean flow per square mile. Roseau River at Ross is in the lake-washed till plain but is similar to the Wild Rice River for recurrence intervals of 5 to 30 years because it is affected by storage in swamps and sandy areas. The highest mean flow for recurrence intervals of 2, 5, 10, 20, and 30 years for 7, 15, 30, 60, and 90 consecutive days for these same 7 streams is shown in table 4.

Low flow

Droughts call attention to the need for facts on the reliable yield of streams for present and future water supply needs. Low streamflow is affected by many natural factors which include 1) precipitation, 2) the amount of water stored in ground and surface reservoirs, 3) evapotranspiration, 4) length and severity of winter freezeup, 5) pattern of groundwater movement, and 6) the type, number, and location of lakes, potholes, and marshes in a river basin. Although factors affecting low flow are more homogeneous within the lake plain and lake-washed till plains (beach ridges and incised channels are exceptions) great variations exist within the

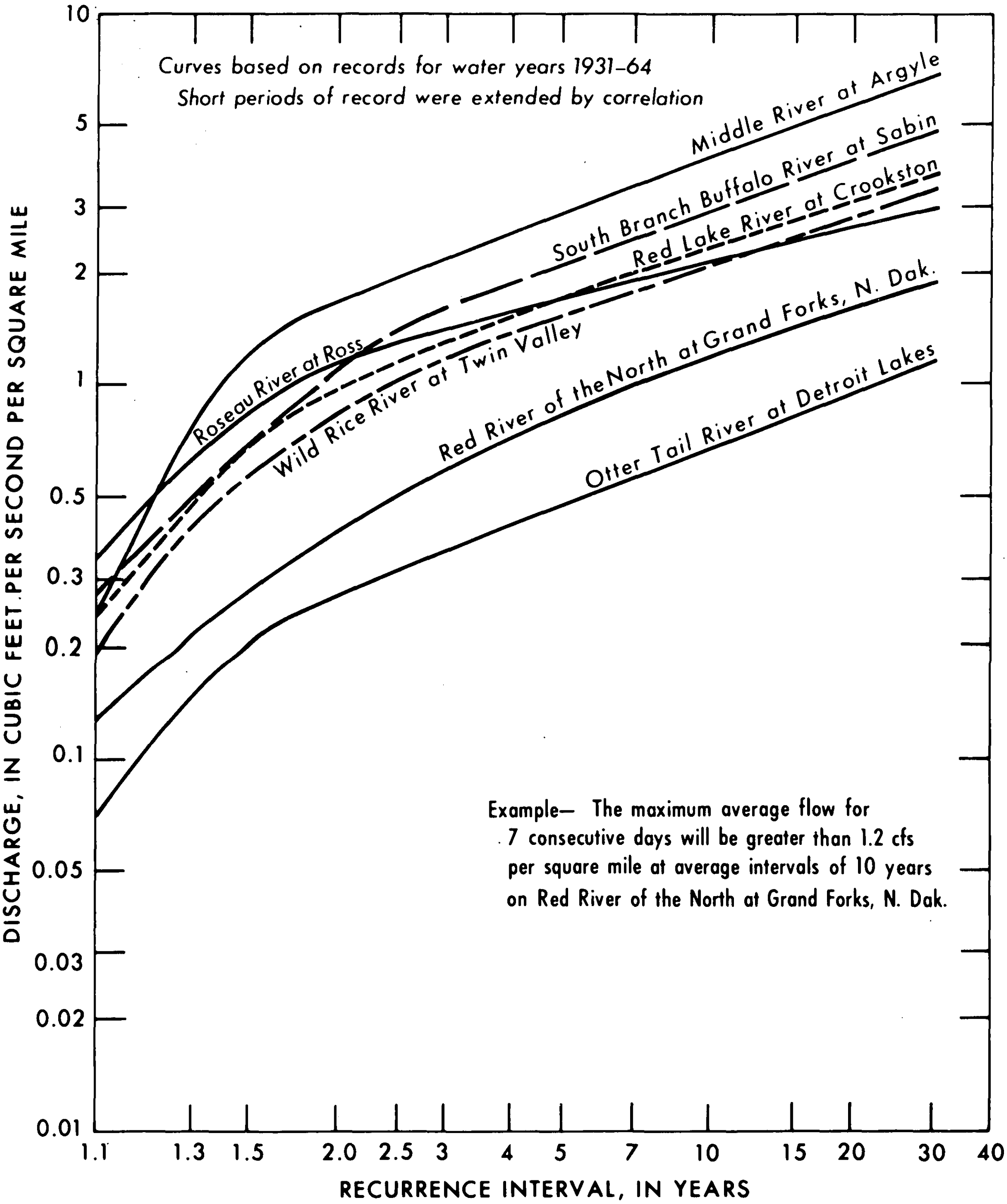


Figure 41.--Frequency of maximum average flows for 7 consecutive days show higher values for streams in the lake plain than for those in the moraine.

Table 4.--Magnitude and frequency of annual high flow at selected stream-gaging stations

Station Name	Drainage area (sq mi)	Period of record (water years)	Period (consecutive days)	Highest mean flow, in cubic feet per second, for indicated recurrence intervals, in years				
				2	5	10	20	30
Otter Tail River near Detroit Lakes, Minn.	270	1938-64	7	154	234	300	360	400
			15	145	219	275	330	368
			30	137	207	256	303	330
			60	122	183	228	270	299
			90	107	162	200	234	252
So. Branch Buffalo River at Sabin, Minn.	522	1946-64	7	760	1,300	1,740	2,300	
			15	540	890	1,170	1,530	
			30	340	580	790	1,030	
			60	198	350	490	660	
			90	148	247	340	460	
Wild Rice River at Twin Valley, Minn.	888	1910-17 1931-65	7	920	1,600	2,080	2,650	3,020
			15	760	1,280	1,650	2,120	2,440
			30	615	1,080	1,370	1,710	1,940
			60	445	810	1,040	1,320	1,500
			90	375	680	880	1,120	1,280
Red Lake River at Crookston, Minn.	5,280	1902-65	7	4,830	8,100	10,700	14,000	16,300
			15	4,050	6,550	8,600	11,000	12,600
			30	3,050	5,400	7,000	8,600	9,800
			60	2,300	4,200	5,400	6,400	7,150
			90	1,950	3,520	4,400	5,400	5,950
Red River of the North at Grand Forks, N. Dak.	30,100 (includes 3,800 sq mi in closed basin)	1905-63	7	11,400	20,800	27,200	32,700	36,000
			15	9,300	17,600	23,500	28,700	31,700
			30	7,000	13,800	18,400	23,000	25,600
			60	5,100	9,800	13,100	16,500	18,500
			90	4,400	8,200	10,800	13,500	15,300
Middle River at Argyle, Minn.	265	1951-65	7	460	800	1,040	1,400	
			15	310	560	740	930	
			30	180	360	500	640	
			60	105	210	320	450	
			90	84	170	240	330	
Roseau River at Ross, Minn.	1,220	1929-62	7	1,400	2,120	2,650	3,250	3,630
			15	1,300	2,000	2,480	3,050	3,430
			30	1,080	1,720	2,120	2,600	2,930
			60	780	1,250	1,600	2,000	2,300
			90	640	1,030	1,280	1,580	1,780

morainal area. In this region the effect of droughts on low streamflow is directly related to the presence of lakes, surficial sand and gravel aquifers, and the presence of seeps and springs. Local droughts extending through a few weeks or a season have fairly well-defined recurrence intervals. In contrast, major droughts, such as the drought of the 1930's, have a poorly defined recurrence interval because of lack of long-term streamflow records. Although flow-duration curves reveal the variability of daily discharge, it does not show the sequential character of natural flow. For example, a flow of 12 cfs is equaled or exceeded 90 percent of the time on the Wild Rice River at Twin Valley (fig. 37), but whether this discharge occurred in one drought period or in scattered days cannot be determined from the duration curve. The low-flow frequency curves define the minimum average flow for a specified number of consecutive days for various recurrence intervals. Streams that originate in the lake plain have no flow for long periods and low-flow frequency curves cannot be prepared for many of them. The minimum or no flow periods normally occur between late summer and the spring breakup. In order to consider the low-flow periods as a unit, the climatic year (April 1 to March 31) is used as the yearly unit for the low-flow frequency computations. For comparison the low flow of streams were analyzed on a regional basis and a common and representative period was used.

Ten rivers were selected to show the low-flow characteristics of streams in the Red River basin (table 5). This selection identifies the similarities and differences of low-flow characteristics in the three physiographic regions in the basin. The recurrence interval was determined for the minimum average flow for 7, 14, 30, 60, and 90 consecutive days and the values shown in table 5 for 2, 5, 10, 20, and 30 year recurrence intervals.

Minimum average flows for 7 consecutive days for 8 of the selected sites were converted to cubic feet per second per square mile, and plotted as frequency curves (fig. 42). Curves were not drawn for Middle River because the long periods of no flow precluded its use; or for the Red River of the North because the low flow is regulated and is not comparable to the tributary streams. To remove the differences caused by non-concurrent periods of record, frequency curves were defined also for the climatic years 1931-64. Frequency curves were not developed for 1931-64 for the Pelican River and South Branch Buffalo River because a satisfactory correlation could not be made with data for a long-term station.

Thief and South Branch Buffalo Rivers were selected to show the lack of ground-water contribution to streamflow.

Table 5.--Magnitude and frequency of annual low flow at selected stream-gaging stations

Station Name	Drainage area (sq mi)	Period of record (climatic years)	Period (consecutive days)	Lowest mean flow, in cubic feet per second, for indicated recurrence intervals, in years				
				2	5	10	20	30
Middle River at Argyle	265	1951-64	7	0	0	0	0	0
			14	0	0	0	0	0
			30	0	0	0	0	0
			60	0	0	0	0	0
			90	0	0	0	0	0
Thief River near Thief River Falls	959	1910-16, 1920, 1923, 1929-64	7	0	0	0	0	0
			14	0	0	0	0	0
			30	0	0	0	0	0
			60	0	0	0	0	0
			90	0	0	0	0	0
So. Branch Buffalo River at Sabin	522	1945-63	7	.1	0	0	0	0
			14	.1	0	0	0	0
			30	.1	0	0	0	0
			60	.1	0	0	0	0
			90	.2	0	0	0	0
Pelican River near Fergus Falls	482	1910-11, 1943-64	7	16	.3	0	0	0
			14	17	.6	0	0	0
			30	19	1.2	.1	0	0
			60	20	2.1	.3	0	0
			90	21	2.8	.6	.2	.1
Roseau River at Ross	1,220	1929-61	7	6.5	2.7	1.5	.7	.3
			14	7.5	3.1	1.8	.9	.6
			30	8.5	4.0	2.4	1.5	1.0
			60	11	5.7	3.7	2.3	1.6
			90	13	7.1	4.7	3.2	2.6
Otter Tail River near Detroit Lakes	270	1937-63	7	4.3	1.1	.4	.1	.1
			14	5.8	1.5	.6	.2	.1
			30	6.7	2.1	.9	.4	.3
			60	10	3.7	1.9	1.0	.6
			90	13	5.0	2.8	1.6	1.3
Red River of the North at Grand Forks, N. Dak.	30,100 (includes 3,800 sq mi in closed basin)	1904-64	7	400	160	88	46	31
			14	440	180	99	52	35
			30	480	200	110	58	39
			60	530	230	130	71	49
			90	580	250	140	80	55
Wild Rice River at Twin Valley	888	1910-16, 1931-64	7	16	6.7	3.8	2.2	1.6
			14	18	7.4	4.3	2.7	2.0
			30	19	8.5	5.2	3.3	2.6
			60	22	10	6.2	4.1	3.2
			90	27	13	8.0	5.3	4.3
Red Lake River at Crookston	5,280	1902-64	7	200	45	18	8.3	5.7
			14	220	53	20	9.5	6.6
			30	245	69	27	12	7.8
			60	285	80	31	14	9.2
			90	320	93	34	15	10
Buffalo River near Dilworth	1,040	1931-64	7	8.4	1.9	.4	.1	0
			14	9.0	2.2	.6	.1	.1
			30	9.8	2.6	.8	.2	.1
			60	11	3.8	1.4	.5	.2
			90	12	5.0	2.5	1.3	.9

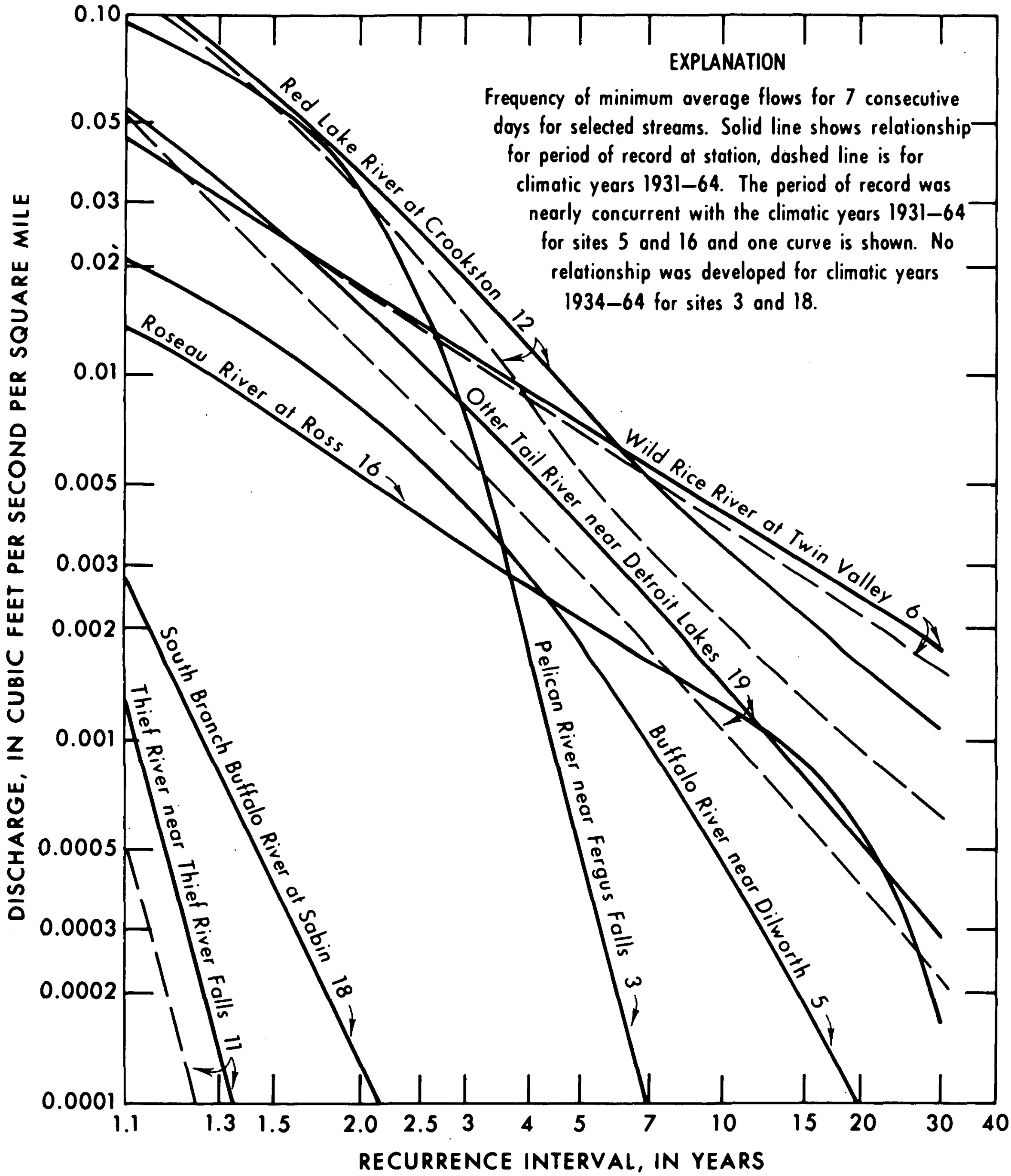


Figure 42.--Frequency of minimum average flows for 7 consecutive days show the contrasting characteristics between streams in the lake plain such as South Branch Buffalo River at Sabin and those in the moraine, such as Wild Rice River at Twin Valley.

Thief River is in the lake-washed till plain and drains large areas of peat and glacial till and has long periods of no flow. South Branch Buffalo River is in the lake plain and drains lake clay and fine lake sand. The low-flow frequency curve for South Branch Buffalo River does not include the period of extreme low flow during the 1930's, and consequently is relatively high in discharge in comparison to the Thief River curve. Most of the streams in the lake plain that head near the edge of the moraine, such as the South Branch Buffalo River, have much ground-water contribution from seeps and springs in the headwaters area. Three factors tend to reduce the amount of base flow in downstream reaches of these streams: 1) evapotranspiration is high in the bogs and at the base of the moraine; 2) long periods of no flow occur during winter because of freezeup and continual buildup of ice throughout the winter in the poorly developed drainage channels in the flat terrain; and 3) small ground-water contribution to base flow along the stream channels within the lake plain.

Although the Roseau River is within the lake-washed till plain, ground water in the large areas of sand, especially in the Beltrami Island area, contributes heavily to the low flow at Ross. The Wild Rice and Otter Tail Rivers have high base flow from large amounts of ground-water storage in sand and gravel deposits in the morainal area. In contrast, the Pelican River has lower sustained flows and goes dry during severe winters. Red Lake River is a large contributor of low flow to the Red River of the North below East Grand Forks because of surface storage. The low-flow frequency curve for Crookston does not reflect natural flow conditions because of regulation from the Red Lakes.

The 2-year 7-day low flow is useful in determining the adequacy of streamflow for water supply or its capability to dilute waste effluent. The median 7-day flows are a direct indication of the base-flow characteristics of the streams in the basin. The median 7-day low flows were converted to cubic feet per second per square mile and whenever possible the short term records were extended by correlation to the climatic years of 1931-64. These median 7-day values at the gaging stations were extended along the streams based on miscellaneous discharge measurements, size of drainage area, surficial geology, and topography (fig. 43). As previously emphasized, the low-flow figures do not include streams draining small areas because locally there are great variations in basin characteristics.

Since the question of adequacy is one of the first to be considered for a water supply, tables 3 and 5 and figures

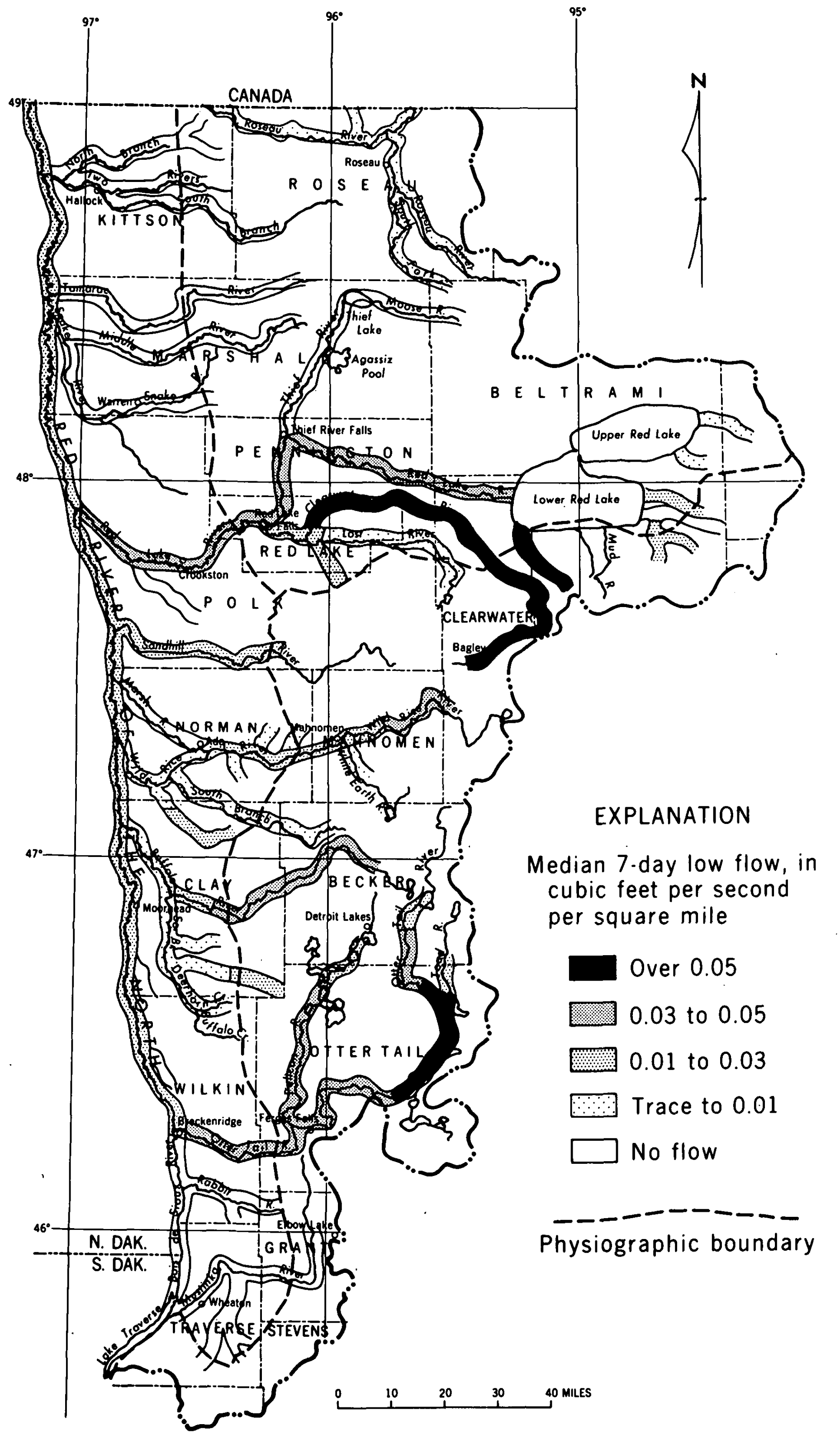


Figure 43.--The highest median 7-day low flow occurs in the Otter Tail and Clearwater Rivers where they traverse the areas of outwash and ice-contact sand and gravel.

42 and 43 should be considered in answering: 1) will there be enough flow to meet the minimum requirements; 2) will the no-flow periods be of such short duration that they may be neglected; and 3) will the recurrence intervals of specific low flows be great enough to warrant the use of a surface supply.

An indication of the extent to which streams in the basin go dry is shown by the 30 selected gaging stations on tributary streams in figure 44. Streams selected were those that are representative of natural conditions throughout the basin. Each year in which 7 consecutive days of no flow occurred is identified. It has been concluded by Erskine (1962) that the minimum flows of the 1930's were probably the lowest that occurred in the Red River of the North during a period of at least 150 years and because of its severity the years 1931-40 have been accentuated by the shaded band in the table in figure 44. Streamflow records show a marked reduction in discharge during the drought years, but it is apparent from figure 44 that the streams that had no flow for 7 consecutive days during 1931-40 continued to have similar periods of no flow in most other years of record.

Ground-Water System

The ground-water reservoir, the saturated zone lying between the water table and the top of the basement rocks, forms a highly complex system. Because of the internal variability of the reservoir, the ground-water flow patterns are complex in detail; however, the larger aspects of ground-water flow can be described by a model based on water-level measurements and topography (fig. 45). This model is conceptual, especially for much of the upland recharge area, because reliable information on water levels were not available to delineate more precisely areas of recharge and discharge. Quantitative estimates of input and output cannot be determined from this model; however, they are in approximate balance. Tentative interpretations that can be drawn from the descriptive model are: 1) the ground-water reservoir is essentially full, the water table is usually within 30 feet of the land surface in the morainal area, and within 10 feet in the Glacial Lake Agassiz area; 2) much of the recharge is not transmitted from the morainal recharge area to the lake plain but is locally discharged; 3) some of the recharge that enters the upland area is discharged in a belt that lies near the edge of the lake plain and lake-washed till plain; and 4) streams and lakes are not generally a source of large quantities of natural recharge in the morainal upland but are areas of discharge. The last conclusion has particular significance to water management because it is

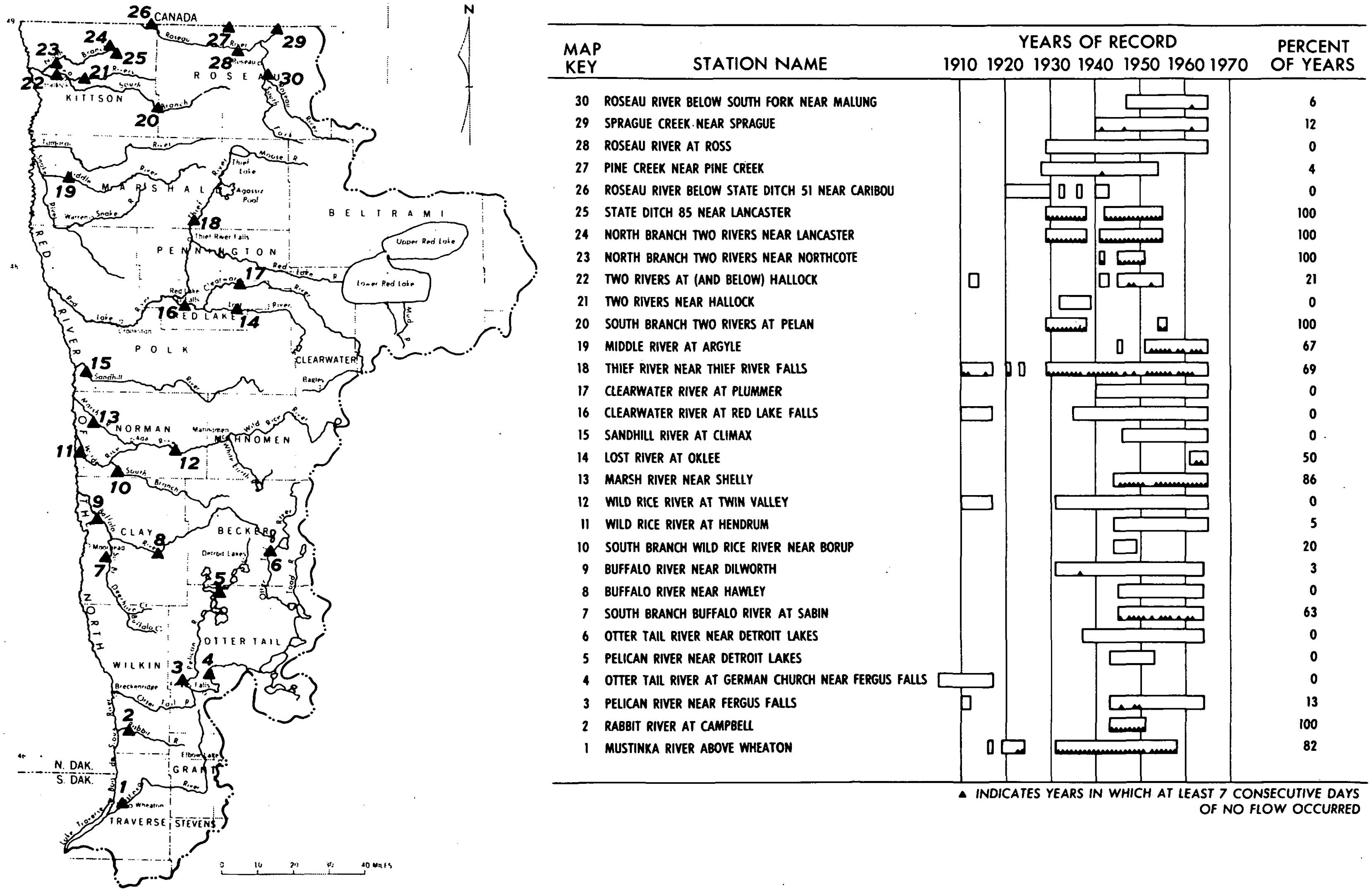
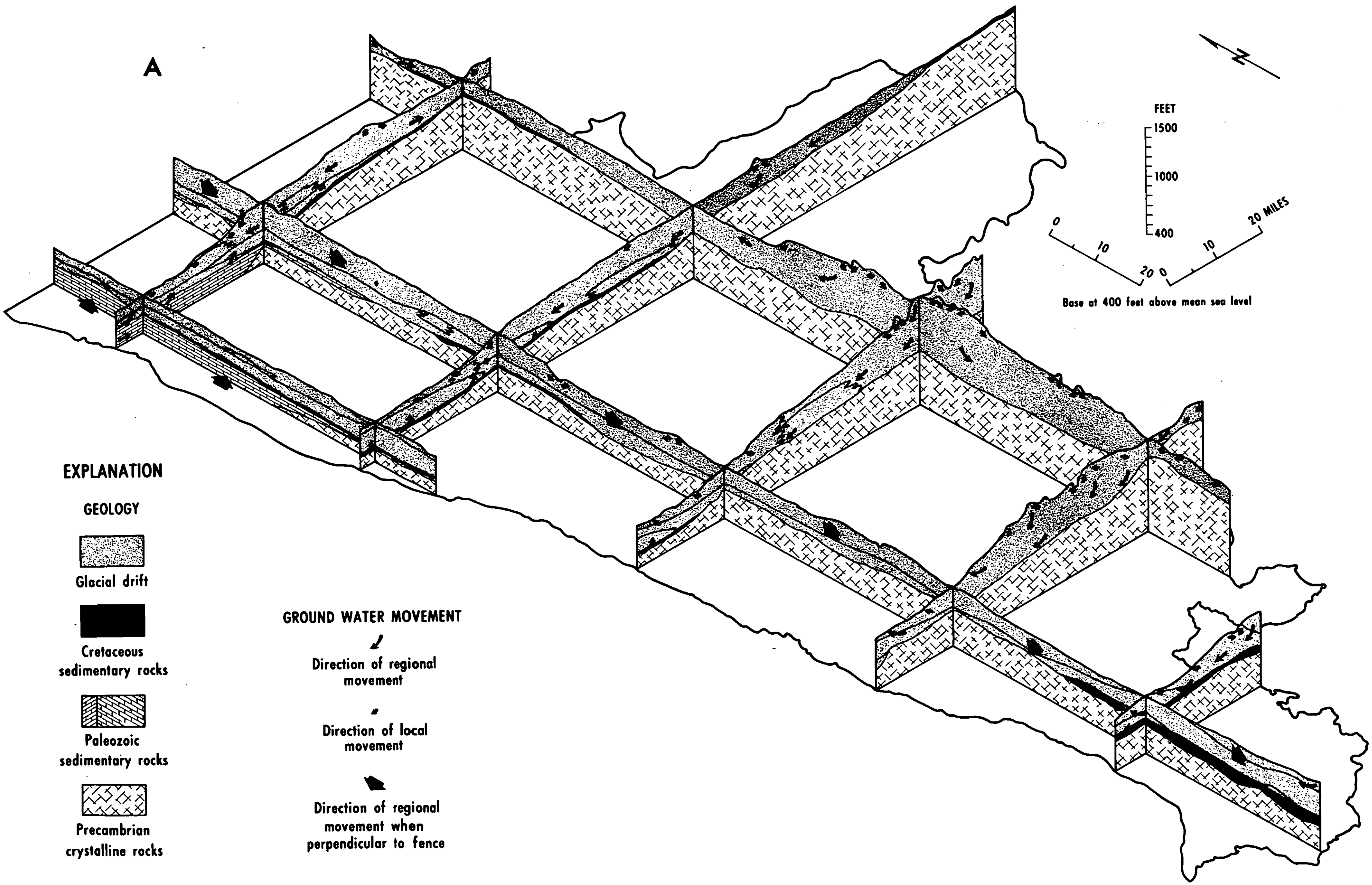


Figure 44.--Many streams in the basin, particularly those confined largely to the lake plain or lake-washed till plain, have years in which at least 7 consecutive days of no flow occur.


A
FEET
1500
1000
400
0
10
20
0
10
20 MILES
Base at 400 feet above mean sea level
EXPLANATION
GEOLOGY
Glacial drift
Cretaceous sedimentary rocks
Paleozoic sedimentary rocks
Precambrian crystalline rocks
GROUND WATER MOVEMENT
Direction of regional movement
Direction of local movement
Direction of regional movement when perpendicular to fence

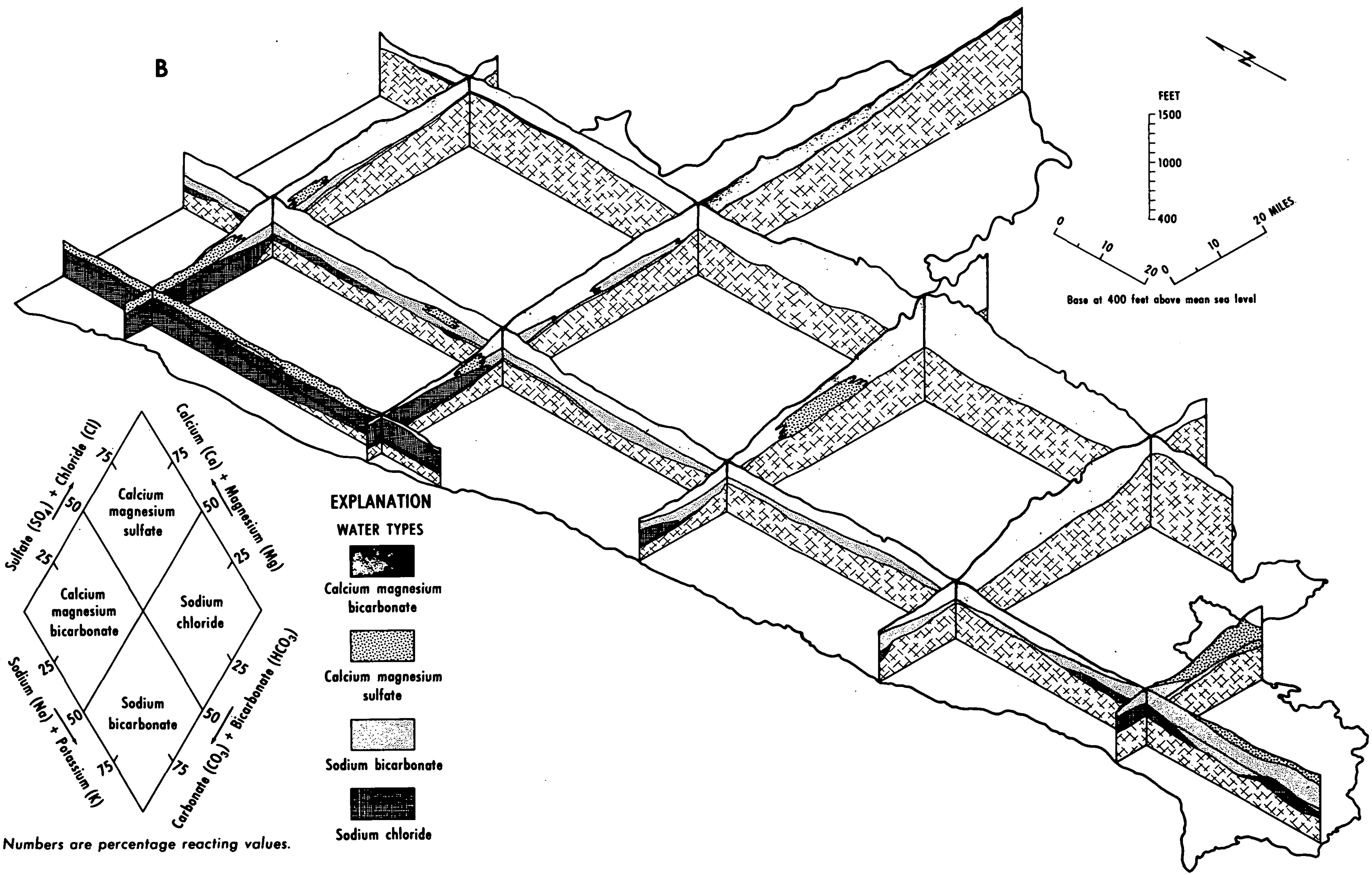


Figure 45.--As shown in A, ground water moves generally from the morainal area to the lake plain. However, large amounts of water move from high areas to adjacent lowlands in the morainal area. As shown in B, highly saline water in the northwestern part of the basin moves into Minnesota from North Dakota in the stratified sedimentary rocks.

generally believed by many in the area that lake levels and stream discharges in the upland areas contribute substantially to ground water.

Recharge to the Ground-Water System

The most important controls on regional ground-water recharge are local relief, overall slope of the basin, and permeability of the ground-water reservoir. These factors determine how much water can move through the ground-water reservoir and, thereby, how much water may enter the reservoir. In the Red River of the North basin the relief and overall land slope is generally low and the permeability is small, therefore, little ground water moves to the deeper flow systems.

The factors that locally affect ground-water recharge are the condition of the soil surface, density of vegetation, temperature, physical properties of the soil (porosity and permeability, grain-size distribution, and soil-moisture content), transmissivity of the ground-water reservoir, and climatic conditions including intensity of the rainfall and time and space distribution of precipitation.

Field methods used in this report for determining recharge to the ground-water system in specific areas are based largely upon fluctuations of water levels in observation wells. By knowing the change in water level and the specific yield of the aquifer the amount of recharge can be estimated. Fluctuations of water levels in typical wells for different geologic and hydrologic conditions are shown on figure 46.

All the wells show a typical pattern of a large rise in level in spring to gradual recession throughout the remainder of the year. The graph for the well near Warren shows the decline of artesian pressure over a 10-year period caused by pumping. In general, fluctuation of water levels in deeper wells isolated from pumping indicate long range variations in the recharge due to long range variations in precipitation. Fluctuations of the shallow wells isolated from pumping reflect local climatic conditions within local flow systems.

For estimating regional recharge, base flow analysis of the streams, pumpage inventories, and the flow system in the regional discharge areas were analyzed. By this method ground-water discharge is equated to ground-water recharge assuming that the natural system is in hydrologic equilibrium. With these concepts in mind, it is estimated that recharge to local flow systems may be as great as 5 or 6 inches in sandy areas, whereas, recharge to the deeper flow systems is probably of a magnitude of an inch or less. For water management purposes,

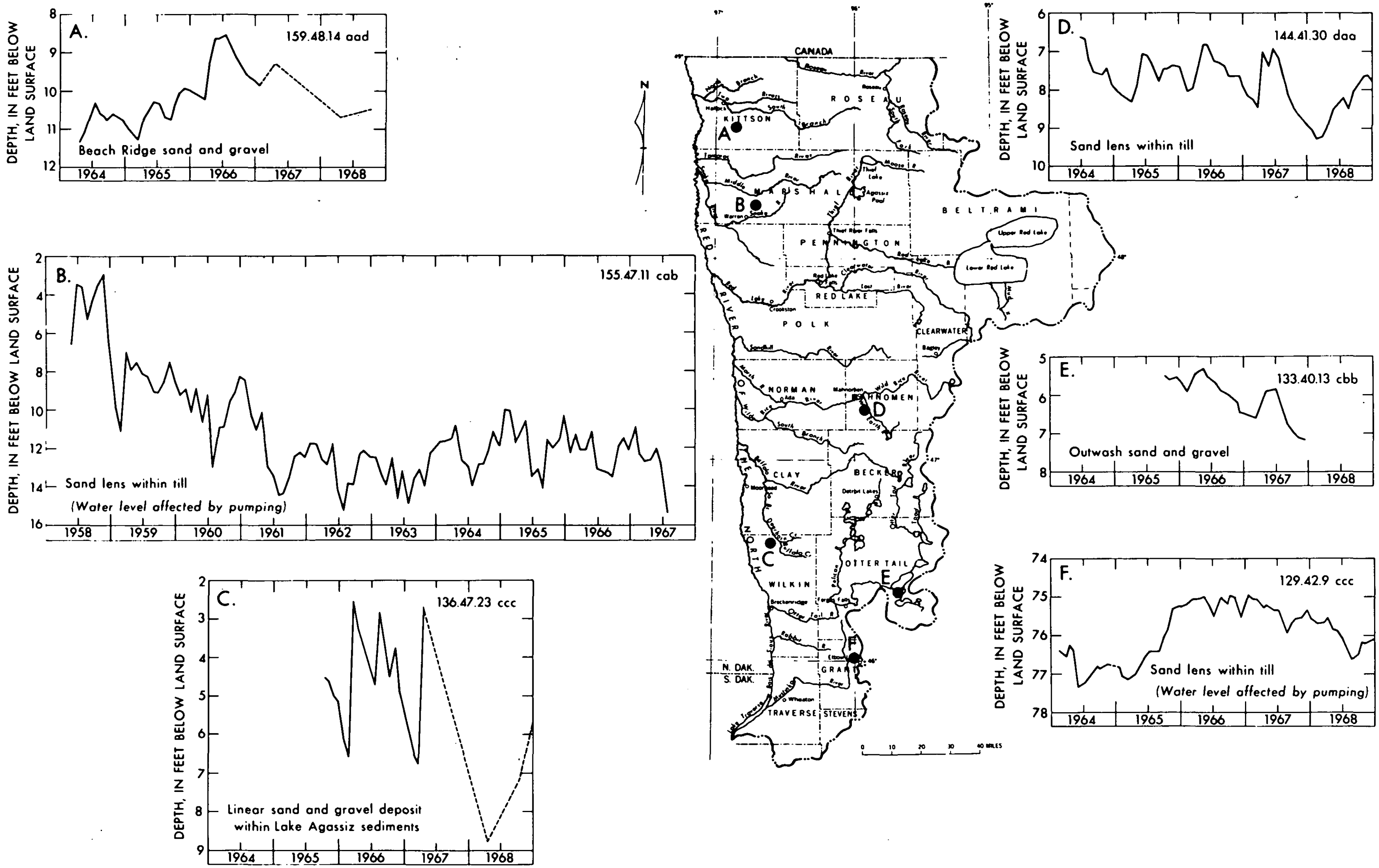


Figure 46.--Water levels in observation wells in different types of aquifers have similar patterns of fluctuation when they are not affected by pumping. Generally the fluctuations are greater in water-table aquifers in recharge areas than those in discharge areas near lakes and in artesian aquifers.

the factor of most interest is the recharge within the flow system in which the aquifer occurs. However, for regional water planning when total water development is anticipated or ground-water pollution is involved, knowledge of the total recharge to both local and regional flow systems is important.

Movement Within the Ground-Water System

One of the main objectives of this investigation was to determine patterns of ground-water circulation within the ground-water reservoir. To map ground-water movement in the Red River of the North basin; first, a generalized water-table map for the entire basin was made using the maps published in the hydrologic atlases, and secondly, flow profiles were constructed normal to the water-table surface at selected intervals from south to north within the basin (fig. 45).

A water-table map shows direction of lateral ground-water movement. Vertical movement can be inferred but not mapped or delineated. For example, it is assumed downward movement of water occurs under water-table highs.

Flow profiles (fig. 45) show the vertical component of ground-water flow. This interpretation of flow patterns is based upon reported and measured water levels in selected wells completed at various depths within the ground-water system supplemented by topographic evidence, chemical quality of water within the ground-water reservoir, and observations of seeps and alkali belts on the land surface.

Theoretical work of Hubbert (1940), and field applications of ground-water flow by Meyboom (1962) and Meyboom, Van Everdingen, and Freeze (1966) were useful in interpretations of movement patterns in the Red River basin. Altitude of water level in wells is a measure of the energy potential of water at the point of intake which is generally the well screen. This potential energy is made up of an elevation component which is determined by the elevation of the well screen from some given datum plus the pressure head which is represented by the height of the water column above the well screen. The hydraulic potential is defined as: $\emptyset = z + hp$,

where: $\emptyset$ is the potential head at measuring point, in feet.
hp = pressure head in feet, which is equivalent to the height of the water column above the measuring point divided by the specific gravity of water.
z = elevation of datum, in feet.

In general, the flow profiles indicate a decrease in hydraulic potential with depth in the higher morainal areas and a general increase in potential with depth in the discharge area lying along the western edge of the moraine. Two significant interpretations can be made from the profiles. First, that there is no simple flow system within the Red River basin that describes all ground-water movement although gross interpretations can be made. In the morainal area the effect of topography results in many local flow systems; deeper flow to the ground-water reservoir probably occurs only under the higher upland areas of the morainal area. Much of the recharge that occurs within the moraine is locally discharged to springs and lakes or rivers in the lowlands or valleys within the morainal area. This idea is developed further in the section on ground water-surface water relationships. Second, a regional discharge area was identified along the edge of the lake plain near the moraine. This discharge zone occurs because less energy is required to move the water upward to the land surface than to move it laterally through the tight ground-water reservoir in the western part of the lake plain. Low natural base flow of the Red River and tributary streams in the lake plain supports the above interpretation.

Discharge From the Ground-Water System

Ground-water discharge areas were determined by mapping seeps, wetlands, alkali soil belts, and vegetation patterns, and analyzing selected stream hydrographs and ground-water flow patterns. Major ground-water discharge areas for the Red River basin, other than streams, include wetlands and lakes in the morainal area and zones of upward seepage of ground water in the Glacial Lake Agassiz region (fig. 47). The most significant continuous belt of upward movement is along the eastern edge of the lake plain adjacent to the morainal area. This belt of ground-water discharge is indicated also by the increase in hydraulic potential with increasing depth as indicated by water level and well depth data (fig. 45). In Wilkin and Clay Counties, areas of alkali soil are widely scattered throughout this discharge area. It is believed that the alkali results from the migration of mineralized ground waters to near the surface where the alkali minerals are concentrated because of evaporation of the water.

Numerous springs, some of which flow at more than several hundred gallons per minute are found throughout this belt and are particularly abundant in Wilkin and Clay Counties. An unusual type of spring that flows from tops of low mounds occurs in the vicinity of Lawndale, in the northeastern part of Wilkin County. The spring mounds range in height from about 5 to 15 feet and may cover an area up to about a half acre in extent. The springs occur within wet, grassy, pastureland below which the water table usually lies within a few feet of the land

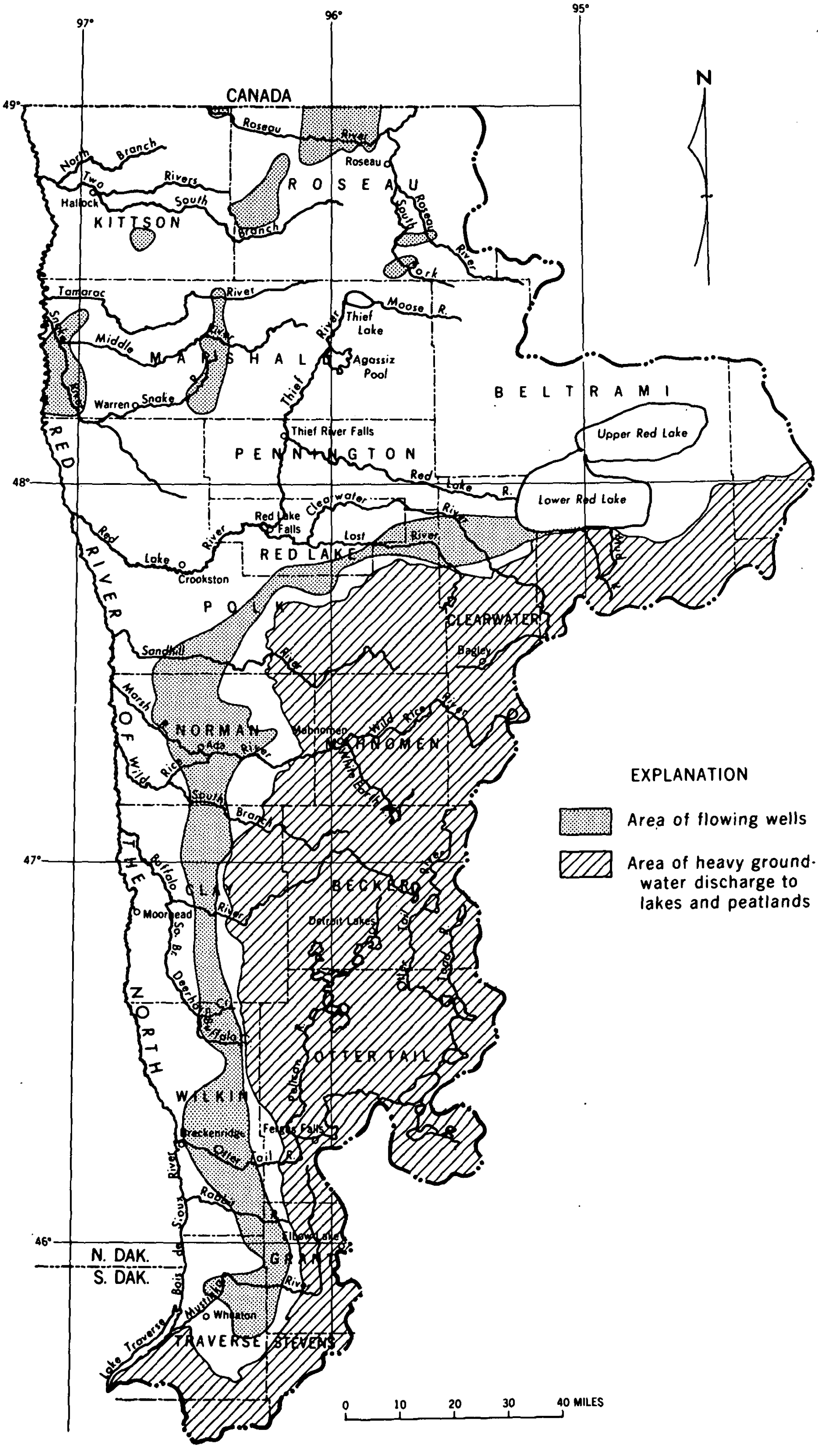


Figure 47.--Most ground water is discharged locally to lakes, peatlands, and rivers. A significant quantity of ground water is discharged by upward movement to the water table where it is removed by evapotranspiration. This area is shown by the zone of flowing wells.

surface. The mound itself consists largely of peat, and near the top of the mound the materials become increasingly spongey. In the area near Barnesville, Clay County, difficulty was encountered in preventing the creation of artesian springs at the site of shallow exploratory auger holes. At one auger hole site near Lawndale a spring was created that flowed about 200 gpm. This spring was later grouted at considerable expense in order to stop the flow.

In the later 19th century and early 20th century, before the major influx of population within the lake plain area, wells tapping the drift below the lake deposits flowed in the vicinity of the Red River of the North. Since then water levels within the western part of the lake plain have slowly declined to the extent that flowing wells no longer exist near the Red River of the North. The average decline in water level near the Red River of the North is probably between 5 and 10 feet for the period since the early part of the century. Locally, the water-level decline has been as much as 150 feet at Moorhead where buried sand and gravel aquifers have been tapped for a municipal water supply. Because of the declines in water levels in this area, ground water has locally reversed its gradient and now is recharging the underlying drift aquifers rather than discharging upward toward the land surface.

Ground-water discharge areas for the sedimentary rocks that underlie the glacial drift occur within the lake plain area (fig. 12). The Paleozoic and overlying Cretaceous rocks in the northwestern part of the Red River basin contain highly saline water which has migrated eastward from North Dakota, and is being discharged where these rocks pinch out against the crystalline rocks in Minnesota. The Paleozoic and Cretaceous rocks contain permeable zones; however, the discharge from them is greatly restricted by the overlying relatively impermeable drift. Slow upward migration of saline water has resulted in contamination of ground water within the overlying drift.

Water in Cretaceous rocks in the southern part of the Red River basin locally moves upward and mixes with the waters in the overlying drift deposits. Upward movement of water from Cretaceous rocks occurs largely in the lake plain. In the morainal area, some recharge to the Cretaceous rocks occurs. This water moves westward and in the lake plain also moves upward.

In summary, most of the ground-water discharge occurs near the place of recharge within the Red River basin. Because of the relatively impermeable reservoir rocks, regionally low gradients, and dominance of local flow systems in the morainal area, only a small part of the water that falls within the upland morainal area reaches the regional discharge areas.

Relation of Ground Water to Surface Water

Although it is convenient to discuss the details of surface water and ground water separately, at certain places in the system the two are very closely related and it is useful to discuss them together. At time of low flow, surface water consists entirely of ground-water discharge, and in regard to lakes, particularly closed lakes, ground-water flow is closely related to lake levels.

Relation of Ground Water to Streams

The effect of ground-water discharge on streamflow can be shown areally or temporally. To determine areal effects, the stream discharge is measured at many points along a stream to identify reaches of the stream where ground water is entering or leaving and at what rate. This must be done within a relatively short period of time. To show the time effect, hydrographs of streamflow are separated to determine the base flow, or ground-water component. Low-flow frequency analysis and flow-duration analysis supplement the techniques described here. These are discussed in the section on the Surface Water System.

Numerous low-flow measurements were made on the Wild Rice, Sand Hill, and Clearwater Rivers. Results of these three studies are described in the Hydrologic Atlas series (HA-339 and 346). The increase in ground-water contribution to the Wild Rice River, for example, is about 1 to 1.5 cubic feet per second per mile (cfs/mi) in the area of ice-contact sand and gravel in the morainal area and in the beach ridge sand and gravel area. Ground-water flow to the stream is low to moderate in the area of glacial till and in the lake-plain area is less than 0.1 cfs/mi. At the time of this study the stream was at about 82 percent flow duration.

Separation of streamflow hydrographs was done for the Wild Rice River at Twin Valley for 1937 and 1947 to show the relationship of base flow to total flow with a wide range in discharge. (See HA-339.) Hydrograph separation can also be used to show the effects of basin geology on ground-water contribution to streams. A comparative study was made between the South Fork Roseau River basin near Malung (sand covers about 20 percent of its drainage area), and Pine Creek near Pinecreek (sand covers about 60 percent of its drainage area). Base flow is relatively stable and an important part of the streamflow on Pine Creek; whereas, South Fork Roseau River is a very flashy stream that has widely variable ground-water inflow and many periods of no flow. (See fig. 48).

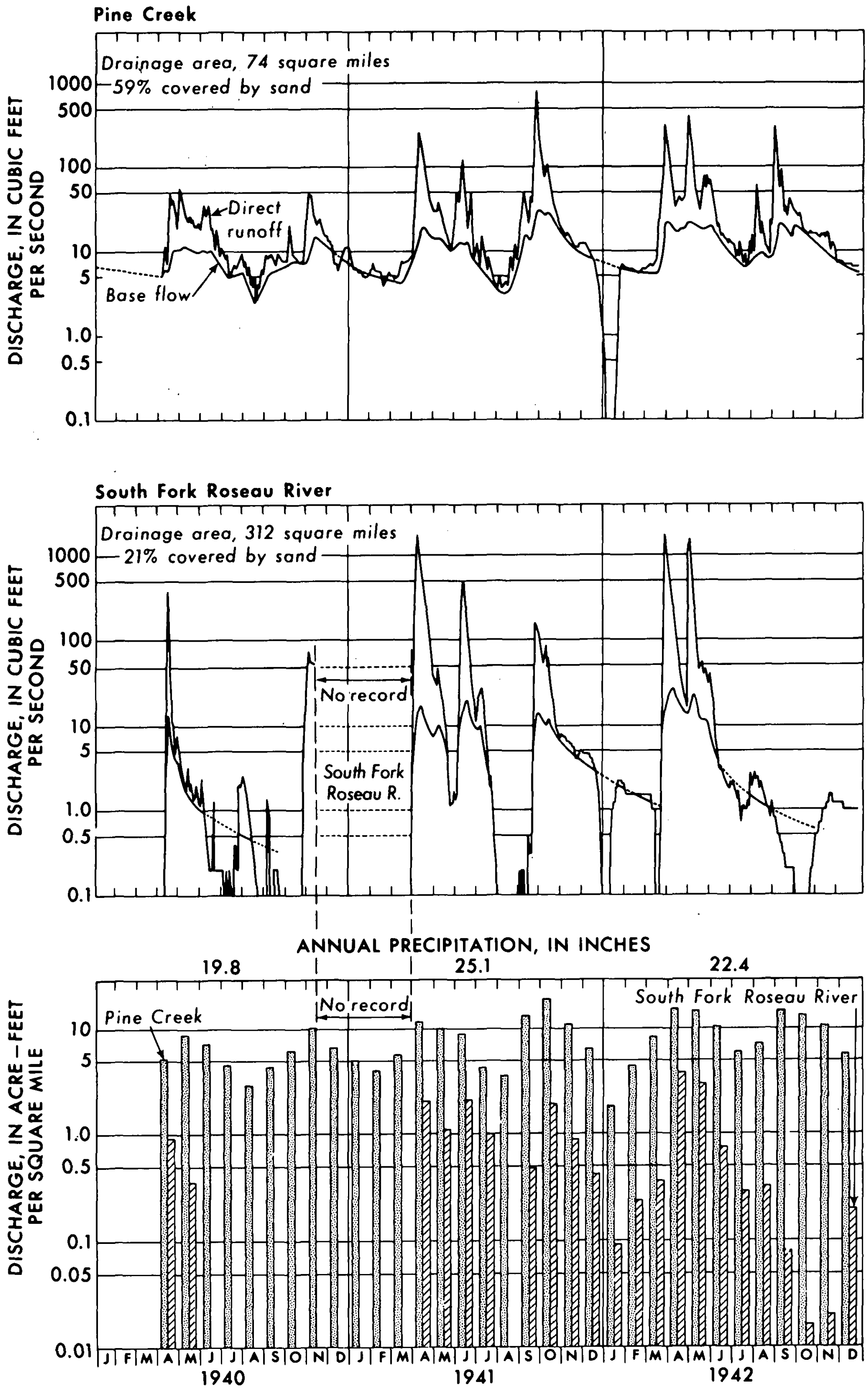


Figure 48.--Separation of baseflow on hydrographs of Pine Creek and South Fork Roseau River show a much more stable flow pattern for Pine Creek (59 percent of area covered by sand) than for South Fork Roseau River (21 percent of area covered by sand).

Relation of Ground Water to Lakes

In the morainal area most ground water moves from recharge areas at topographic highs to adjacent lowlands where the water is discharged. The lowlands generally contain lakes or bogs which are not only the recipient of surface runoff, but also ground water that has moved from nearby recharge areas. The study of ground-water contribution to lakes is, therefore, largely a study of local flow systems, although knowledge of regional ground-water flow systems is also important.

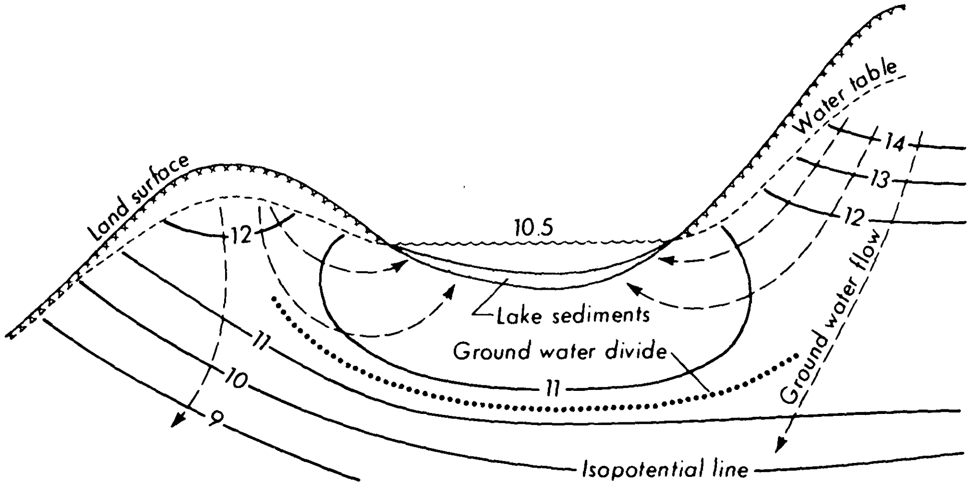
Little thorough work has been done on the ground-water relationship to lakes. The U.S. Geological Survey is studying the ground-water system near potholes in North Dakota (Sjeflo and others, 1962). The University of Minnesota (Manson, Schwartz, and Allred, 1968) is also studying ground-water near lakes in Minnesota. In the prairies of western Canada, Meyboom (1966) studied ground-water flow near sloughs. The conceptual models discussed below show relationships that could likely exist near lakes in the Red River basin.

Diagrammatic sketches of lake basins in homogeneous, isotropic geologic material are shown on figure 49. In figure 49A the isopotential lines are drawn in such a manner that ground water can move into, but not out of, the lake. This is because the isopotential line labeled 11 is closed. Another 11 line would then have to be drawn below the line that is closed around the lake and a divide is then established. The presence of this divide makes it impossible for water to move from the lake into the ground-water system.

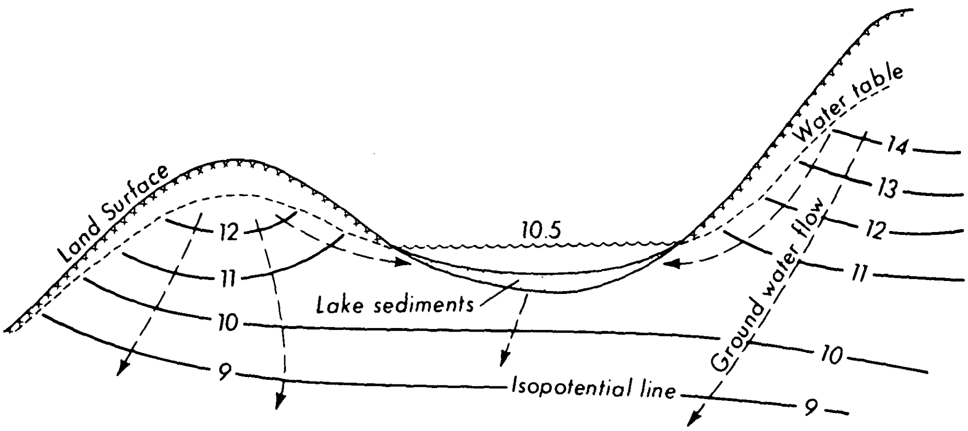
Another diagrammatic sketch of the same lake basin but with the isopotential lines drawn another possible way is shown on figure 49B. In this situation an isopotential line does not close around the lake and the possibility for water movement from the bottom of the lake does exist. It is very likely that water would move to the lake around the edges and away from the lake in the center. The line separating inflow and outflow is unknown.

A third possible situation could exist where the water table on one side of the lake is lower than lake level (fig. 49C). In this case, water would flow from the lake into the ground on the side that has the lower water table, and from the ground to the lake on the other side. Again, the line separating inflow from outflow is not known. If one is to study the ground-water relationship to lakes it is necessary to establish piezometers around the lake and within the lake to measure ground-water gradients directly.

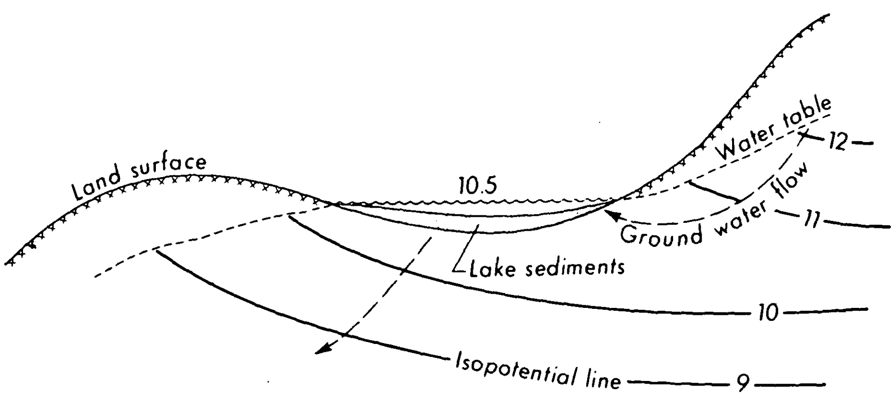
The examples used here are very simple and are used only to present concepts. In nature, many variations in geologic



A.



B.



C.

Figure 49.--Hypothetical sketches of 3 possible relationships of ground water to lakes: A) lake is end point of closed ground water flow system; B) lake receives ground water along sides but loses water to ground in central area; C) lake receives ground water on one side but loses water to ground on other side.

and topographic settings exist and the ground-water relation to the lake is different in each case. Where the ground-water level in the area near the lake is about the same as the lake stage, wide fluctuations in lake level over the year will affect the direction of movement. For example, in the spring if the water level in the lake rises above the surrounding water table, water will move from the lake to the ground-water system. Conversely, throughout the remainder of the year when the lake level drops below the surrounding water table, ground water will move into the lake.

Because of the lack of data and studies it is not known which, if any, of the conditions described above is the most common. In any case, much ground water from local flow systems discharges to lakes around the edges.

Lake sediments affect the ground-water relation to lakes. The sediments are generally fine-grained, organic material with very low hydraulic conductivity that greatly restrict water movement, especially in the deeper parts of the lake where sediment accumulation is usually thickest.

Ground-water flow patterns likely are very complex around lakes. However, if lakes were grouped according to their geologic and topographic settings, and studies made of one or several of each group, a general knowledge of lake level - ground-water relationships would develop that could be applied to other lakes.

Hydrochemical System

Described in this section of the report are the relations between the chemical characteristics of water and the hydrogeologic environment.

Relationship of Water Quality to the Geologic Environment

Areal variations in the chemical characteristics of ground and surface water in the Red River of the North basin are influenced by the mineral composition of the ground-water reservoir, the ground-water flow patterns in the basin, and the length of time water has been in contact with the formations.

Mineral solutes in ground waters of the Red River basin strongly reflect the lithologic character of the rocks. Water in marine Cretaceous sediments containing ion-exchange minerals and sources of chloride tend to contain higher percentages of chloride, sodium, and smaller percentages of calcium and magnesium than waters in other geologic units. Water in calcareous clay drift of western Minnesota tends to have relatively high concentrations of calcium, sulfate, and bicarbonate ions. Sulfate reduction in the presence of organic matter within the drift has significant affects locally on the concentration of sulfate, bicarbonate, hydrogen, calcium, and magnesium ions.

The relation between water quality and water movement within the ground-water reservoir may be better understood if concepts of ground-water flow as described in the previous section are used in conjunction with hydrochemical methods. In most of the basin much less mineralized water and water of a different hydrochemical type occur within local flow systems than water that occurs in the larger intermediate and regional flow systems.

To relate water chemistry to flow systems, it is necessary to have some understanding of the solubilities and exchange capacities of the minerals within the ground-water reservoir and the chemistry that affects the equilibria between minerals and ground water. The main factors that affect dissolution are the chemical character of the water, temperature, the area of the interface between soluble minerals and ground water, and the time the water is in contact with the minerals. It follows from the law of mass action that the rate of dissolution of a mineral solid is proportional to the saturation deficit and solubility of specific minerals. Hence, ground water receives much of its mineral solutes from dissolution in the upper part of the ground-water reservoir where the water is undersaturated with respect to particular minerals. Fine-grained material restricts ground-water movement, causing greater time in contact between water and mineral particles whose total surface area is great; consequently, mineralization of water tends to increase.

During its passage through the ground-water reservoir within the Red River basin, water undergoes frequent changes in chemical composition due to reduction, ion exchange, and equilibrium reactions due to changes in ion concentration. In northwestern Minnesota, reduction of sulfate ion concentration in ground water by the action of anaerobic bacteria associated with organic materials commonly occurs in buried lake deposits in the drift and in lignite deposits in the underlying Cretaceous sediments. Ion exchange commonly softens water in the Cretaceous deposits as indicated by a high ratio of sodium to calcium plus magnesium ion. In Kittson County, hardening of water is due largely to mixing, but may be due to base exchange, locally (Piper and others, 1953).

Water Types in the Red River basin

Changes in total dissolved solids and water type (the dominant ion or ions in solution) are the basis for the hydrochemical interpretation of water movement in the watershed. Water types were determined graphically by plotting the concentrations of the major ions on a trilinear diagram (fig. 45). Schoeller (1959) has shown that on a regional scale ground water progressively changes toward a type that approximates sea water. The full sequence of water types from the recharge area to the discharge area or deep stagnant area commonly is:

$$HCO_3^- \rightarrow HCO_3^- + SO_4^= \rightarrow SO_4^= \rightarrow SO_4^= + Cl^- \rightarrow Cl^- + SO_4^= \rightarrow Cl^-$$

Local modifications of sequence of water type occurs where highly soluble minerals exist in the reservoir. Where several aquifer systems within the ground-water reservoir are hydrologically connected, mixing of ground waters will often occur. Mixing of ground water of the drift and Cretaceous systems in the southern part of the basin is indicated on figure 45. In this area water moves upward from Cretaceous deposits and m xes with the overlying drift aquifers. In the drift of the eastern part of the Red River basin the water type changes from a water of high relative concentration of calcium and bicarbonate ions near the source of recharge to a water of high relative concentration of sulfates and/or sodium ions at greater depths or at a greater distance from recharge (fig. 45).

Calcium bicarbonate type water occurs in the glacial drift in the eastern part of the watershed, in the surficial beach sands, shallow channel and outwash deposits, and in the upper 25 feet of the lake deposits in the northwestern part of the watershed. The major chemical reaction in these deposits is the dissolution of limestone and dolomite by carbonic acid which results in relatively fast increase in concentration of calcium, magnesium, and bicarbonate ions in solution. Carbonic acid is produced largely by the reaction of water with gaseous carbon dioxide which is abundant in the soil zone due to organic decay. Sulfate concentration in this shallow zone is low because most of the readily soluble sulfate minerals have been leached. Also, sulfate concentration in water is commonly reduced by bacteria associated with plant materials.

Total dissolved solids concentration in the calcium bicarbonate water is generally less than 500 mg/l, which is the lowest concentration of all water types found in the Red River basin. Calcium bicarbonate water is the most common type in areas of ground-water recharge. It is common in shallow wells in the watershed and in surface water in most tributary streams during periods of low flow. Within the lake plain where deposits are locally more permeable and where mounds on the ground water table exist, such as beach ridges, calcium bicarbonate water may extend to greater depths in the ground-water reservoir than in the more clayey and silty parts. The deeper penetration of the calcium bicarbonate water indicates relatively rapid ground-water movement through the permeable deposits.

Sulfate type water occurs in the glacial drift in the southern part of the watershed and locally underlies bicarbonate type water in the northern part of the watershed. These occurrences of sulfate waters may be due to local occurrences of gypsum and iron sulfide or may be due to the relative increase of the sulfate ions in the direction of ground-water flow, as suggested in the geochemical sequence of Schoeller. Locally, within areas of sulfate waters, sulfate concentrations are very low; probably as a result of reduction by anaerobic bacteria. Total dissolved solids in the sulfate water range from about 400 to about 1,200 mg/l. The higher dissolved solids within sulfate waters is compatible with the interpretation that in the ground-water flow system, sulfate water occurs downgradient from the lesser mineralized bicarbonate waters.

Sodium bicarbonate type water occurs mostly in the deeper drift deposits and in the underlying Cretaceous rocks in the western half of the watershed. These rocks and sediments contain clays and disseminated organic materials (such as lignite and humus) of high ion exchange capaciites which probably are widely distributed throughout the sediments. Hard waters moving from the drift into the Cretaceous rocks or into the drift immediately overlying the Cretaceous rocks are softened by base exchange resulting in an increase in sodium concentration in the water. At some places, sulfate concentration in the sodium bicarbonate type water was lowered by reduction resulting in an exceptionally high bicarbonate concentration. Bicarbonate ion is one of the products of sulfate reduction in presence of organic decay. The total dissolved solids of the sodium bicarbonate water is generally less than 1,000 mg/l.

Chloride type water that occurs in the sedimentary rocks in the western part of the watershed is highly saline in relative composition of the major ions and is similar to that of ocean water. The Paleozoic and Cretaceous rocks contain highly soluble minerals which contribute to the high salinity of the water. However, most of the salinity probably has accumulated during the slow eastward migration of ground water through the Paleozoic rocks underlying North Dakota toward a regional discharge area, part of which is in northwestern Minnesota. Highly saline waters occur at depth in the drift near the margin of the Paleozoic rocks. These high salinities are due to the upward movement of saline water in zones of Paleozoic rocks along their contact with the drift. The saline water mixes with bicarbonate or sulfate water in the drift to form a calcium magnesium chloride type. The total dissolved solids concentration of the chloride waters in Paleozoic rocks range from about 5,000 to 60,000 mg/l and in the drift from 2,000 to 4,000 mg/l.

The greater knowledge derived from the use of geochemical methods should prove useful to the prediction of effects of different management practices on the entire hydrologic system and to indicate ways in which water quality may be managed. Among the chemical equilibrium reactions which need to be studied in greater detail within the Red River basin are those involving natural softening of water. It may prove feasible to inject hard waters into zones where natural softening occurs, thereby obtaining soft waters at relatively low cost. Reactions involving oxidation or reduction of iron may have significant effect on permeabilities of the material within the ground-water reservoir.

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