

FRANZIN

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RED RIVER OF THE NORTH BASIN, MINNESOTA,
NORTH DAKOTA, AND SOUTH DAKOTA¹*Jeffrey D. Stoner, David L. Lorenz, Gregg J. Wiche, and Robert M. Goldstein²*

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ABSTRACT: The environmental setting of the Red River of the North basin within the United States is diverse in ways that could significantly control the areal distribution and flow of water and, therefore, the distribution and concentration of constituents that affect water quality. Continental glaciers shaped a landscape of very flat lake plains near the center of the basin, and gently rolling uplands, lakes, and wetlands along the basin margins. The fertile, black, fine-grained soils and landscape are conducive to agriculture. Productive cropland covers 66 percent of the land area. The principal crops are wheat, barley, soybeans, sunflowers, corn, and hay. Pasture, forests, open water, and wetlands comprise most of the remaining land area. About one-third of the 1990 population (511,000) lives in the cities of Fargo and Grand Forks, North Dakota and Moorhead, Minnesota. The climate of the Red River of the North basin is continental and ranges from dry subhumid in the western part of the basin to subhumid in the eastern part.

From its origin, the Red River of the North meanders northward for 394 miles to the Canadian border, a path that is nearly double the straight-line distance. The Red River of the North normally receives over 75 percent of its annual flow from the eastern tributaries as a result of regional patterns of precipitation, evapotranspiration, soils, and topography. Most runoff occurs in spring and early summer as a result of rains falling on melting snow or heavy rains falling on saturated soils. Lakes, prairie potholes, and wetlands are abundant in most physiographic areas outside of the Red River Valley Lake Plain. Dams, drainage ditches, and wetlands alter the residence time of water, thereby affecting the amount of sediment, biota, and dissolved constituents carried by the water.

Ground water available to wells, streams, and springs primarily comes from sand and gravel aquifers near land surface or buried within 100 to 300 feet of glacial drift that mantles the entire Red River of the North basin. Water moves through the system of bedrock and glacial-drift aquifers in a regional flow system generally toward the Red River of the North and in complex local flow systems controlled by local topography. Many of the bedrock and glacial-drift aquifers are hydraulically connected to streams in the region.

The total water use in 1990, about 196 million gallons per day, was mostly for public supply and irrigation. Slightly more than one half of the water used comes from ground-water sources compared to surface-water sources. Most municipalities obtain their water from ground-water sources. However, the largest cities (Fargo, Grand Forks and Moorhead) obtain most of their water from the Red River of the North.

The types and relative amounts of various habitats change among the five primary ecological regions within the Red River of the North basin. Headwater tributaries are more diverse and tend to be similar to middle-reach tributaries in character rather than the lower reaches of these tributaries for the Red River of the North.

Concentrations of dissolved chemical constituents in surface waters are normally low during spring runoff and after thunderstorms. The Red River of the North generally has a dissolved-solids concentration less than 600 milligrams per liter with mean values ranging from 347 milligrams per liter near the headwaters to 406 milligrams per liter at the Canadian border near Emerson, Manitoba. Calcium and magnesium are the principal cations and bicarbonate is the principal anion along most of the reach of the Red River of the North. Dissolved-solids concentrations generally are lower in the eastern tributaries than in the tributaries draining the western part of the basin. At times of low flow, when water in streams is largely from ground-water seepage, the water quality more reflects the chemistry of the glacial-drift aquifer system.

Ground water in the surficial aquifers commonly is a calcium bicarbonate type with dissolved-solids concentration generally between 300 and 700 milligrams per liter. As the ground water moves down gradient, dissolved-solids concentration increases, and magnesium and sulfate are predominant ions. Water in sedimentary bedrock aquifers is predominantly sodium and chloride and is characterized by dissolved-solids concentrations in excess of 1,000 milligrams per liter.

Sediment erosion by wind and water can be increased by cultivation practices and by livestock that trample streambanks. Nitrate-nitrogen concentrations also can increase locally in surficial aquifers beneath cropland that is fertilized, particularly where irrigated. Nitrogen and phosphorous in surface runoff from cropland fertilizers and nitrogen from manure can contribute nutrients to lakes, reservoirs, and streams. Some of the more persistent pesticides, such as atrazine, have been detected in the Red River of the North. Few data are available to conclusively define the presence or absence of pesticides and their break-down products in Red River of the North basin aquifers or streams.

Urban runoff and treated effluent from municipalities are discharged into streams. These point discharges contain some quantity of organic compounds from storm runoff, turf-applied pesticides, and trace metals. The largest releases of treated-municipal wastes are from the population centers along the Red River of the North and its larger tributaries. Sugar-beet refining, potato processing,

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poultry and meat packing, and milk, cheese, and cream processing are among the major food processes from which treated wastes are released to streams, mostly in or near the Red River of the North. (KEY TERMS: water quality; hydrologic systems; assessment; water contamination; stream biota.)

INTRODUCTION

The Red River of the North basin (Figure 1) was selected as a study unit under the National Water-Quality Assessment (NAWQA) program because (1) the basin represents an important hydrologic region where good-quality water is a valued resource vital to the region's economy, (2) the quality of the Red River of the North, which flows north into Manitoba, Canada, is of international concern, (3) the basin represents a significant agricultural area (and, in keeping with the President's Water-Quality Initiative, provides opportunities to study sediment, nutrients, and pesticides through the national assessment part of NAWQA), and (4) the northern location and potential interaction of surface and ground water are essential physical factors necessary for a complete National assessment of water quality.

the United States. This area includes certain depressional areas that do not contribute surface drainage to the Red River of the North during many periods of time. The closed Devils Lake basin in North Dakota, an area of 3,800 mi² that does not contribute surface or significant ground water (Pusc, 1993) to the Red River basin, is not included as part of the NAWQA study unit (Figure 1). Glacial-drift aquifers and shallow sedimentary bedrock aquifers located in the basin are being investigated to study water-quality relations between surface and ground water.

Purpose and Scope

This report describes the physical, chemical, and aquatic-biological characteristics that could affect regional water quality in the Red River of the North study unit. These characteristics define the overall environmental setting of the study unit. This report provides base line and historical information for future reports that will address specific water-quality issues and processes controlling and affecting water quality in the study unit, and for reports for the national-synthesis component of the NAWQA program that will integrate the results of the study-unit investigations.

Previous Studies

The description of the environmental setting is based on a review of currently available information, and reports and data from Federal, State, local, and Canadian agencies. Much of the following description was derived from hydrologic reports by Maclay *et al.* (1972), Miller and Frink (1984), Souris-Red-Rainy River Basins Commission (1972), and Winter *et al.* (1984). There are many natural-resources studies conducted by Federal, regional, State, and local governments, universities, and the private sector that have been cited within the text of this report.

ENVIRONMENTAL SETTING

A review of the environmental setting of the Red River of the North basin study unit is needed to put the water-quality assessment in perspective with the historical land uses, hydrology, and ecology of the region. The general physical, chemical, hydrological, and ecological characteristics of the Red River of the North basin comprise the environmental setting of the study unit. These characteristics are diverse in



Figure 1. Location of the Red River of the North Basin Study Unit.

The study-unit area [35,000 mi² (square miles)] includes all of the surface drainage to the Red River of the North and the Roseau River (Figure 2) within

ways that could significantly control the areal distribution and flow of water and, therefore, the distribution and concentration of constituents that could affect water quality. Specifically, this description is not comprehensive, but focuses on components of the environmental setting of the Red River of the North basin that could affect water quality, that could be affected by the water quality, and that improve the understanding of environmental factors related to the quality of water in the basin.

Physical and Cultural Features

The Red River of the North basin is located near the geographic center of the North American continent. The river flows north and drains parts of the States of Minnesota, North Dakota, and South Dakota, as well as parts of the Provinces of Manitoba,

and Saskatchewan, Canada (Figure 1). The area characterized as glaciated plain with moraines, lake wetlands, and lake plains.

The name Red River was first applied by the Ojibway Indians to the outlet stream of Lower Red Lake, Minnesota, which flows westward toward Grand Forks, North Dakota, and then northward to Lake Winnipeg (Upham, 1895, p. 52, with reference to an 1852 report of the Geological Survey of Wisconsin, Iowa, and Minnesota). The idea that the Red River formed the headwaters of the Red River probably relates to the fact that it is a major source of flow to the Red River of the North. The Red River of the North begins at the confluence of the Bois de Sioux and the Otter Tail Rivers (Figure 2). The name Red distinguishes it from the Red River in Texas and Louisiana. Herein the text, the Red River of the North will be referred to as Red River and the study unit will be referred to as the Red River basin.

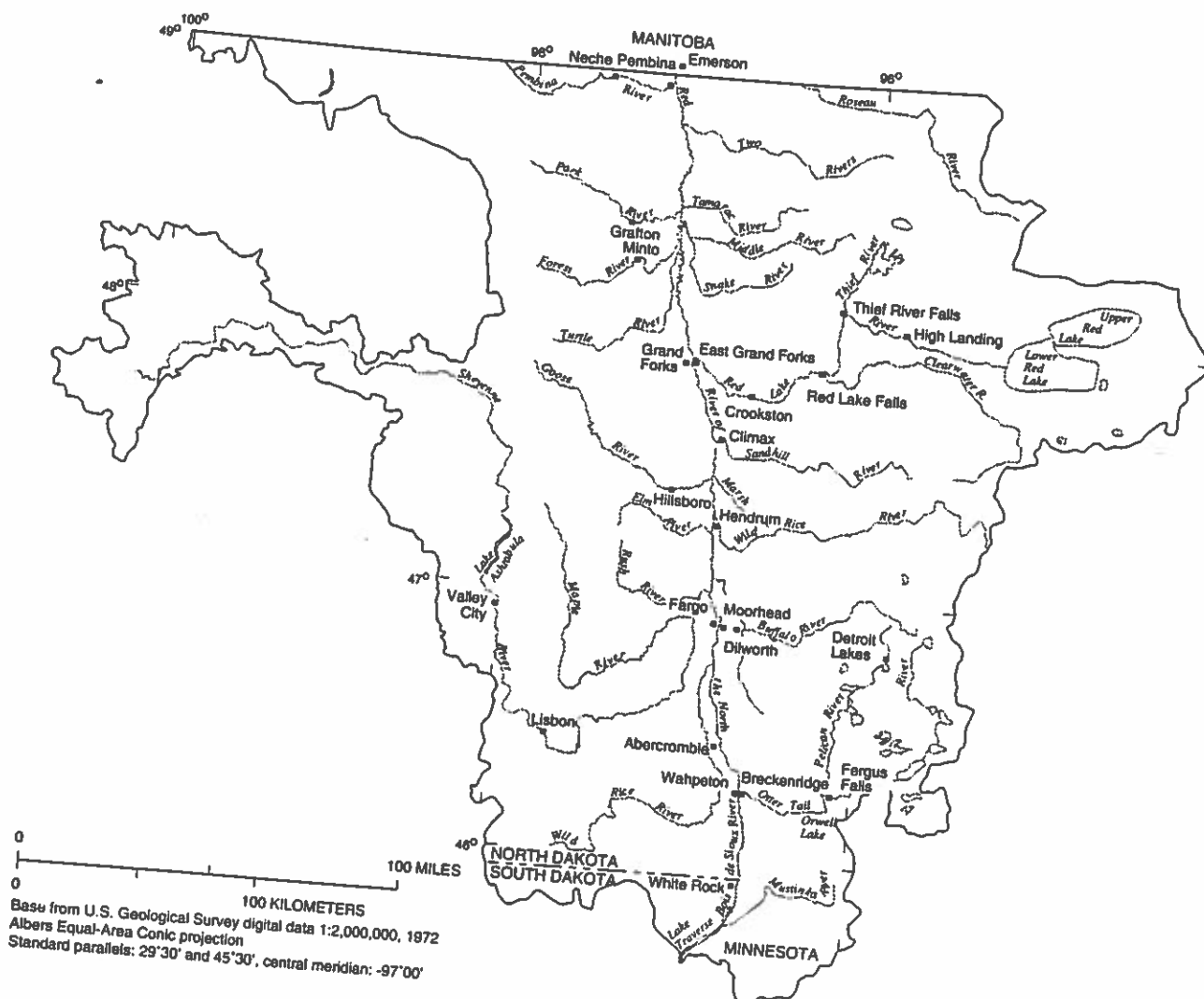


Figure 2. Major Streams in the Red River of the North Basin.

Physiography

The relatively small topographic relief of about 1,600 ft (feet) and gently rolling hills and plains in the Red River basin were largely caused by the actions of glaciation and geologically recent erosion. Glacial Lake Agassiz left clay-rich sediments in a flat lake plain along the axis of the Red River and a lake-washed till plain in the northeastern part of the Red River basin. Ice sheet advances and recessions left upland moraines and glacial drift that extend east and west of the lake plain. Glaciers and glacial melt-water also left elongated ridges of beach sands and gravels, and flat plains of outwash sands.

Land-surface altitudes in the basin range from about 2,350 ft in the extreme western part of the Red River basin to about 750 ft where the Red River crosses the international boundary (Figure 2). In the southeastern part of the Red River basin, the plain rises almost uniformly into upland hills of the glacial Moraine area (Figure 3) and merges with numerous lakes and wetlands. The gentle slopes of the valley terminate abruptly at the Pembina escarpment in the northwestern part of the Red River basin. The Drift Prairie of the western part of the Red River basin is an area of low rolling hills and numerous prairie potholes. Prairie potholes are small ponds surrounded by marshy borders that occupy closed basins and do not contribute runoff to streams. The Coteau du Missouri and Coteau des Prairie are steep areas with up to 500

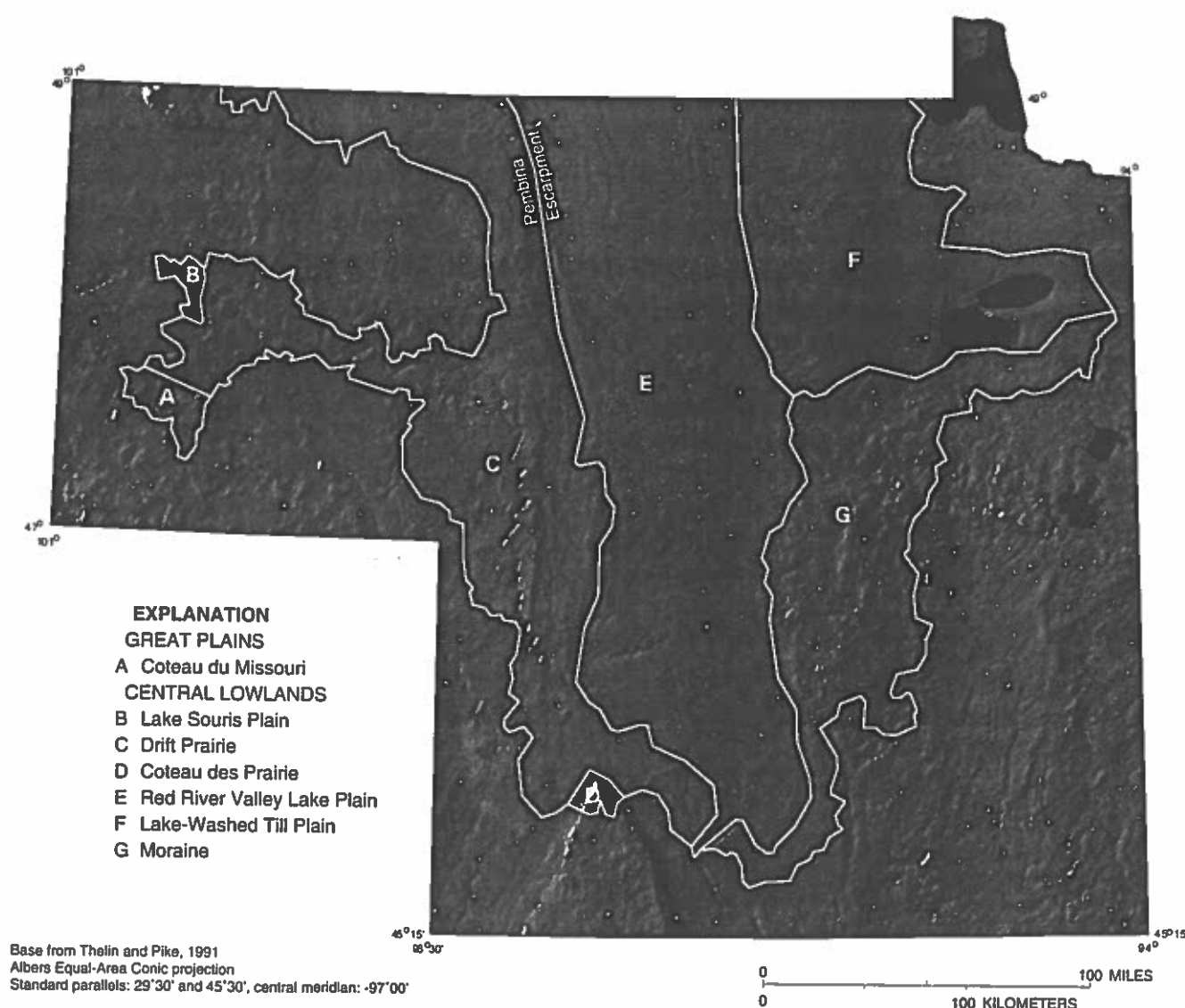


Figure 3. Physiographic Areas in the Red River of the North Basin.
[Modified from Maclay *et al.* (1972) and Winter *et al.* (1984).]

ft of local relief. The Lake-Washed Till Plain in the northeast is a flat area of extensive wetlands and some peatlands.

The surface slope of the upland areas (Moraine and Drift Prairie in Figure 3), although relatively flat, is much greater than the slope of the Red River Valley Lake Plain. The Drift Prairie includes noncontributing areas of surface runoff such as closed lakes, ponds, and depressional storage areas. The slope of the main stem of the Red River is flat; the river drops only about 200 ft in its 394 mi (mile) course from its beginning (confluence of the Bois de Sioux and Otter Tail Rivers) to the Canadian border.

Geology

An understanding of the geology of the area is critical to understanding the location, movement, and natural quality of ground water. Also, the hydrologic character and geochemical controls on streams and lakes are strongly affected by surface geology and topography (MacLay *et al.*, 1972). The rocks and rock debris in the Red River basin can be categorized as three general types: Crystalline rocks of Precambrian age, stratified sedimentary rocks, and glacial drift.

The oldest and deepest rocks underlying the Red River basin are crystalline and are of Precambrian age. (These include all igneous rock, such as granite, and metamorphic rocks, such as schists and gneiss). Except locally east of the Red Lakes, these crystalline rocks are deeply buried beneath the Red River basin and little is known about them. Granite and greenstone are the most prevalent rocks, especially in the Minnesota part of the basin.

Extensive deposits of water-bearing sedimentary rocks underlie the Red River basin within the eastern flanks of the Williston structural basin (Figures 1 and 4). Drill-hole and well-log data indicate that the sedimentary rocks in the basin range in age from Cambrian to Tertiary age (Table 1). Figure 5 shows how these sedimentary formations gradually thin eastward beneath the Red River basin and become only a few hundred feet thick beneath the Red River valley. Many of these formations lie unconformably over older units and are absent beneath the Red River basin. Principle lithologies of the water-bearing sedimentary rocks are sandstone, limestone, and dolomite. Cretaceous age sediments, the most common rocks subcropping under the Red River basin, are located mainly in North and South Dakota and are fairly continuous (Figure 4). However, many areas not shown as Cretaceous in Minnesota probably have isolated remnants (islands) of these rocks which generally are less than 25 ft thick. The Fox Hills, Pierre Shale, and Niobrara Formations crop out along the

steep valley walls of the Sheyenne River upstream from Lisbon, North Dakota and along several drainages that cut through the Pembina escarpment and represent the primary locations where bedrock is visible at land surface in the basin.

Glacial drift thickly mantles most of the basin, and has left the two distinct land forms described earlier; the very flat Red River Valley Lake Plain and Lake-Washed Till Plain, and the gently rolling uplands. The drift, which ranges from 0 to more than 600 feet thick, was deposited by continental glaciers that moved through the region during the past million years. In most areas, the glacial-drift thickness ranges from 150 to 300 feet thick.

The surface exposure of the principal glacial-drift deposits are shown in Figure 6. Glacial drift in the uplands consists mainly of an unsorted and unstratified mixture of clay, silt, sand, gravel, and boulders, commonly referred to as till. Clay and silt are the dominant lithologies of the till in most places. Many of the prairie potholes, lakes, and undrained depressional areas in the uplands are attributed to the melting of stagnant glacial ice. Isolated deposits of sorted and stratified sand and gravel associated with moving meltwaters beneath, along margins, and beyond melting glaciers, are found within the till on or beneath the present land surface. These sand and gravel deposits, that range in size from an acre to many square miles, comprise the principal aquifers within the glacial drift and will be discussed in greater detail under the ground-water section. The stratified sands and gravels commonly are elongated deposits, but some are broad outwash plains or deltas. These deposits can be as much as several tens of feet thick. Because of the complex nature of deposition, it is difficult to map and predict the extent of these units without extensive drill-hole information.

The till beneath the central Red River Valley Lake Plain is overlain by as much as 95 ft of clay- and silt-rich lake deposits from Glacial Lake Agassiz, which existed in this area during the melting of the last glaciers about 12,000 years ago. Other deposits associated with this lake include sandy beach ridges and scarps that formed along the shoreline, and linear sand and gravel deposits buried in the subsurface of Lake Agassiz (Winter, 1967). These beach ridges are composed of stratified and sorted sand and gravel ranging in thickness from 1 to 35 ft, but commonly are less than 10 ft.

Soils

Soils differ from one another in the proportion of pore spaces, the size and type of mineral material, and the amount and source of organic material.

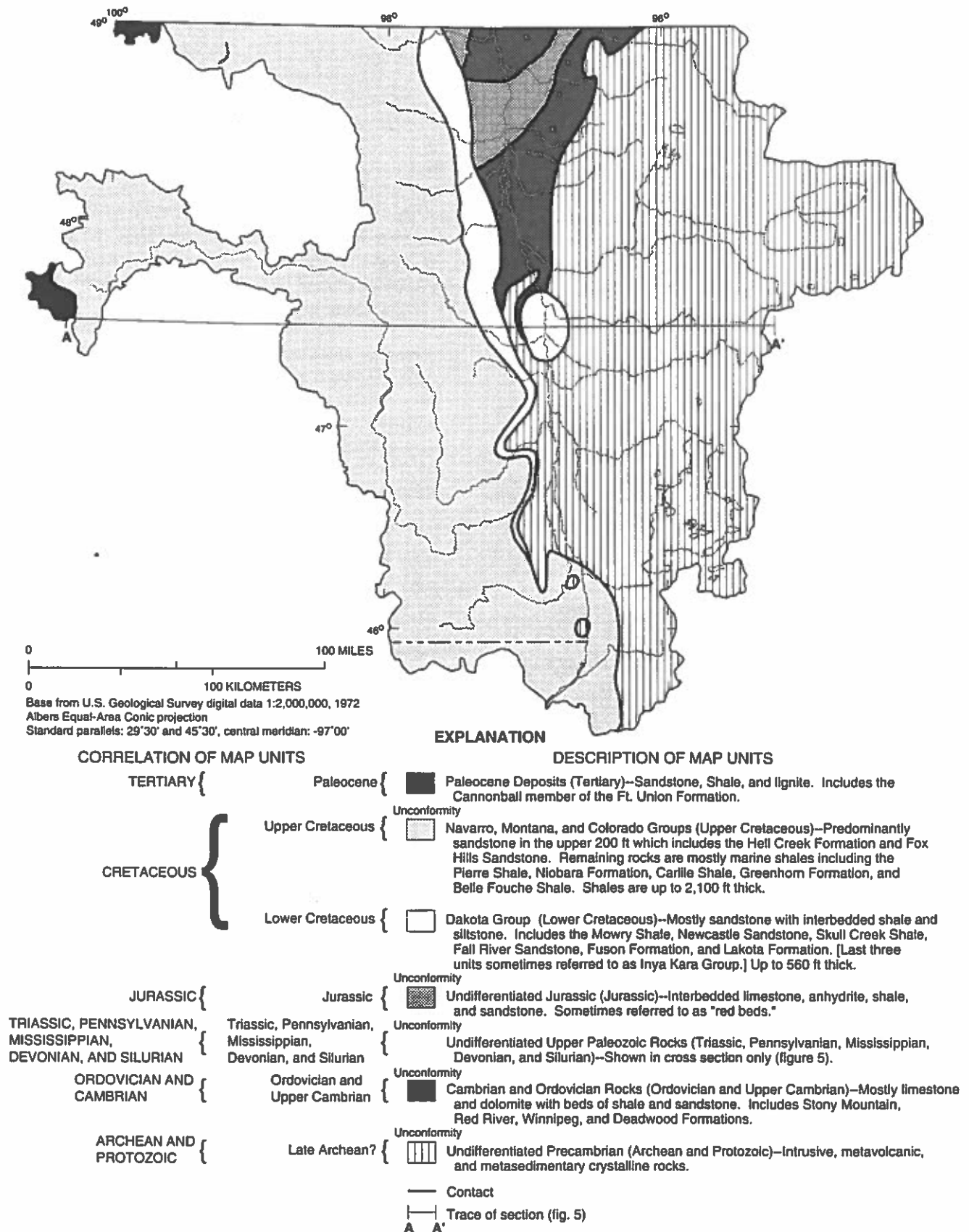


Figure 4. Subcrops of Bedrock Geology in the Red River of the North Basin.
[Modified from King and Beikman (1974) and Downey (1986).]

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

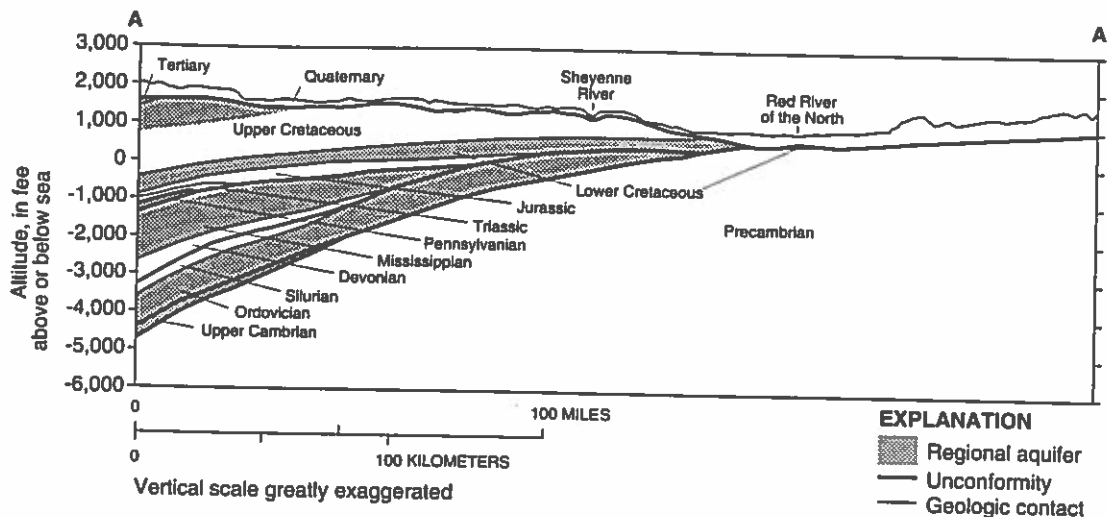


Figure 5. Generalized Section of Bedrock Formations and Regional Aquifers in the Red River of the North Basin. [Modified from Bluemle (1977).]

Mineral material consists of sand-, silt- and clay-size particles. The clay particles, which have a larger ratio of surface area to volume than the sand and silt part, are the most active chemically. The clay fraction also is essential for soil development and supporting the growth of plants.

The source of mineral material in soils of the Red River basin primarily is from glacial sediments. Surficial deposits more recent than glacial origin are wind-blown silts and sands in North Dakota and river alluvium. Soils derived from the geologic deposits range from heavy, poorly drained clays and silts in the lake-bed areas to light, well-drained sands along beach ridges, outwash plains, and wind-blown deposits. Heavy organic soils and peat are common in depressional areas, especially in the Lake-Washed Till Plain area.

Figure 7 shows the eight major soil associations that occur in the Red River basin (Omdt *et al.*, 1968; Minnesota Soil Survey Staff, 1983; U.S. Dept. of Agriculture, 1975, 1977). A soil association is a landscape that has a definite pattern of soils. The association is based on similarities in slope, texture, natural drainage, and special features. Soils that comprise these associations are classified according to geographic location, natural vegetation, topography, and other distinguishing features. Suborders within a soil order are separated on the basis of soil properties that influence plant growth.

1. Hilly and steep land is at the edges of the Coteau du Missouri and Coteau des Prairie (Figure 3). The soil is generally thin and susceptible to water erosion. The suborders comprising this association are ustolls (dry prairie soils) and borolls (northern prairie soils).

2. Rolling, wooded soils are in the Turtle Mountains and Pembina Escarpment in North Dakota and in the moraine area in Minnesota (Figure 3). The soil can be either a gray soil, typical of woodlands or a black loam. These areas are predominantly forested. These soils are borolls in North Dakota and borolls and boralfs (soils of the Aspen forest) in Minnesota.

3. Black, loamy soils are found in the Drift Prairie in North and South Dakota and in the southern Moraine area of Minnesota (Figure 3). The landscape is level or has gently rolling hills. The soil is black and rich and may have a limy subsoil. The predominant suborder is borolls with some aquolls (wet prairie soils).

4. Black, limy, clayey soils are found in the Drift Prairie, Red River Valley Lake Plain, and Lake-Washed Till Plain areas (Figure 3). The land is level or has gently rolling hills. The subsoil is very limy (contains calcium carbonate). Because the soil is very wet in the spring, the soil type is aquoll.

5. Clayey soils are in the Red River Valley Lake Plain area (Figure 3). The land is nearly level and drainage is poorly developed. The rich, black soil is also classified as an aquoll.

6. Loamy soils are located in the Red River Valley Lake Plain and the moraine areas of Minnesota. They are found in level areas and on hilly terrain, where prairie potholes are common. They are classified as aqualfs (wet forest soils), borolls, and boralfs.

7. Sandy soils are found along the western and eastern edge of the Red River Valley Lake Plain and in the Lake-Washed Till Plain area in Minnesota and in outwash plains (Figure 3). The land is nearly level with narrow, low ridges along the border of the Red River Valley Lake Plain area. The soils are classified

TABLE 1. Generalized Stratigraphic Column of Geology and Correlation to Regional Hydrogeologic Units (Fm., Formation; Ss., Sandstone; -, stratigraphic unconformity).

System	Series	Stratigraphic Unit	Principle Lithology	Thickness (feet)	Regional Hydrogeologic Unit
Quaternary	Holocene	River alluvium and wind-blown deposits	sand and silt	0-30	Local aquifers
	Pleistocene	Undifferentiated glacial deposits	sand, gravel, cobbles, clay and silt	0-750	Glacial Drift Aquifer System
Tertiary	Palocene	Cannonball Member of the Fort Union Fm.	sandstone, shale and lignite	0-225	Upper Cretaceous and Tertiary Aquifer
Cretaceous	Upper Cretaceous	Hell Creek Fm. Fox Hills Ss.	sandstone sandstone	0-525	
		Pierre Shale Niobrara Fm. Carlili Shale Greenhorn Fm. Belle Fouché Shale	shale shale (calcareous) shale shale (calcareous) shale	0-2110	
	Lower Cretaceous	Mowry Shale Newcastle Ss. Skull Creek Shale Fall River Ss.	shale sandstone shale and siltstone sandstone and shale	0-380	Lower Cretaceous Aquifer
		Fuson Fm. Lakota Fm.	shale and sandstone sandstone, siltstone and shale	0-285	
	Jurassic	Undifferentiated Jurassic	Undifferentiated	limestone, anhydrite, shale and sandstone	0-150
Triassic	Undifferentiated Paleozoics	Undifferentiated	siltstone and sandstone	0-200	
Pennsylvanian*			dolomite, limestone and shale	0-125	Minor Aquifer
Mississippian			shaly limestone		Confining Unit
			limestone	0-1200	Mississippian Aquifer
Devonian			dolomite and limestone	0-1000	Confining Unit
Silurian			dolomite	0-300	
Ordovician	Upper Ordovician	Stony Mountain Fm. Red River Fm.	limestone and dolomite limestone and dolomite	0-135 0-585	Cambrian-Ordovician Aquifer
	Middle Ordovician	Winnipeg Fm.	shale and sandstone	0-230	
	Cambrian	Lower Ordovician	Deadwood Fm.	sandstone and shale	
Upper Cambrian					
Precambrian	Undifferentiated Precambrian		igneous and metamorphic rocks undifferentiated		Base of Regonal Aquifer System

*Pennsylvanian age rocks are not principle aquifers in the Red River basin.
(Modified from Downey, 1986.)

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

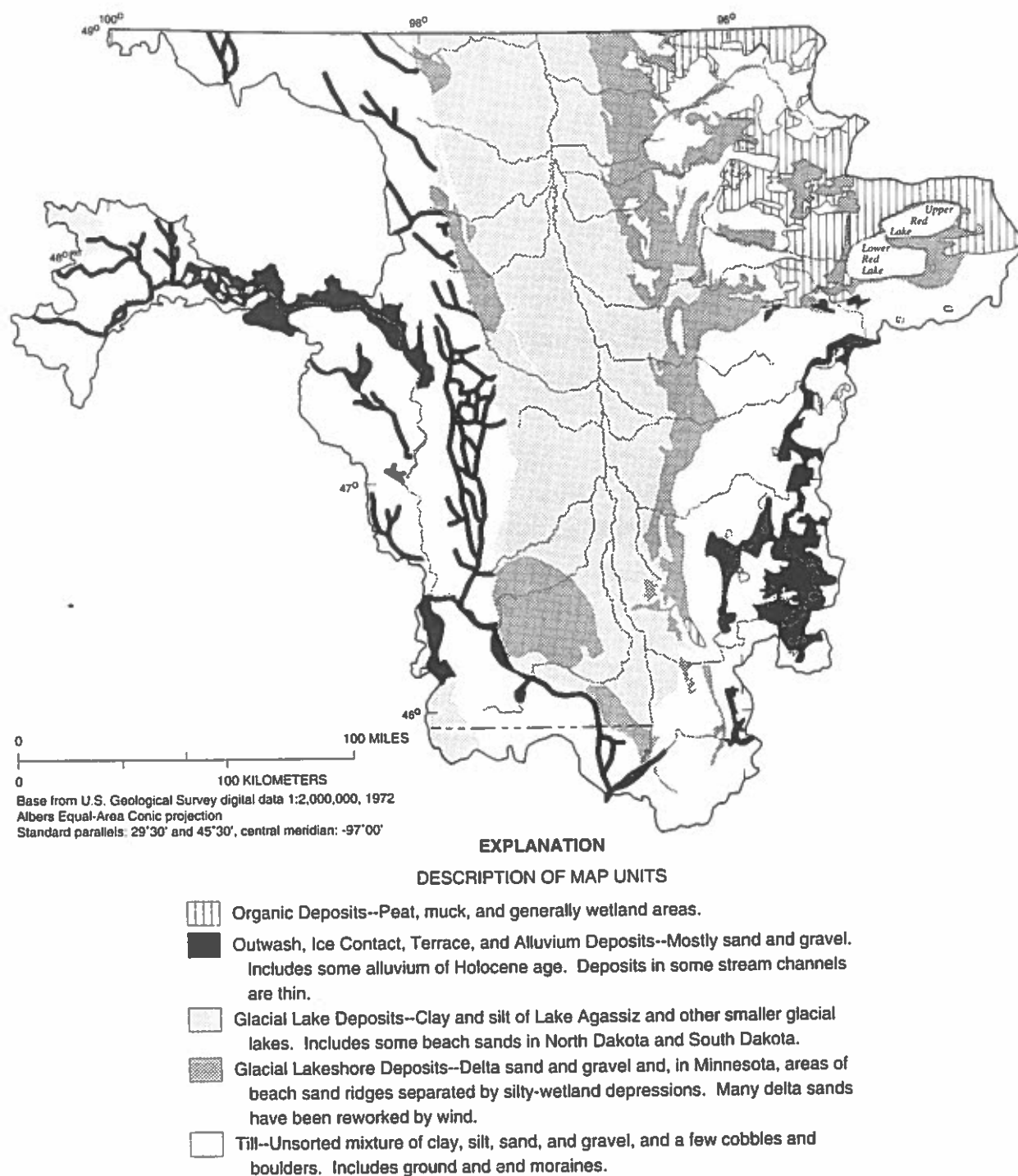


Figure 6. Generalized Glacial Deposits and More Recent Deposits in the Red River of the North Basin. [Modified from Souris-Red-Rainy River Basins Commission (1972).]

as borolls in North Dakota and borolls and psamments (sandy, soils formed from quartz sand) in Minnesota. The sandy soils in the northeastern part of the basin are classified as aquents (wet, poorly developed soils).

8. Organic soils are located in the Lake-Washed Till Plain area in Minnesota. The topography is nearly level and the soils are in depressions in ground moraines, lake plains, and outwash plains. These soils are classified as hemists (organic soils composed primarily of peat).

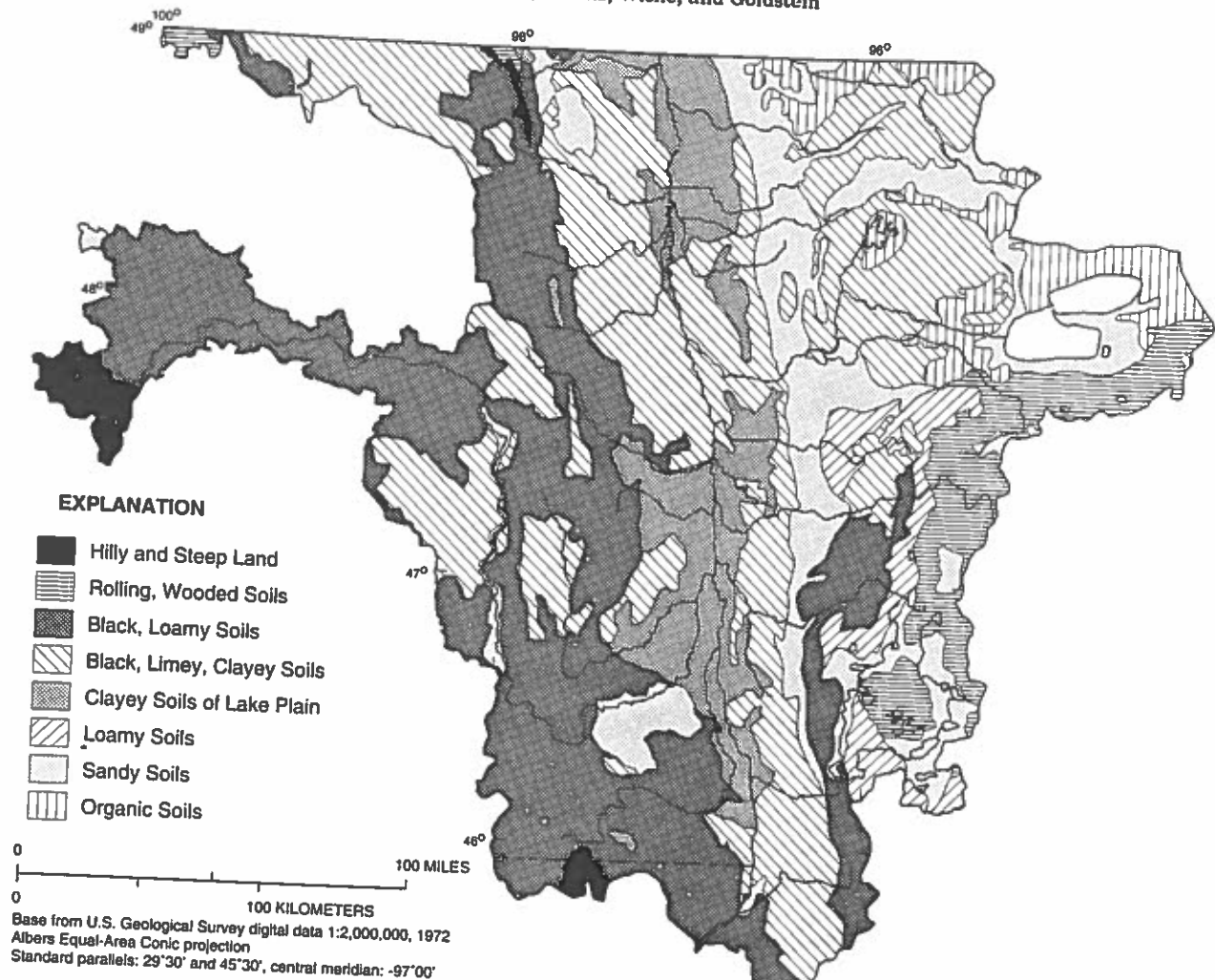


Figure 7. Soil Associations in the Red River of the North Basin. [Modified from Minnesota Soil Survey Staff (1983), Omodt *et al.* (1968), and U.S. Department of Agriculture (1975, 1977).]

Population and Land Use

The 1990 population in the largely rural Red River basin is about 511,000 (U.S. Bureau of Census, 1991). Almost one-third of the population lives in the cities

of Fargo and Grand Forks, North Dakota and Moorhead, Minnesota (Figure 8). The population increased 8 percent between 1980 and 1990. Native Americans inhabit the Indian Reservations of Fort Totten, Red Lake, Lake Traverse, and White Earth, which are wholly or partially within the Red River basin.

Population of Principal Communities

Community	Population	
	1980	1990
Fargo, North Dakota	61,383	74,111
Grand Forks, North Dakota	43,765	49,425
Moorhead, Minnesota	29,998	32,295
Fergus Falls, Minnesota	12,579	12,362
Wahpeton, North Dakota	9,064	8,751
East Grand Forks, Minnesota	8,537	8,658
Crookston, Minnesota	8,628	8,119
Thief River Falls, Minnesota	9,105	8,010
Valley City, North Dakota	7,774	7,163
Detroit Lakes, Minnesota	7,106	6,635
Breckenridge, Minnesota	3,909	3,708
TOTAL	201,848	219,237

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

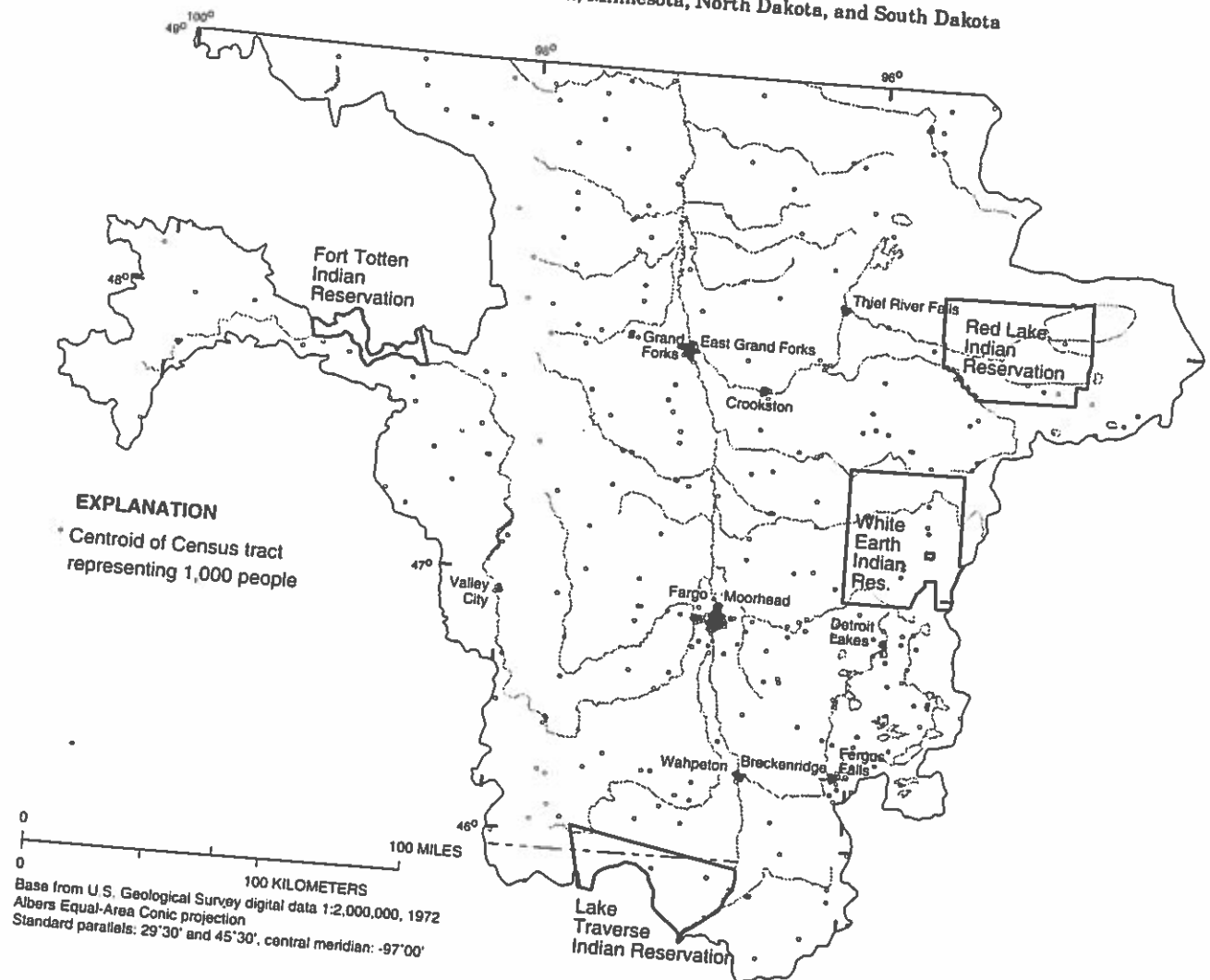


Figure 8. Distribution of 1990 Population and Locations of Indian Reservations in the Red River of the North Basin [U.S. Bureau of Census (1991)].

Upham (1895, p. 582 and 604-606) predicted that agriculture would be the chief industry and principal land use of the prairie part of the region because of the fertility of the alluvial, lacustrine, and drift deposits. He attributed the abrupt change in vegetation from prairie in the west to forest in the east to the relatively large increase in annual precipitation eastward across the basin and to the effects of almost annual prairie fires before the area was settled. The prairie fires destroyed seedling trees and shrubs, preventing the advancement of the forest and thereby maintaining the prairie grasses. Although parts of the forested area have been cleared for agriculture, the abrupt change still is apparent.

Most of the presettlement prairie grasses of the Red River valley and glaciated plains have been replaced by small-grain and row crops (Figure 9). Strips of trees, such as oak, cottonwood, elm, willow, and ash grow along major water courses. Many trees

have been planted to form windbreaks near farmsteads. The Lake-Washed Till Plain is covered by two general types of vegetation; aspen parkland and marshland. The aspen parkland consists largely of aspen, balsam, poplar, and scrub. Many scattered lowlands within the area contain marsh plants. The large marshlands near Upper and Lower Red Lakes are some of the most extensive marshlands in the United States. The western part of the moraine area consists mostly of cropland and pasture with intervening wooded areas predominantly of oak, but with other hardwoods and aspen also present. Forests comprised of pines and hardwoods are the dominant cover in the eastern part of the moraine area. The pine forests were cut extensively and the second growth is largely aspen. Farm land has replaced native prairie grasses in part of the outwash plain in the southeastern part of the study area. Greater detail of presettlement and

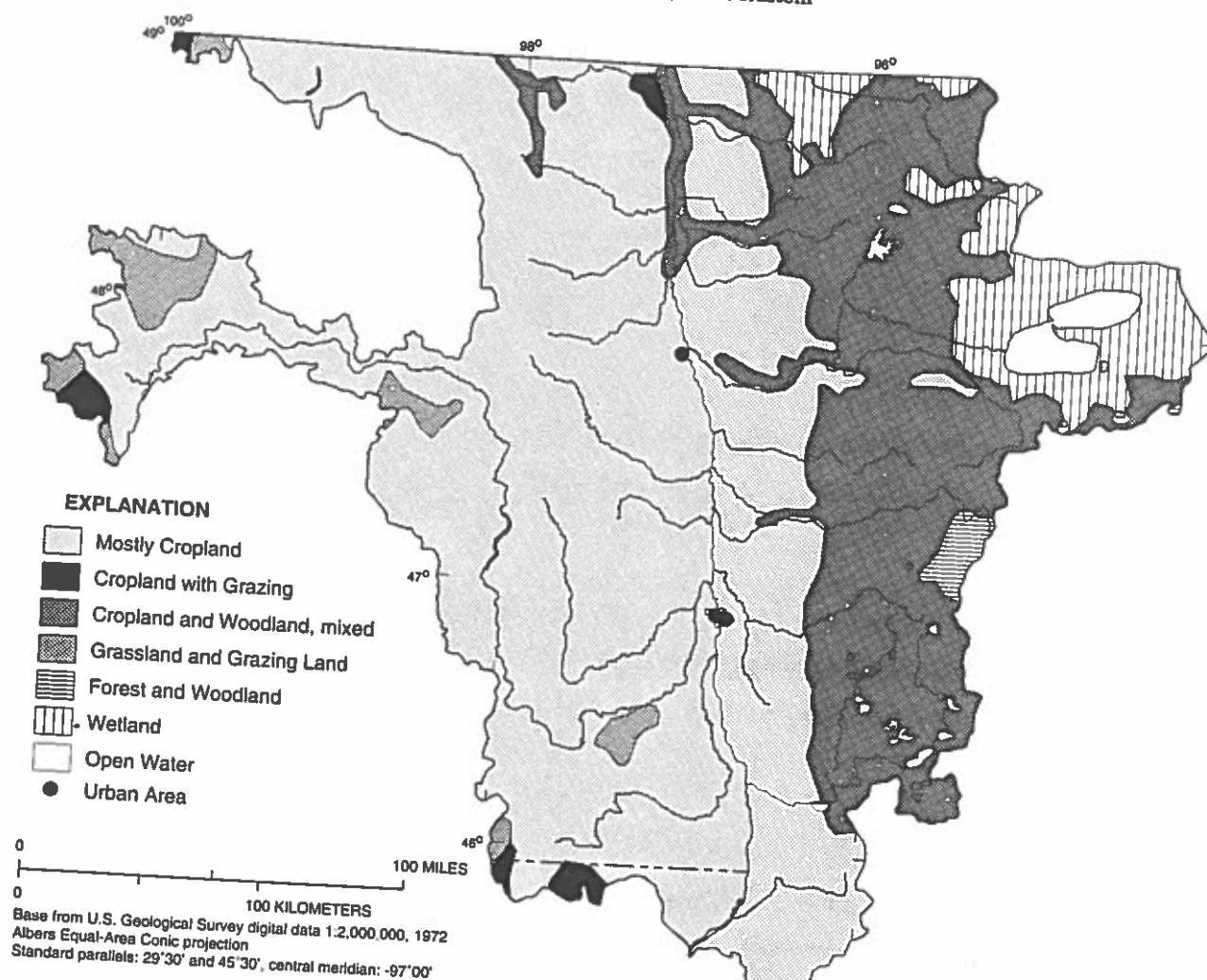


Figure 9. Land Use and Land Cover in the Red River of the North Basin. [Modified from Anderson (1967).]

present vegetation is provided by McAndrews (1966) and Shay (1967).

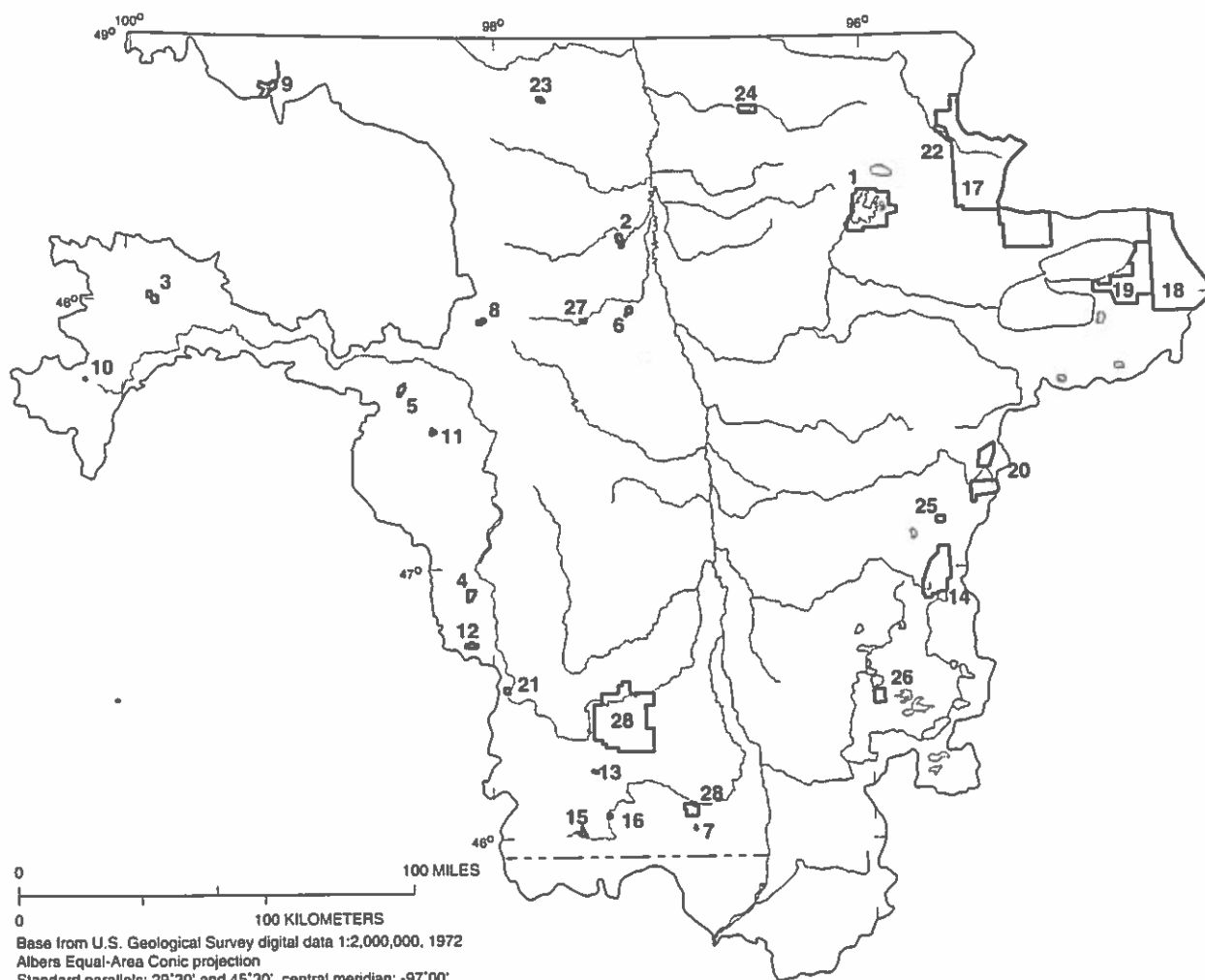
About 74 percent of the land area in the Red River basin is agricultural (Figure 9) of which 66 percent is cropland and 8 percent is pasture and range land (Souris-Red-Rainy River Basins Commission, 1972). Principal crops are wheat, barley, oats, sugar beets, potatoes, corn, beans, forage grasses, and sunflowers. The remaining 26 percent of the land area consists of forests (about 12 percent), water and wetlands (about 4 percent), urban land (3 percent), and other categories (7 percent). Figure 10 shows the location of a National grassland, and numerous National wildlife refuges, State forests, and State parks.

Agricultural cropland is the predominant land use throughout most of the Red River basin (Figure 9). However, the cropping patterns and associated agricultural treatments are not homogeneously distributed within the Red River basin. Using the agricultural census of 1987 and the Anderson Classification of

land use and land cover, principal cropping patterns and (or) other land uses were identified. Row crops and small grains that are planted fairly uniformly across the Drift Prairie and the Red River Valley Lake Plain are listed below in order of acreage planted from largest to smallest in 1989 (Minnesota Agricultural Statistics Service, 1991, and North Dakota Agricultural Statistics Service, 1990) within each region.

Drift Prairie	Red River Valley
Wheat	Wheat
Barley	Barley
Sunflowers	Soybeans (south)
Hay	Corn (south)
Corn (south)	Edible Beans
	Sugar Beets

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EXPLANATION

National Wildlife Refuges	State Forests
1 Agassiz	17 Beltrami
2 Ardoch	18 Pine Island
3 Buffalo Lake	19 Red lake
4 Hobart Lake	20 White Earth
5 Johnson Lake	
6 Kellys Slough	State Parks
7 Lake Elsie	21 Fort Ransom
8 Lambs Lake	22 Hayes Lake
9 Rock Lake	23 Icelandic
10 Sheyenne Lake	24 Lake Bronson
11 Sibley Lake	25 Little Elbow Lake
12 Stoney Lake	26 Maple Wood
13 Storm Lake	27 Turtle River
14 Tamarac	
15 Tewaukon	National Grassland
16 Wild Rice Lake	28 Sheyenne

Climate

There is some geographic pattern to certain crops within the diversely cropped Red River Valley Lake Plain. For example, potatoes and edible beans, both rotated with wheat, are planted mostly in the northern half of this region and soybeans and corn are planted mostly in the southern third of the region.

Other land uses or land cover include forest and woodland, urban areas, grazing (livestock), wetland, and open water (Figure 9). The predominant forest areas are in the eastern part of the moraine region of Minnesota. The major urban areas are located along the Red River. Beef and dairy cattle are the primary livestock that graze in the Red River basin. Beef cattle are pastured mostly in the Drift Prairie area, whereas beef and dairy cattle are found in the eastern uplands of the Red River basin. Turkey farms are found mostly in the southeastern uplands of the basin. Wetlands dominate the landscape of the Lake-Washed Till Plain, but also occur in most low areas of the Moraine and Drift-Prairie areas (Figure 11).

Climate of the region is a primary factor causing a diverse hydrologic regime for streams and surficial aquifers. Plans for monitoring water quality in streams and surficial aquifers must consider the climatic position within the basin and the seasonal and shorter-term variability of precipitation amounts and intensity. Atmospheric deposition of contaminants also may be important to the understanding of surface-water quality in the Red River basin.

The climate of the Red River basin is continental and ranges from dry subhumid in the western part of the basin to subhumid in the eastern part. The basin lies in the path of the westerlies. During most of the year the upper-level winds flow from west to east across the basin, and at the surface the predominant wind direction has a westerly component. Air masses from different source regions commonly pass over the

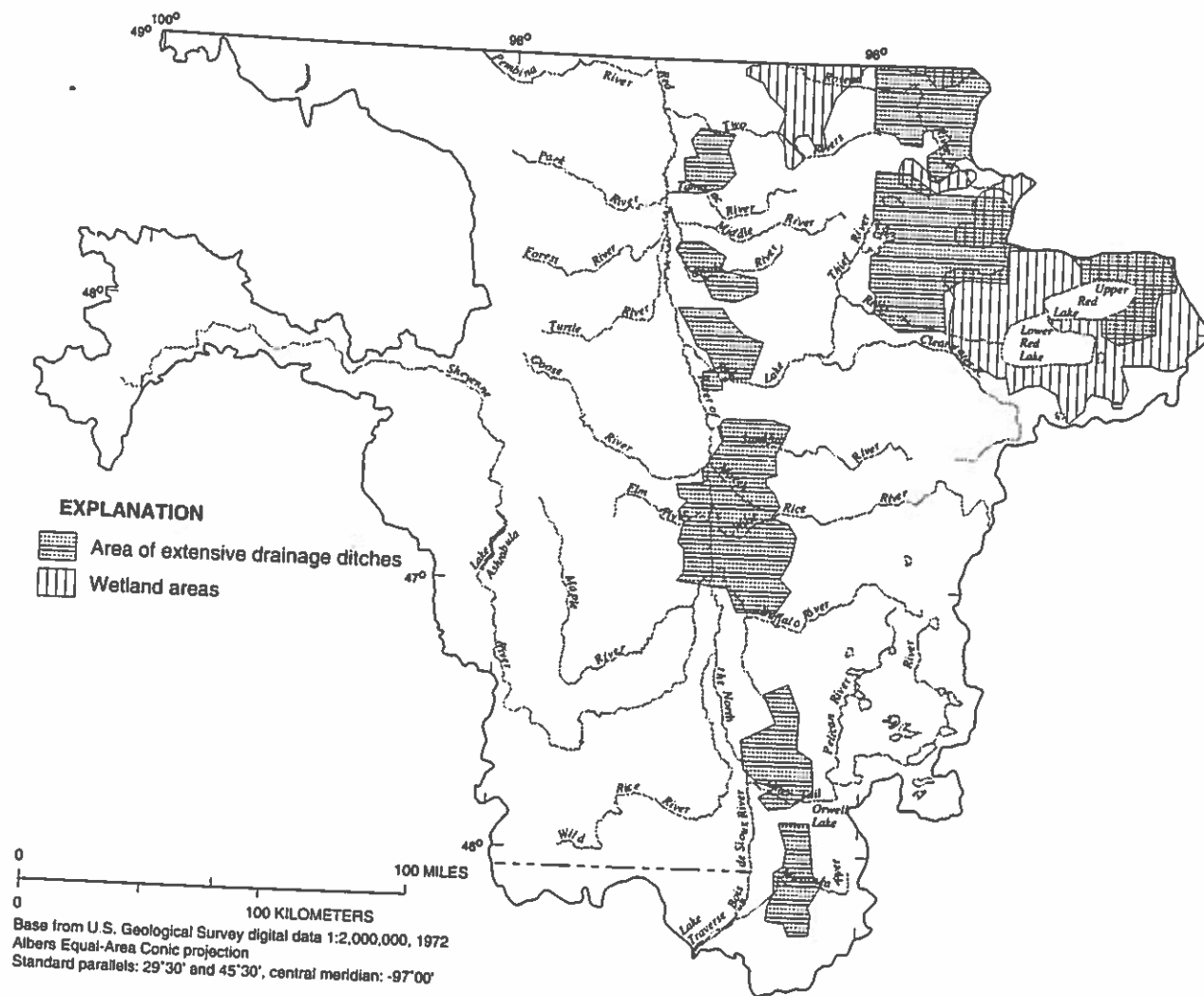


Figure 11. Areas of Wetlands and Drainage Ditches in the Red River of the North Basin. [Modified from Anderson (1967) and U.S. Geological Survey 1:100,000 scale topographic and planimetric maps.]

Red River basin and cause frequent and rapid changes in weather. The physiography of the Red River basin plays a role in the climate of the basin. One of the reasons the weather is variable in the Red River basin is because the northwestern-southeastern movement of air masses is not modified by any topographical barriers (Blair, 1989). Thus, arctic air masses that are largely unmodified can move from great distances in the north across the basin during fall, winter, or spring. However, the arctic air masses are much more frequent in winter, when a high pressure ridge develops along the west coast of North America and a low-pressure trough develops over eastern North America. This pressure pattern causes a cold and relatively dry northwesterly wind to flow across the basin. In spring and summer the westerlies weaken and retreat north. Winds are from the south or southwest, and this circulation allows warm subtropical air masses from the southern United States to move into the basin. Pacific air masses are modified as they pass over the western mountains of North America before reaching the Red River basin. The Red River basin is positioned along the eastern margin of a large rain shadow caused by the western mountains. Significant precipitation only occurs when low-level moisture from the south is transported into the basin.

The Red River basin has cold winters and moderately warm summers. The mean annual temperature is 37 to 43°F (degrees Fahrenheit) in the basin (U.S. Department of Commerce, 1982). The mean monthly temperature ranges from -1°F in January near the United States-Canadian border to 73°F in July (Figure 12) in the southern part of the Red River basin (U.S. Department of Commerce, 1982). Climate divisions (Figure 12a) (Karl and Riebsame, 1984) are used to summarize temperature and precipitation statistics because measurement at individual stations do not adequately reflect how stream basins respond to weather patterns. All climate-division precipitation and temperature data were obtained from the National Climatic Data Center, Asheville, North Carolina (written communication). The minimum normal monthly temperature for the period of record 1895-1989 occurred in February 1936 at most locations in the Red River basin. The mean climate division temperature in February 1936 ranged from -7.0°F in the southern part of the Red River basin to -14.5°F in the northern part of the Red River basin. The maximum mean normal temperature occurred in July 1936 at most locations in the Red River basin. The mean climate division temperature in July 1936 ranged from about 81°F in the southern part of the Red River basin to 74°F in the northern part of the basin. A difference in mean monthly climate division

temperature of about 90°F occurred between February and July 1936.

Mean annual precipitation increases from about 17 inches in the west to about 26 inches in the east (Figure 13). About three-fourths of the annual precipitation falls from April through September and about 60 percent of the annual precipitation falls during the growing season, generally from middle May through middle September. The growing season ranges from 100 to 140 days and averages 110 days (Souris-Red-Rainy River Basins Commission, 1972). December through February usually are the driest months.

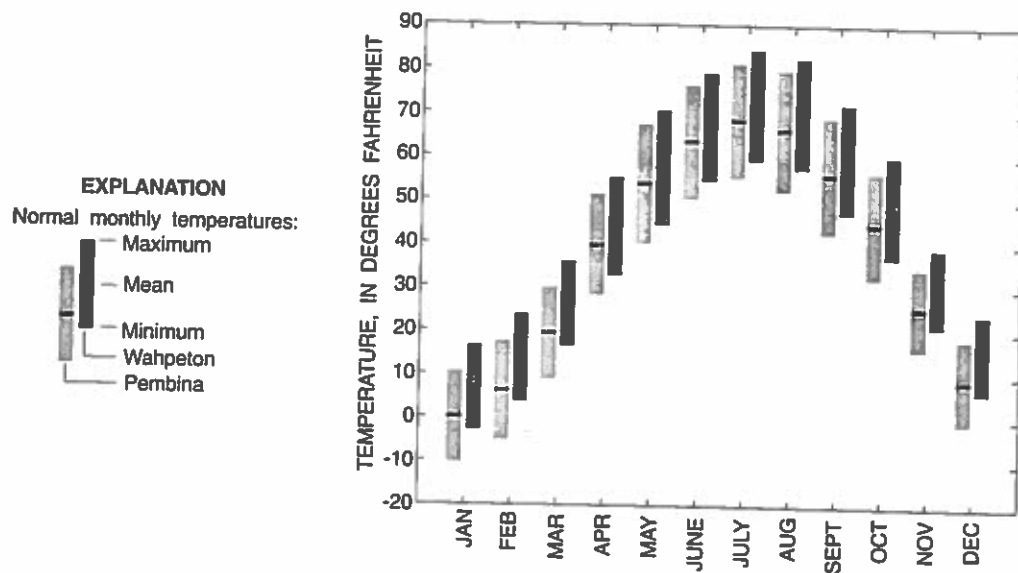
The variability in annual precipitation by climate divisions of the Red River basin is shown in Figure 12b. Annual precipitation in the Red River basin exhibits large spatial and temporal variability given the basin size and small topographic relief. The median annual precipitation for climate divisions in the North Dakota part of the Red River basin ranges from 17.7 inches to 19.7 inches. A substantial increase in median annual climate division precipitation occurs from west to east across the Red River basin (Figure 12b). The relatively large annual precipitation, in the west central and north central climate divisions in Minnesota, produces a substantial part of the runoff within the Red River basin.

Precipitation in the Red River basin also varies dramatically between wet and dry periods that range from a year to a decade. Multi-year droughts, such as for the periods 1930-40 and 1988-90, have caused water shortages, and wet periods, such as during 1966-75 have caused persistent floods and drainage problems. As an example of the precipitation variability, in the east central climate division (Grand Forks is located in this division) mean annual precipitation was 16.48 inches during 1930-40 and 20.57 inches during 1964-75. Short-term extremes in precipitation have been observed during opposite extremes in precipitation of longer periods. Therefore, a description of precipitation distribution in space and time using only averages can be misleading.

Evaporation increases substantially from east to west across the Red River basin. Evaporation computed in energy-budget studies at Cottonwood Lake (Winter and Carr, 1980), Devils Lake (Wiche, 1991), and Williams Lake (Sturrock *et al.*, 1992) (see Figure 12b for locations) indicate that mean annual net evaporation ranges from about 4 inches in the eastern part of the Red River basin to 22 inches in the western part. Potential evapotranspiration is greater in the western part of the basin than in the eastern part, but actual evapotranspiration depends on the moisture available during the year.

A monthly water-balance equation was used to identify the seasonal and annual surplus and deficit patterns in the Red River basin. Thornthwaite (1948)

(a):



(b):

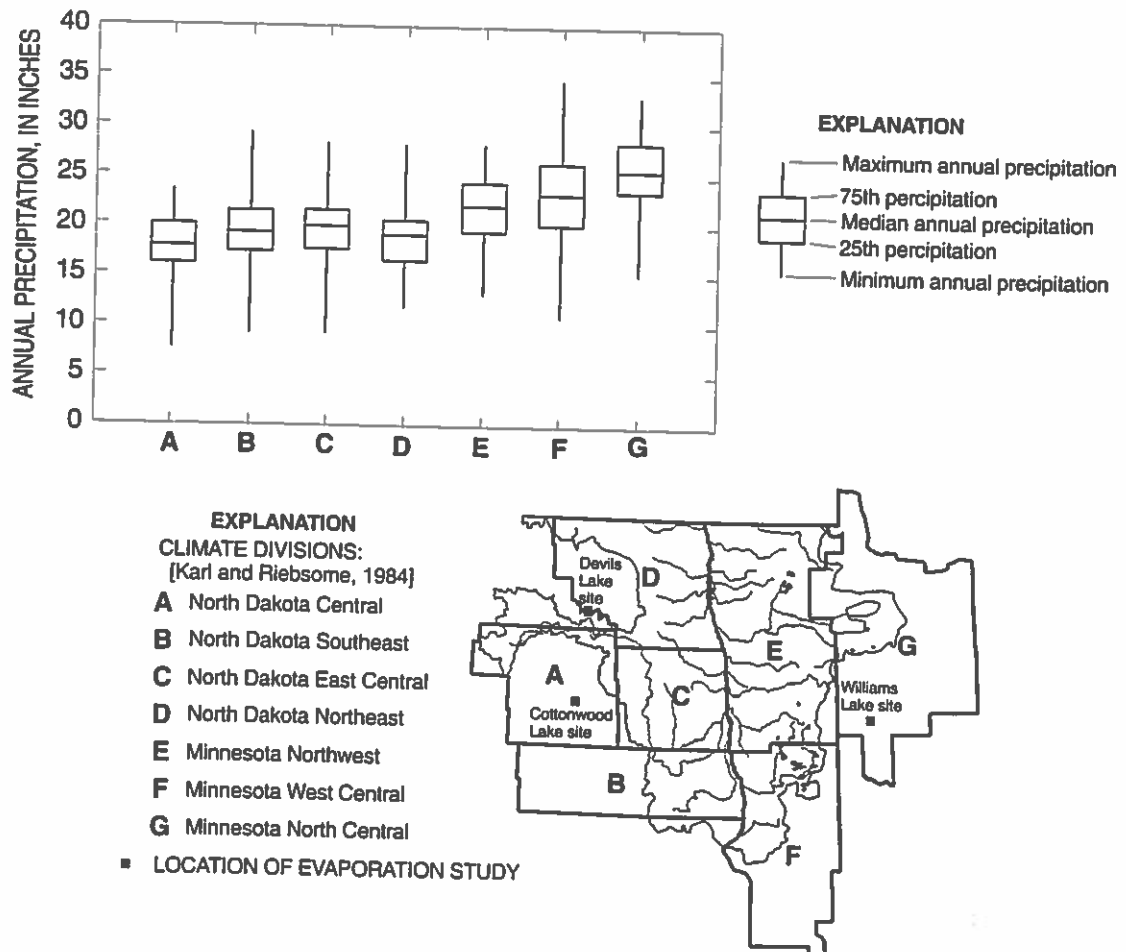


Figure 12. (a) Maximum, Mean, and Minimum Normal Monthly Air Temperature for Pembina and Wahpeton, North Dakota (1951-1980) [U.S. Department of Commerce, 1982]; and (b) Annual Precipitation Ranges by Climate Division and Locations of Evaporation Studies Near the Red River of the North Basin (1985-1989). [Data from National Climate Center, Asheville, North Carolina.]

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

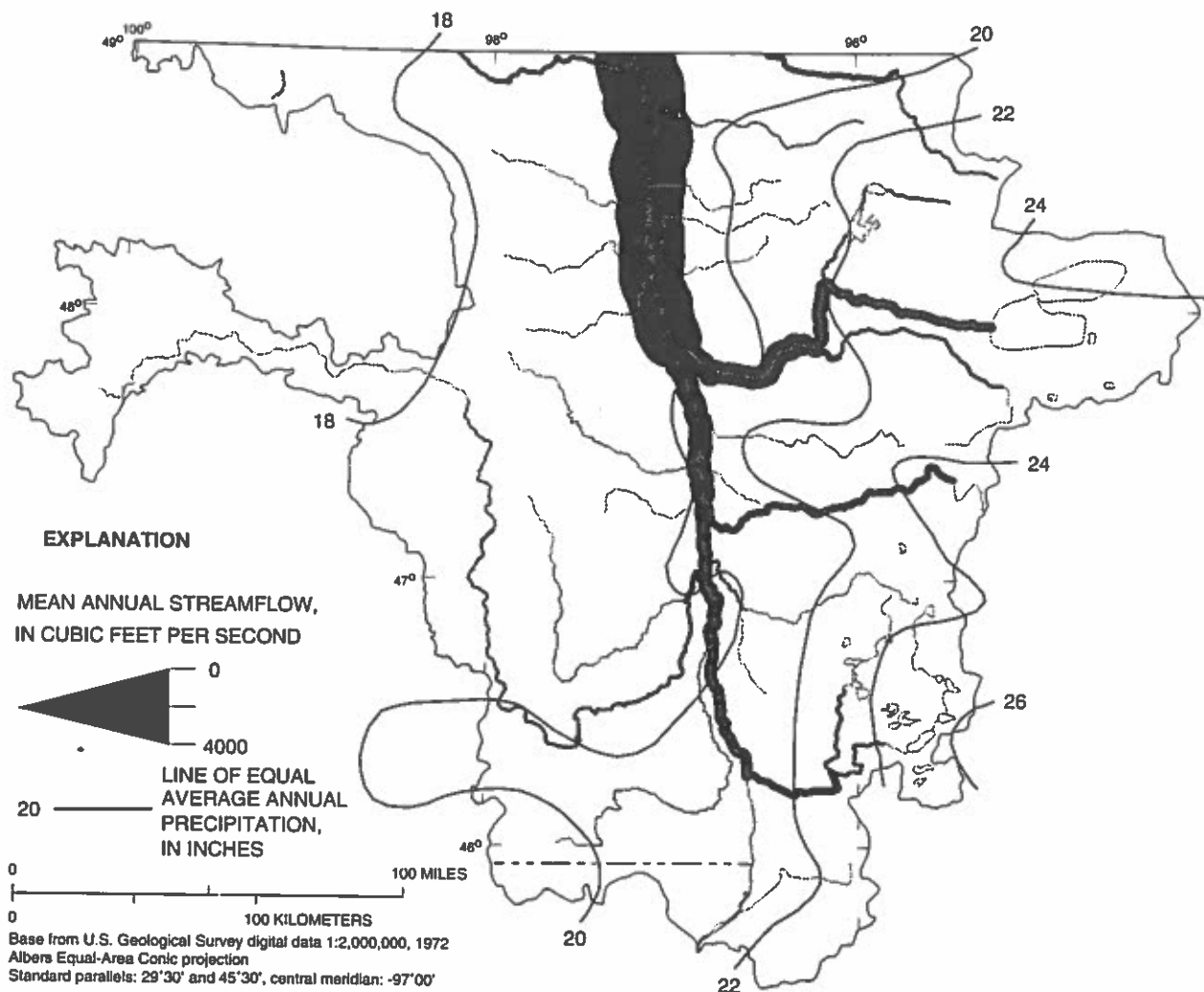


Figure 13. Average Annual Precipitation and Streamflow (1951-1980) in the Red River of the North Basin. [Precipitation Data from Minnesota and North Dakota State Climatologists, written communication.]

developed a water-balance technique to identify surplus and deficit patterns. Numerous modifications and applications of Thornthwaite's technique can be found in the literature (Sanderson, 1948; Thornthwaite and Mather, 1955; and Laycock, 1957). The water-balance equation is:

$$P = (PE - D) + S + SC \quad (1)$$

where, P = precipitation, in inches; PE = potential evapotranspiration, in inches; D = deficit, in inches; S = surplus, in inches, and; SC = storage change in inches.

Potential evapotranspiration is dependent on temperature, annual heat index (relation between temperature and potential evapotranspiration), and day length. The deficit is equal to the difference between the potential evapotranspiration and the actual evapotranspiration. Surplus is equal to the precipitation

minus the potential evapotranspiration after the soil has reached field capacity. Surplus is the water available for surface runoff or ground-water recharge. Storage change is the increase or decrease of moisture held in the soil below field capacity.

Mean monthly temperature data for each climate division for 1895 through 1989 were used to estimate potential evapotranspiration. Monthly precipitation data for each climate division for 1895 through 1989 were used in Equation (1). A maximum soil moisture storage (field capacity) of 6 inches was used (Thornthwaite, 1948). Calculated moisture storage was decreased each month potential evapotranspiration was greater than precipitation. An exponential decay function was used to compute the amount of water remaining in soil moisture storage.

The water-balance technique was modified to account for precipitation during the winter. No changes occur in surplus and soil moisture storage

during the winter (Thornthwaite, 1948). Each month when the mean temperature is less than 32°F and the soil moisture storage is less than field capacity, 20 percent of the precipitation is held as surplus and, 80 percent of the precipitation is held as soil-moisture storage. If the mean temperature is less than 32°F and the soil moisture storage is equal to or greater than field capacity, all precipitation is held as surplus until the first month the temperature is greater than 32°F (Thornthwaite, 1948).

Annual potential evapotranspiration rates are lowest over the eastern part of the Red River basin and highest over the western part of the basin. Mean annual potential evapotranspiration ranges from 22.2 inches in the north central climate division of Minnesota to 24.3 inches in the west central climate division of Minnesota. Annual potential evapotranspiration in the north central climate division of North Dakota ranged from 19.5 inches to 24.5 inches, and in the west central climate division of Minnesota the annual potential evapotranspiration ranged from 21.5 inches to 26.8 inches.

Maximum annual actual evapotranspiration occurs in the eastern part of the Red River basin, and the minimum actual evapotranspiration occurs in the western part of the Red River basin. Annual mean actual evapotranspiration ranged from 16.3 inches in the north central climate division of North Dakota to 24.3 inches in the west central climate division of Minnesota.

Maximum annual actual evapotranspiration for 1895 through 1989 ranged from 9.4 inches in 1934 in the north central climate division of North Dakota to 24.2 inches in 1986 in the west central climate division of Minnesota. Maximum annual deficits occur in the North Dakota central climate division where the upper reaches of the Sheyenne River are located, and minimum deficits occur in the eastern part of the Red River basin. Annual deficits have ranged from 0.1 inch in the Minnesota north central climate division during 1944 to 15.3 inches in the North Dakota central climate division in 1988.

Hydrologic System

Surface Water

From its origin at the confluence of the Otter Tail and Bois de Sioux Rivers, the Red River meanders northward for 394 mi to the United States-Canadian border, a path that is nearly double the straight-line distance. The mouth of the Red River is at Lake Winnipeg in Manitoba. According to Miller and Frink (1984), bank-full channel capacities at selected cities on the main stem of the Red River are: Wahpeton-

Breckenridge, 3,100 ft³/s (cubic feet per second); Fargo-Moorhead, 7,000 ft³/s; Grand Forks, 27,000 ft³/s; and Emerson, 35,000 ft³/s. Channel width range from 200 to 500 ft, and depths at bank-full stage range from 10 to 30 ft.

The slope of the Red River main stem ranges from 1.3 ft/mi (feet per mile) at Wahpeton-Breckenridge to 0.2 ft/mi at the international boundary. The meanders are mature and the stream bed is mostly comprised of clay- and silt-size materials.

The principal tributaries to the Red River (major streams in Figure 2) generally have similar stream slope characteristics. Stream slopes are about 2 to 4 ft/mi in the upland areas and decrease to about 1 to 1.6 ft/mi within the broad Red River Valley Lake Plain.

Streamflow. The Red River receives most of its flow from its eastern tributaries because of regional patterns in precipitation, evapotranspiration, soils, and topography. Annual streamflow varies greatly, and most streamflow occurs in spring and early summer as a result of snowmelt, rains falling on melting snow, or heavy rains falling on saturated soils. Streamflows during most of the year are less than one-fourth of the flows indicated by the average flow (Figure 13 and Table 2). Flooding is a major problem that is aggravated by the flat slope of the Red River and the flatness of the overbank areas.

Mean annual runoff increases from southwest to northeast across the basin (Figure 13). Mean annual runoff to tributaries originating in North Dakota and South Dakota range from 0.49 in. for the Wild Rice at Abercrombie to 1.34 in. for the Park River at Grafton (Table 2). Mean annual runoff of tributaries originating in Minnesota range from 2.03 in. for the Buffalo River near Dilworth to 4.07 in. for the Red Lake River at High Landing (Table 2). Thus, the headwater areas of the Red Lake River produce the greatest annual runoff in the Red River basin. The drainage area of the Red Lake River is only 13 percent of the total drainage area of the Red River at Emerson, but the streamflow for the Red Lake River is about one-third of the streamflow for the Red River at Emerson.

The coefficient of variation of mean annual streamflow (a measure of the variation of streamflow from year to year) in the Red River basin decreases from southwest to northeast (Figure 14, Table 2). The coefficient of variation of the mean annual streamflows ranges from 113 percent for the Bois de Sioux River near White Rock to 41 percent for the Otter Tail River near Fergus Falls. The Otter Tail River and the headwaters of the Red Lake River have the lowest coefficient of variation of mean annual streamflow in the Basin.

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

TABLE 2. Drainage Area, Mean Annual Streamflow and Runoff, and Coefficient of Variation for Selected Gaging Stations in the Red River of the North Basin, 1947-1987.

Gaging Station Name	Gaging Station No.	Drainage Area (square miles)	Mean-Annual Streamflow (cubic feet per second)	Mean-Annual Runoff (inches)	Coefficient of Variation of Mean-Annual Streamflow (percent)
Otter Tail River below Orwell Dam, near Fergus Falls, Minnesota	05046000	1,830	387	2.87	41
Bois de Sioux River near White Rock, South Dakota	05050000	1,160	81	0.95	113
Red River at Wahpeton, North Dakota	05051500	4,010	554	1.88	52
Wild Rice River near Abercrombie, North Dakota	05053000	2,170	80	0.49	110
Red River at Fargo, North Dakota	05054000	6,800	724	1.45	62
Sheyenne River at West Fargo, North Dakota	05059500	3,090 ^a	211	0.93	56
Buffalo River near Dilworth, Minnesota	05062000	1,040	155	2.03	58
Wild Rice River near Hendrum, Minnesota	05064000	1,600	264	2.25	57
Rush River at Amenia, North Dakota	05060500	116	9.7	1.13	91
Goose River near Hillsboro, North Dakota	05066500	1,203	88	0.99	96
Sandhill River at Climax, Minnesota	05069000	405	73	2.45	61
Red Lake River at High Landing, Minnesota	05075000	2,300	689	4.07	56
Thief River near Thief River Falls, Minnesota	05076000	959	223	3.16	72
Clearwater River at Red Lake Falls, Minnesota	05078500	1,370	362	3.59	51
Red Lake River at Crookston, Minnesota	05079000	5,280	1,420	3.66	49
Red River at Grand Forks, North Dakota	05082500	26,300 ^a	3,340	1.73	52
Forest River at Minto, North Dakota	05085000	740	52	0.96	92
Park River at Grafton, North Dakota	05090000	695	69	1.34	96
Pembina River at Neche, North Dakota	05100000	3,410	241	0.96	81
Red River at Emerson, Manitoba	05102500	36,400 ^{a,b}	4,390	1.48	55

^aDoes not include the 3,800 mi² of noncontributing Devil's Lake basin.

^bDoes not include the Roseau River basin, but does include all of the Pembina River basin.

The timing and magnitude of streamflow during the year affects water quality because of the seasonal availability of chemicals near the land surface. Water availability, water excess, and water routing are the three factors that control the timing and amount of streamflow in the Red River basin (Miller and Frink, 1984). Most of the streamflow in the basin occurs as a result of snowmelt or rain during snowmelt. About 50 percent of the mean annual streamflow for the Red River at Emerson occurs in April and May and 70 percent occurs during April-July (Figure 14). Most of the annual streamflow for tributaries to the Red River originating in North Dakota and South Dakota occurs in April and May (Figure 14). As an example, about 77 percent of the mean annual streamflow for the Park River at Grafton occurs in April and May. Tributaries to the Red River originating in Minnesota do not have as large a percentage of the mean annual streamflow occurring in April and May as the tributaries originating in North Dakota because of the greater number of lakes and wetlands in Minnesota

(Figure 14). As an example, about 45 percent of the mean annual streamflow for the Buffalo River near Dilworth occurs during April and May.

The timing and magnitude of streamflow between years also affects water quality. The timing and amount of streamflow in the basin have large yearly variability. Mean daily streamflow during a flood year (1950) and a low-flow year (1977) for the Red River at Emerson are shown in Figure 15. The major difference in streamflow between 1950 and 1977 occurs during the spring and early summer. In 1977, no significant streamflow occurred as a result of snowmelt and spring rains, but in 1950 snowmelt in April and rain falling over saturated ground in May set the stage for the devastating flood in April and May. The volume of water measured at the Red River at Emerson April 29 through May 1, 1950 was 432,400 acre-feet, about equal to the annual volume of 433,700 acre-feet during the entire year in 1977.

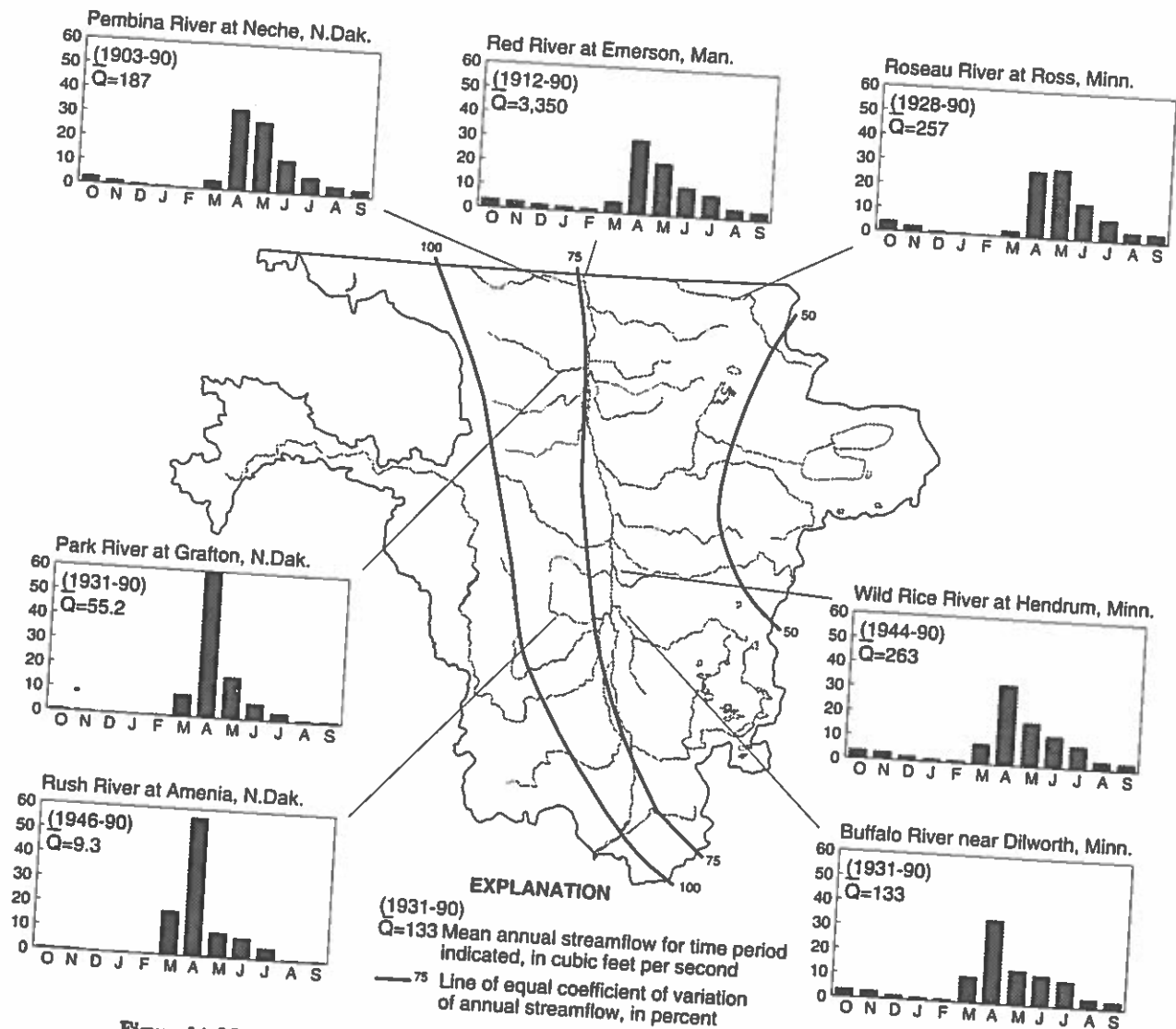


Figure 14. Monthly Percent of Mean Annual Streamflow of Selected Streams and Distribution of Coefficient of Variation of Annual Streamflow in the Red River of the North Basin.

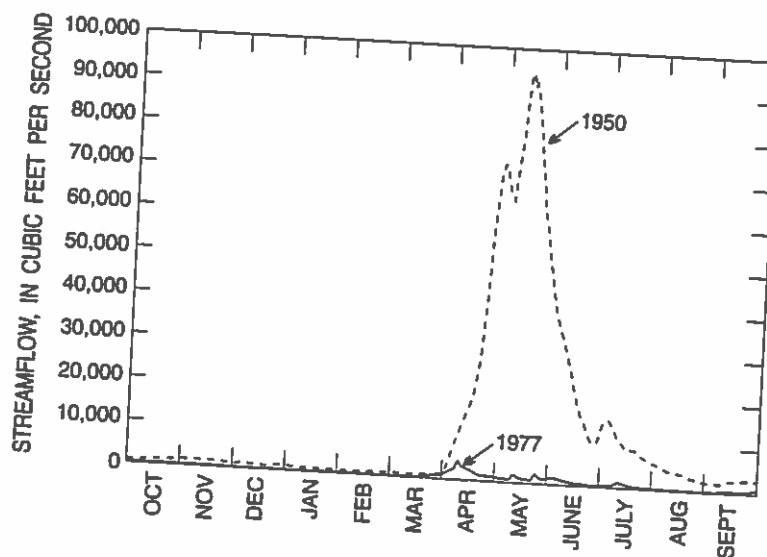


Figure 15. Mean Daily Streamflow for the Red River of the North at Emerson, Manitoba, 1950 and 1977.

Although decadal streamflow is not as variable as annual streamflows, large differences have occurred. As an example, the mean annual streamflow of the Red River at Grand Forks (Figure 16) for the ten years ending 1940 was 548 ft³/s, and the mean annual streamflow for the 10 years ending 1975 was 4110 ft³/s. Thus, the ratio of the largest to the smallest decadal streamflow for the Red River at Grand Forks is 7.5.

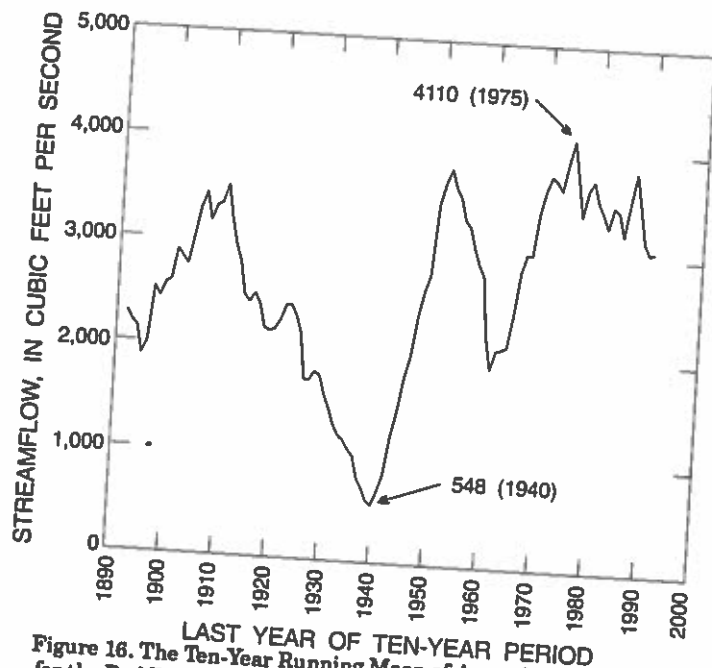


Figure 16. The Ten-Year Running Mean of Annual Streamflow for the Red River of the North at Grand Forks, North Dakota.

Floods and Droughts. The factors that affect water availability and surplus that can cause flooding in the Red River basin are: (1) greater than normal precipitation during October-November (2) deep frost penetration before the first significant snow (3) greater than normal precipitation during December-March, especially during late winter (4) below normal temperatures during March and early April followed by rapid warming and, (5) greater than normal precipitation during spring snowmelt. All of these factors do not have to occur to have flooding in the Red River basin, but all major floods can be attributed to most of these factors (Miller and Frink, 1985).

The floods of 1950, 1966, and 1979 are the largest and most damaging floods that have occurred throughout the Red River basin since streamflow records began in the early 1880's. Upstream of the confluence of the Turtle River and Red River; however, the streamflow during the 1897 flood probably was greater than the streamflow during the 1950, 1966, and 1979 floods.

The 1826 flood is the greatest flood in the Red River valley in the last 200 years. The 1826 flood probably was the greatest on many streams in the basin. From the accounts of the 1826 flood several conclusions can be reached: (1) the fall of 1825 was extremely wet and most of the lakes and wetlands were overflowing, (2) a major snowstorm occurred in late fall, (3) a cold, snowy winter permitted an exceptionally deep snow pack to develop over much of the basin, and (4) the coldest estimated March-April mean temperature at Winnipeg since 1815 was 17°F in 1826.

The greatest runoff during most years, including flood years, occurs in the Red Lake River basin and the least runoff occurs in the Sheyenne River basin and the Wild Rice River basin in North Dakota. About 8.5 inches of runoff occurred in the Red Lake River basin during 1950 and 1966, but only about 4.8 inches of runoff occurred in 1979. The 1950 flood was exceptional because of the large amount of basin-wide runoff.

The most severe droughts have a large spatial distribution; therefore extreme low-flows occur over large areas. The longest extended period of low-flow throughout the Red River basin occurred during 1930-40. Annual runoff was less than the long-term mean annual runoff during every year from 1930 to 1940 at all gaging stations in the Red River basin. The smallest annual runoff throughout the Red River basin occurred in 1934 when annual runoff ranged from 0.01 inch in the Wild Rice River basin upstream of Abercrombie, North Dakota to 0.25 inch in the Pembina River basin upstream of Nettle, North Dakota.

Runoff in the Red River basin during the more recent drought years 1977 and 1990 is shown in Table 3. Although runoff was less in 1977 and 1990 than in 1934 in the Park River basin and the Pembina River basin, the drought during 1934 was much more severe throughout the Red River basin (Table 3). The exceptional low-flow in 1934 in the Red River was caused in part by the lack of runoff from the eastern part of the Red River basin.

Lakes, Prairie Potholes, and Wetlands. Lakes, prairie potholes, and wetlands are abundant in most physiographic areas outside of the Red River Valley Lake Plain (Figure 3). Natural lakes, ranging in surface area from 10 to 13,800 acres, can occur at a density greater than one lake per square mile in the moraine area of the southeastern part of the Red River basin. Numerous potholes and wetlands also are located in the Prairie Drift and Coteau du Missouri physiographic areas; wetlands are common in the low areas between beach ridges. The area of organic deposits (Figure 6) of the Lake-Washed Till

TABLE 3. Annual Runoff During Flood and Low-Flow Years for Selected Gaging Stations in the Red River of the North Basin (-, no data).

Station Name	Square Miles	Flood Years			Drought Years		
		1950 (inches)	1966 (inches)	1979 (inches)	1934 (inches)	1977 (inches)	1990 (inches)
Otter Tail River below Orwell Dam, near Fergus Falls, Minnesota	1,830	2.54	4.95	3.38	--	0.28	1.99
Bois de Sioux River near White Rock, South Dakota	1,160	1.65	1.77	2.26	--	< 0.01	--
Red River at Wahpeton, North Dakota	4,010	2.19	3.15	1.50	--	0.18	0.97
Wild Rice River near Abercrombie, North Dakota	2,170	0.86	0.90	0.64	0.01	0.03	0.02
Red River at Fargo, North Dakota	6,800	2.06	2.55	2.56	0.03	0.13	0.61
Sheyenne River at West Fargo, North Dakota	3,090	2.56	1.66	1.81	0.16	0.26	0.23
Buffalo River near Dilworth, Minnesota	1,040	3.23	3.39	2.31	0.33	0.35	0.86
Wild Rice River near Hendrum, Minnesota	1,600	3.08	4.03	3.94	--	0.24	1.03
Sandhill River at Climax, Minnesota	405	6.83	5.09	3.93	--	0.62	0.94
Thief River near Thief River Falls, Minnesota	959	8.55	8.59	4.79	0.06	0.10	0.06
Clearwater River at Red Lake Falls, Minnesota	1,370	8.47	5.78	4.89	--	0.88	0.95
Red Lake River at Crookston, Minnesota	5,280	8.04	6.71	4.93	0.22	0.72	0.48
Red River at Grand Forks, North Dakota	26,300	3.91	3.12	3.08	0.13	0.26	0.45
Park River at Grafton, North Dakota	695	6.89	2.81	3.02	0.15	0.07	0.03
Pembina River at Niche, North Dakota	3,410	2.42	1.21	2.21	0.25	0.10	0.23
Red River at Emerson, Manitoba	36,400	4.51	3.24	3.12	0.12	0.22	0.37

Plain contain a special type of wetland that is part of the most extensive peatlands in the United States (MacLay *et al.*, 1972).

Lakes, potholes, and wetlands can have a profound effect on the hydrologic flow regime of Red River basin streams and the residence time of water in the Red River basin. For example, Lower Red Lake, which forms the beginning of the Red Lake River, maintains a fairly uniform discharge throughout the year. The chain of lakes along the Otter Tail River also have the effect of stabilizing streamflow throughout the year. The Red River basin also contains thousands of natural wetlands and prairie potholes. In the Drift Prairie physiographic area of North Dakota, the potholes commonly are in closed basins that retain local runoff.

Flood and Drainage Structures

Channel and flood-plain obstructions such as ice jams, trees, dams, and levies can cause backwater effects that increase residence time, retard peak flows, and affect local flood elevations. These conditions possibly can affect the amount and timing of contaminants in water and sediment, but data are insufficient to define the effect. Major reservoirs, operated by the U.S. Army Corps of Engineers for flood control and water supply, include Upper and

Lower Red Lakes (storage capacity of 1,810,000 acre feet (ac-ft), Lake Traverse (137,000 ac-ft), Lake Ashtabula (69,100 ac-ft), and Orwell (13,100 ac-ft). Although the altitude of the Upper and Lower Red Lakes currently is controlled at the outlet of Lower Red Lake, the surface area of the lakes (288,800 acres) is not much different from the surface area before the outlet altitude was modified. There are about 350 dams of various sizes and purposes in the Red River basin (Figure 17). They vary in size from small Soil Conservation Service reservoirs (normal capacity of less than 2.0 ac-ft) to the Upper and Lower Red Lakes. Most dams are on tributaries to the major streams and the larger dams are used for flood mitigation. There are several small dams on major streams that are used for public water supply. There are also many small dams used for soil conservation and wildlife refuges.

An extensive drainage system of ditches has been constructed in the Red River Valley Lake Plain and in the Lake-Washed Till Plain (Figure 11). Miller and Frink (1984, p. 22-24) summarize the history of drainage development in the Red River basin that was significant in the early 1900's and again in the 1940's and 1950's. Drainage ditches in the Red River Valley Lake Plain are typically oriented in an east-west direction (perpendicular to the Red River) to promote spring runoff and early drainage of the heavy soils. Drainage ditch morphology in the Lake-Washed

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

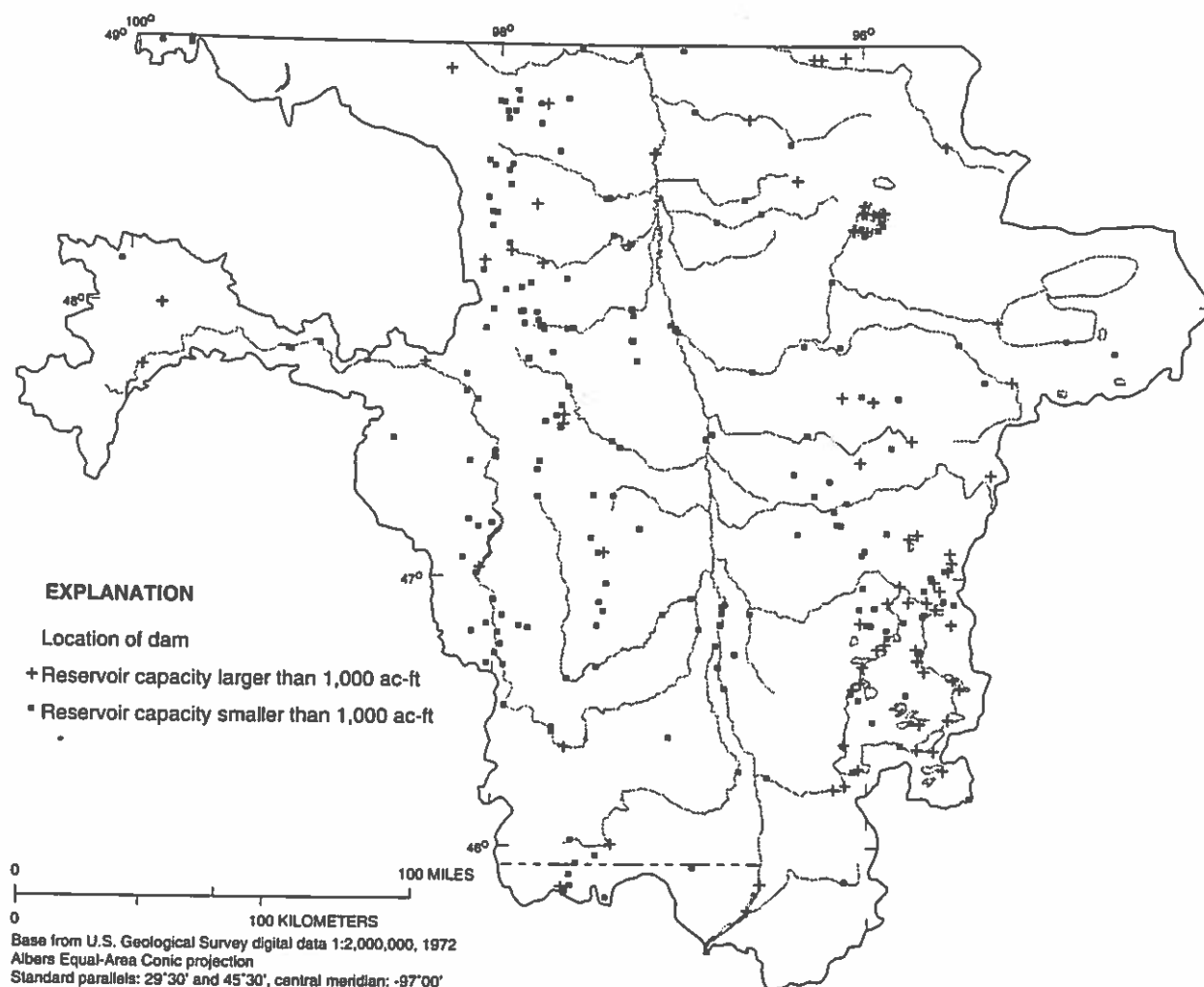


Figure 17. Locations of Dams and Reservoirs in the Red River of the North Basin. [Minnesota Department of Natural Resources, North Dakota State Water Commission, and South Dakota Department of Environment and Natural Resources, written commun.]

Till Plain is a network of north-south and east-west ditches in level terrain. Drainage boundaries are difficult to define because of the level terrain and numerous drainage ditches constructed in a dense, rectangular network throughout much of the area. Ditch morphology varies from broad, shallow, grass-lined depressions, which are found in nearly every field, to large Judicial ditches (ditches established by district courts) that extend many miles. Many of the main arteries of these Judicial ditches have 10-foot depths and well-defined banks and channels. Ditch slopes are nearly flat. Many are choked with vegetation or cross watershed divides which rendered them ineffective.

Ground Water

Ground water available to wells, streams, and springs primarily comes from sand and gravel aquifers near land surface or buried within the glacial drift that mantles the entire Red River basin. In the western half of the basin, some ground water also is available from bedrock aquifers (sandstone, limestone, and dolomite) beneath the glacial drift. The term aquifer in this part of the report refers to water-yielding rocks or unconsolidated sediments with no implication to water quality. In most locations, the Precambrian crystalline rocks are considered relatively impermeable to ground-water movement. For regional assessment of water quality, the surface of the Precambrian crystalline rocks marks the base of the ground-water system. These rocks lie at depths

ranging from near land surface at the southern end of Lake Traverse and near the eastern edge of the basin to as much as 6,000 ft below land surface in the northwestern part of the basin.

Glacial-Drift Aquifers. The extent of the known principal glacial-drift aquifers in the Red River basin are shown in Figure 18. These sand and gravel aquifers have been delineated through cooperative investigations among the Minnesota Department of Natural Resources, the Minnesota and North Dakota Geological Surveys, the North Dakota State Water Commission, Universities, and U.S. Geological Survey. The aquifers have been separated into either surficial or buried aquifers based on available information. However, this separation is not easily done because of the complexity of glacial deposits. The

same sand and gravel deposit could comprise both types of drift aquifers in some parts of the basin. Some of the areas shown as surficial aquifer may include locations where thin (less than 20 ft.) and discontinuous layers of till overlie the aquifer. Numerous narrow lenses of sand buried within glacial till that are known to yield small quantities of water to domestic wells are not shown as principal aquifers in Figure 18.

Surficial aquifers generally have larger porosity and water-storage capacity than buried aquifers, are more susceptible to the effects of land-surface activities than buried aquifers, and can be hydraulically connected to surface water, such as streams, lakes, and wetlands. The upper surface of the surficial aquifer, the water table, is in equilibrium with the atmosphere and the aquifer is unconfined. Buried

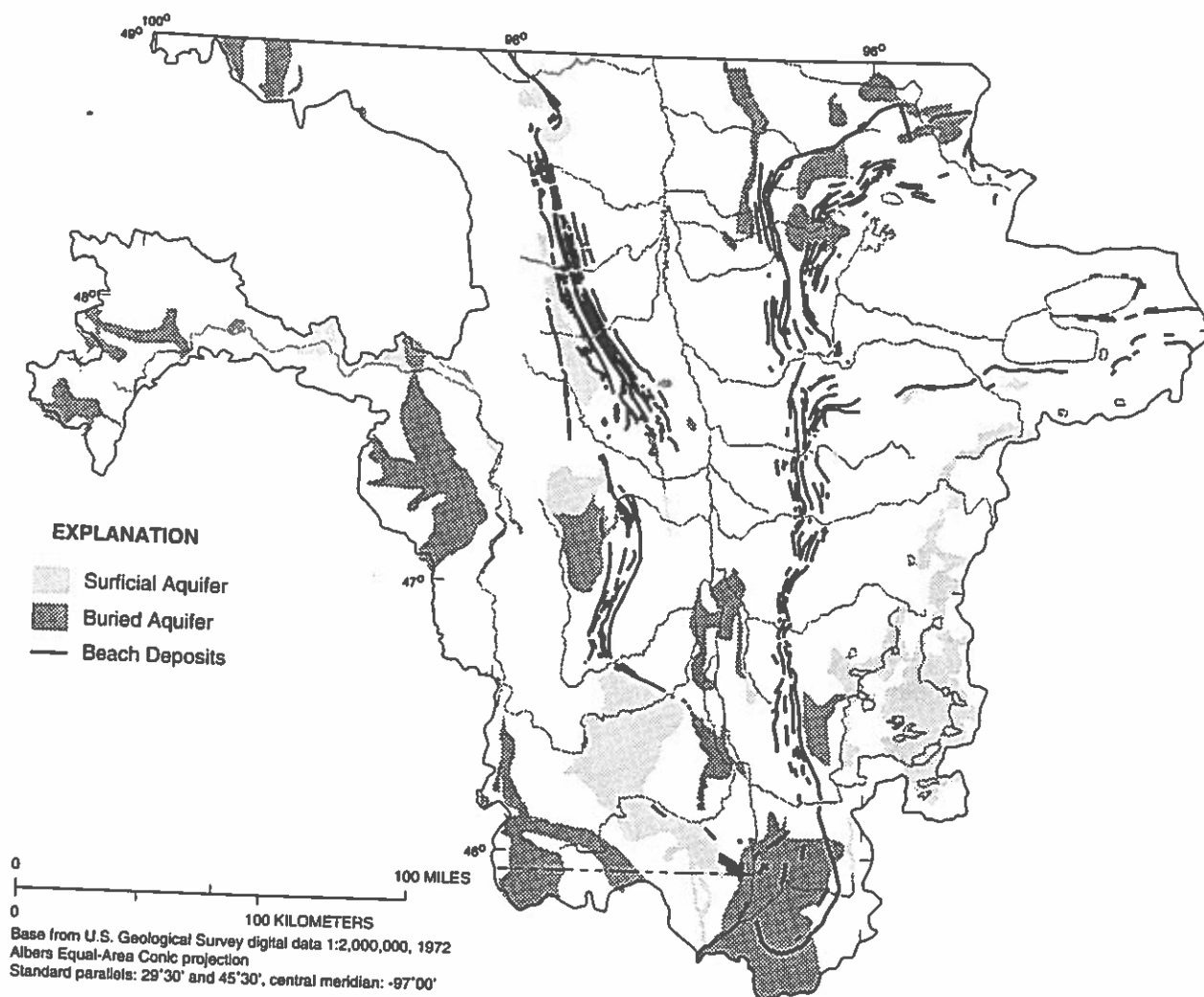


Figure 18. Major Surficial and Buried Aquifers and Beach Deposits in Glacial Drift in the Red River of the North Basin. [Aquifers compiled from U.S. Geological Survey Hydrologic Atlases and water resources studies in Minnesota and South Dakota, and North Dakota State Water Commission ground-water studies of North Dakota counties; beach deposits from Clayton *et al.* (1980) and Hobbs and Goebel (1982).]

aquifers generally are confined by less permeable clay and silt materials and contain water under artesian pressure.

Glacial-drift aquifers fall under two general types of geometric forms in the basin: (1) broad, sheet-like deposits and (2) elongated deposits. The sheet-like deposits may have been deposited as outwash from glacial meltwaters or deltas associated with glacial Lake Agassiz. Elongated deposits of sand and gravel may have been deposited as glacial-drift fill of bedrock valleys, streams adjacent to glacial ice, or beach ridges associated with glacial Lake Agassiz. These elongated deposits also include alluvium and terrace deposits associated with preglacial, glacial, and modern streams.

Characteristics of the principal surficial and buried-drift aquifers that have been described in the basin are summarized by geometric form in Table 4. Many of the aquifers listed in Table 4 have been given formal names that can be found in individual county and aquifer study reports listed in the references. In general, the buried, drift-filled valley deposits and the surficial outwash and delta deposits comprise the most productive aquifers of the Red River basin. The transmissivity of these aquifers ranges from about 110 to 56,000 feet squared per day. Porosity ranges from about 0.17 to 0.25 for the glacial-drift aquifers depending on grain-size distribution. According to numerical modeling studies of glacial-drift aquifers in the region (Winter and Carr, 1980) the average hydraulic conductivity of till units are one to two orders of magnitude lower horizontally and two to five orders of magnitude lower vertically than the hydraulic conductivity of glacial-drift aquifers.

Bedrock Aquifers. The bedrock underlying the Red River basin is comprised of sandstone, siltstone, shale, limestone, and dolomite. Downey (1986) grouped these sedimentary rocks into aquifers and confining units for a regional study of the ground-water resources of the northern Great Plains, a region that includes the North Dakota and South Dakota parts of the Red River basin. Beneath the Red River basin, the four aquifers (from deepest to shallowest) are (1) Cambrian-Ordovician, (2) Mississippian, (3) Lower Cretaceous, and (4) upper part of the Upper Cretaceous and Tertiary (Figure 5). In the Red River basin, the Cambrian-Ordovician aquifer chiefly consists of the Winnipeg, Red River, and Stoney Mountain Formations. These formations are principally limestone, dolomite, sandstone, and some shale. The Mississippian aquifer is predominately limestone. The Lower Cretaceous aquifer, part of which is known as the Dakota aquifer in North and South Dakota, consists of the Inyan Kara Group (Lakota Formation, Fuson Formation, and Fall River Sandstone), Skull

Creek Shale, and Newcastle Sandstone. These formations are principally sandstone, but they contain considerable interbedded shale (Table 1). The Fox Hills Sandstone and Hell Creek Formation (Upper Cretaceous) and the Cannonball Member of the Fort Union Formation (Tertiary) comprise the Upper Cretaceous and Tertiary aquifer. All of these formations are sandstone and lignite interbedded with shale and siltstone.

The relative location, thickness, and extent of these regional aquifers and the confining units that separate them are shown in Figures 4 and 5. Many of the Cretaceous shales and interbedded sandstones within the regional confining units can yield small quantities of water to domestic wells in the Red River basin.

Water Movement. Water moves through the system of bedrock and glacial-drift aquifers in complex regional and local flow systems. Water generally moves east-northeast within the three deep principal bedrock aquifers (the Cambrian-Ordovician, Mississippian, and Lower Cretaceous aquifers). These aquifers are recharged in mountainous regions of the Williston structural basin that are several hundred miles south and west of the Red River basin (Downey, 1984). Because of high hydraulic heads in the aquifers, water leaks upward into overlying rocks and ultimately into glacial deposits, especially near topographically low areas such as the Red River Valley Lake Plain. The Lower Cretaceous and Cambrian-Ordovician aquifers discharge water upward throughout much of their extent beneath the Red River basin.

The Upper Cretaceous and Tertiary aquifers may have a regional component of flow similar to the deeper bedrock aquifers, but the flow probably is more affected by local recharge and discharge near land surface where this aquifer is under the Red River basin.

Recharge enters the glacial-drift aquifer system by direct infiltration of precipitation to surficial aquifers and by slow leakage to confined aquifers through silt and clay. On a regional scale, ground water generally moves through the glacial-drift aquifer system from the topographically high moraine areas toward the Red River and its major tributaries where it discharges to the surface-water system. Using base flow analysis for the Minnesota part of the basin, Maclay *et al.* (1972) estimated regional recharge rates of 5 to 6 in/yr to the sandy surficial aquifers and probably less than 1 in/yr to buried-drift aquifers.

Local topography, hydrogeology, and available recharge can cause local flow systems that differ from the region flow system. Ground-water in surficial and shallow buried aquifers moves relatively short distances in hilly terrain from hills to adjacent low areas like headwater streams, lakes, and wetlands. Such

TABLE 4. Characteristics of Principal Aquifers Within the Glacial Drift.

Aquifer Description Materials and Areal Extent	Thickness (feet)	Potential Yield (gal/min)	Transmissivity (ft ³ /ft/day)	Storage Coefficient
Surficial Aquifers				
Deltas - Often lenticular, well-sorted fine to coarse-grained sands, occasionally interfingering with silts and clays, associated with glacial lakes. Gravels present in near-shore areas. Deltas range from 1 mile in diameter in small glacial lakes to 35 miles long and 20 miles wide in Lake Agassiz.	10-400	10-1,000	130-8,600	0.001-0.19
Outwash Plains - Predominantly well-sorted very fine to medium sand containing lenses of coarse sand to medium gravel. Lenses of silt, clay and till, including ice-contact deposits, occur locally. Grades laterally into sandy till. Surficial outwash plains are roughly circular and small ranging in diameter from 1 to 10 miles.	10-130 locally to 200	50-500 locally to 900	3,300-22,000	
Surficial Channels - Lenticular fine to very coarse sand with gravel lenses and interbedded with lenses of silt, clay and/or till. Surficial channels occasionally occupy bedrock valleys, are often adjacent to present streams or linear low areas, and some are ice-marginal. They range in length from 5 to 30 miles and in width from several hundred yards to 2 miles.	10-120 locally to 300	10-1,500	200-32,000	0.001-0.18
Beach Ridges - Poorly to well-sorted, very fine to medium sand containing lenses of fine to medium gravel. Beach ridges range from one to tens of miles long and vary from a few hundred feet for single ridges to several miles wide where many occur close together.	10-50 locally to 150	10-500	2,400	0.17
Buried Aquifers				
Bedrock Valley-Fill - Poorly to well-sorted, lenticular very fine sand to medium gravel interbedded with silt, clay, and till. Deposits are generally coarsest in the valley bottoms and fine upward. While the deepest lenses were deposited by pre-glacial streams, most of the valley-fill is glacial channel outwash. Once the pre-existing bedrock valleys filled, braiding outwash streams often capped the filled valley with an outwash plain. Filled bedrock valleys range from 3 to more than 200 miles in length and 1/4 to 4 miles wide (to 8 miles wide including capping outwash plains).	10-550	50-1,500 locally as little as 10	2,100-56,000	0.0003-0.02
Buried Outwash Plains - Very fine sand to coarse sand containing fine to coarse gravel lenses and interfingering with silt, clay, and till locally. Buried outwash plains are roughly equant ranging in diameter from 2 to 20 miles.	10-130	10-750	110-11,000	0.00004
Buried Channels - Lenticular fine to coarse sand with lenses of gravel and locally interbedded with silt and clay. Buried channels may locally underlie present stream valleys or may occupy glacio-fluvial channels cut into till. These channels range from 6 to 27 miles long and 1/2 to 6 miles wide.	10-160	25-750 locally to 1,000	160-36,000	0.00005-0.018

(Compiled from U.S. Geological Survey Hydrologic Atlases and North Dakota Geological Survey and North Dakota State Water Commission ground-water studies of North Dakota counties.)

flow conditions would apply in the Coteau du Missouri, Coteau des Prairies, and the extreme eastern Moraine area of Minnesota (Figure 3) which are considered to be regional recharge areas. Conversely, LaBaugh et al. (1987) and Lissey (1971) showed that in such areas of hummocky glacial till, local ground-water recharge can be focused in lowlands and that

water-table highs may not necessarily fall under topographic highs. These authors also showed seasonal reversals of flow to and from low areas such as wetlands.

Ground-water flow in the flat areas of the Red River basin can be affected by deeper flow systems. Winter et al. (1984) suggest that flow in the glacial-

drift aquifer system beneath the Drift Prairie area is dominated by deep local flow systems. In the Red River Valley Lake Plain, ground water moves under low horizontal hydraulic gradients toward the Red River and major low areas. Many of the shallow buried-drift aquifers below the Red River valley receive some recharge from underlying buried aquifers in the glacial drift and bedrock. This upward leakage is not sufficient to significantly alter local horizontal flow, but can have a measurable effect on ground-water chemistry and potential conditions for flowing wells.

Water-level hydrographs from wells completed in glacial-drift aquifers (Figure 19) show that levels typically fluctuate less than three feet per year. Annual water level changes indicate a pattern of sharp rises in April and May of each year with a gradual recession throughout the remainder of the year. Consistent long-term trends in water-level change are not apparent for the glacial drift aquifers for the past 20 to 30 years. However, ground-water withdrawals can lower levels locally as shown in hydrograph (H) in Figure 19, which is from a well that is near a municipal well field. Also, many of the hydrographs for surficial aquifers show a slight water-level decline at the time of the 1988 to 1990 drought.

Water Use

In the Red River basin, the North Dakota State Water Commission, the Minnesota Department of Natural Resources, and the South Dakota Department of Water and Natural Resources are responsible for permitting and collecting reports on water use. The information in this report is a compilation from these data (Perlman, 1993, U.S. Geological Survey written communication).

Table 5 shows that irrigation and public supply accounted for 68 percent of all 1990 water withdrawals in the Red River Basin. Public supply accounted for 36 percent of surface water withdrawals, due mainly to withdrawals from the Red River by Fargo and Grand Forks, North Dakota and Moorhead, Minnesota.

Ground water accounts for 52 percent of all water withdrawals in 1990. Crop irrigation accounted for 49 percent of ground water withdrawals, primarily from glacial-drift aquifers. Bedrock aquifers are not developed for measurable water use. Figure 20 shows the distribution of ground water used for irrigation in the Red River basin in 1990.

Consumptive water use is that part of withdrawals that is evaporated, transpired, incorporated into crops or products, consumed by humans or livestock, or otherwise not immediately returned to the water

environment. The 1990 consumptive water use rates, as a percentage of category withdrawals, are public supply 0 percent, rural domestic 85 percent, irrigation 88 percent, livestock 100 percent, self-supplied industrial 46 percent, and thermoelectric 2.5 percent.

Total water use in the Red River basin increased about 21 percent between 1980 and 1990. Water-use data compilation methods changed in the early 1980's so that comparisons between 1980 and 1990 by individual categories are not as reliable as those between 1985 and 1990. The first five categories of reported water use in the table are those uses that can affect water chemistry. Water use in the first five categories increased 17 percent between 1985 and 1990, due primarily to increased irrigation. Public supply use increased 8 percent in the same period.

Stream-Aquifer Relations

Many of the bedrock and glacial-drift aquifers are hydraulically connected to streams in the region. These connections can affect the hydrologic-flow regime, water quality, and water development of the basin. The most evident connections are in locations where a surficial aquifer is crossed by a stream and receives direct ground-water discharge. In a 52-mile reach of the Sheyenne River southwest of Kindred, North Dakota, where the river flows across one of the largest surficial aquifers of the basin (Sheyenne Delta), studies have shown ground-water discharge into the river is as much as 28.8 ft³/s (Paulson, 1983). Low-flow studies on the Wild Rice, Sandhill, and Clearwater Rivers of Minnesota showed streamflow gains of 1 to 1.5 ft³/s/mi where these streams flow through surficial outwash, ice contact, and beach-ridge sand and gravel aquifers (MacLay *et al.*, 1972). Ground water also discharges to some streambanks indirectly through seeps and springs in locations where the base of the surficial aquifer lies above the stream.

There are isolated cases where streams lose water to glacial drift aquifers. Wolf (1981) reported flow losses along an eleven-mile reach of the Buffalo River where pumpage from a municipal well field withdraws ground water from the Buffalo aquifer buried beneath the river. Streams also tend to lose flow to adjacent alluvial aquifers during periods of high flow. However, these losses commonly are of short duration (less than a month) and ground-water flow toward the stream is re-established as the streamflow recedes.

On a basin-wide scale, streams tend to receive ground water from the glacial-drift aquifer system in the upland moraine areas. Streams have a smaller tendency to gain flow from ground water in the Red River Valley Lake Plain and commonly lose water in

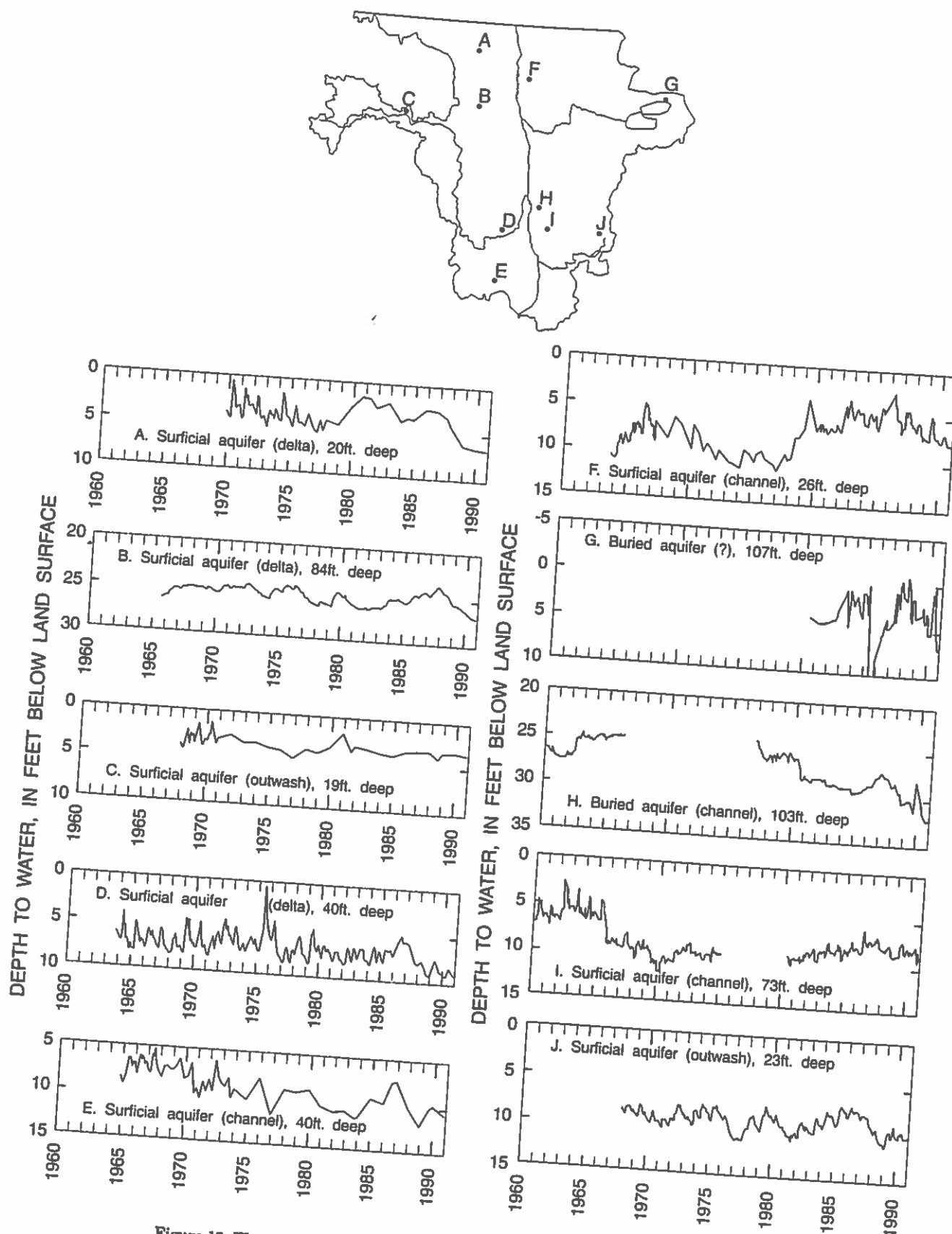


Figure 19. Water-Level Fluctuations in Wells Completed in Glacial-Drift Aquifers in the Red River of the North Basin.

Red River of the North Basin, Minnesota, North Dakota, and South Dakota

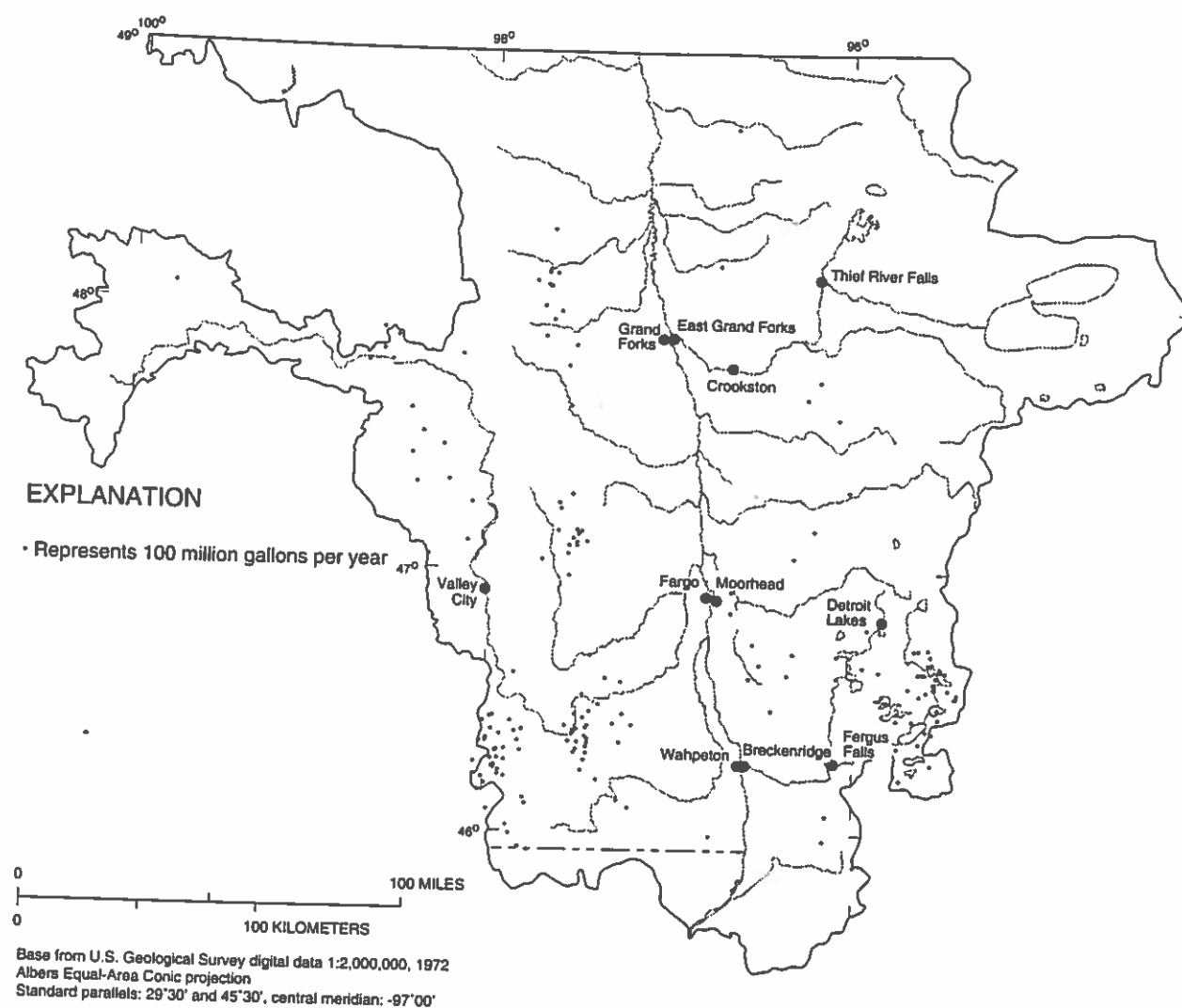


Figure 20. Distribution of Ground-Water Withdrawals Used for Irrigation in 1990 in the Red River of the North Basin.

TABLE 5. Reported Water Use in the Red River of the North Basin, 1980-1990 (nr, not reported for that category; other is primarily thermoelectric in the Red River basin).

Category	Reported Water Use (in million gallons per day)					
	1980		1985		1990	
	Ground Water	Surface Water	Ground Water	Surface Water	Ground Water	Surface Water
Public Supply	19	26	20	32	22	34
Rural Domestic	11	0	16	0	16	0
Irrigation	43	10	36	25	49	28
Livestock	(nr)	(nr)	7	3	12	3
Self-Supplied Industrial	(nr)	(nr)	1	4	1	3
Subtotal	73	36	80	64	100	68
Combined Total		109		144		168
Other	0	53	0	41	1	27
Total	73	89	80	105	101	95
Annual Total		162		185		196

those reaches during summer months, probably as a result of evapotranspiration. Streams that cross the Red River Valley Lake Plain also have the potential to gain small amounts of water indirectly from the regional bedrock aquifers that underlie the valley (Figures 4 and 5) through glacial drift, wetlands, and flowing wells. Although these gains are relatively small, the bedrock ground water which contains dissolved-solids concentrations exceeding 20,000 mg/L can affect stream-water quality particularly during low flow.

Ecological Regions and Aquatic Biology

Biological communities are the product of their physical and chemical environments. Each aspect or factor of these physical and chemical components is

experienced as a range of conditions under which organisms must survive. The ability of a species to survive, grow, and reproduce is constantly tested by its physical and chemical environment as well as by interactions with other species.

Various classification systems have been applied to land areas with the goal of identifying homogeneous areas. Omernik and Gallant (1988) have classified ecological regions called "ecoregions" for the north-central United States based on landscape features such as potential natural vegetation, mineral availability from the soils and geologic materials, physiography, land use, and land cover (including types of wetlands and crops). Ecoregions generally are considered to be regions of homogeneity in ecological systems or in relations between organisms and their environment (Omernik and Gallant, 1988).

All or parts of six ecoregions lie within the Red River basin (Figure 21). These are, from west to east,

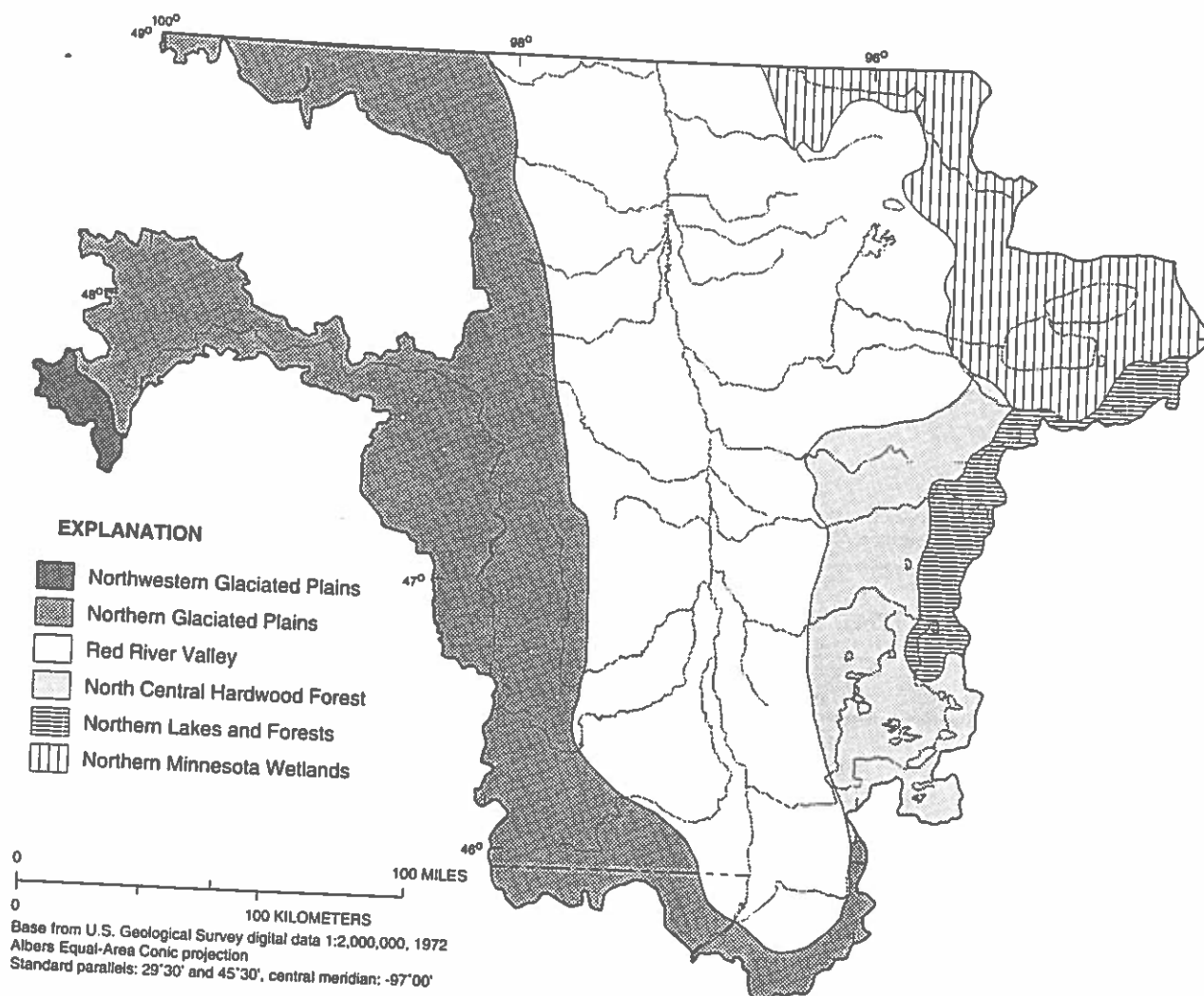


Figure 21. Ecoregions in the Red River of the North Basin. [Adapted from Omernik (1987).]

the (1) Northwestern Glaciated Plains, (2) Northern Glaciated Plains, (3) Red River Valley, (4) North-Central Hardwood Forests, (5) Northern Lakes and Forests, and (6) Northern Minnesota Wetlands. Not surprisingly, these ecoregions resemble physiographic regions (Figure 3) and other regional classification schemes such as Land Resource Regions and Major Land Resource Areas of the United States (U.S. Department of Agriculture, 1981). However, ecoregions were developed with a goal of classifying streams for more effective water-quality management (Omernik and Gallant, 1988).

Only a small portion of the Northwestern Glaciated Plains occurs in the Red River basin and so for purposes of this description it has been grouped with the Northern Glaciated Plains. Each of the five primary ecoregions are described below according to regional landscape features, water-drainage characteristics and river ecology, dominant and riparian vegetation, and predominant land use. Some of these features were described earlier, but they were not summarized and organized by subregion within the Red River basin as they might relate to stream biology. The numbers in parentheses after each ecoregion name represents the ecoregion area and percent area of the Red River basin.

Northern Glaciated Plains (10,969 mi², 31 percent)

The landscape of this region is rolling hills through many moraines and has numerous prairie potholes, particularly in the western headwaters of the Sheyenne River basin. Currently, 90 percent of the land is used for agriculture; dry land farming, and livestock production. The natural vegetation is gone except where it has been encouraged through conservation efforts as in the Sheyenne National Grassland. Major crops in the ecoregion are wheat, sunflowers, and feed grains with corn and soybeans predominant in the southern portion. Riparian areas provide conditions for some trees and some non-woody vegetation including grasses, sedges, reeds, and cattails.

The Sheyenne River is the major river in the ecoregion. Most (up to 90 percent) of the 1st and 2nd order streams (Kuehne, 1962) are ephemeral. Significant habitat in these small ephemeral streams is in the hyporheic zone, the area of subsurface flow in the stream bed (Hynes, 1970). During dry periods ephemeral streams appear as swales with an extensive growth of grasses, cattails, and some shrubs.

The upstream reaches contain riffles, runs, pools, backwaters, and instream woody debris. The greatest habitat diversity is found in conjunction with moraines. The overall gradient of the Sheyenne River

is 1.5 ft/mile, but upstream moraine areas have larger gradients. Substrates are variable and particle sizes correlate to gradient, velocity, and habitat type. Rocks and gravel are dominant in the riffles and runs of streams in the moraines while sand, silt, and fine organic matter are prevalent in the pools, backwaters and on the shallow sides of sharp bends and slow meander curves of streams.

The only major impoundment on the Sheyenne River is Lake Ashtabula (Figure 18) formed by Baldhill Dam, which regulates downstream discharges and maintains flow in the lower reaches year round. Lake Ashtabula discharges from the bottom waters (hypolimnion) and cool, potentially anoxic waters are released from the dam particularly during times of reservoir stratification during summer and early autumn. Numerous low-head dams also exist within this ecoregion.

Few studies have been made of the biological communities in North Dakota streams. Peterka (1978) listed 31 species of fish from nine families in the upper Sheyenne River. In a later inventory, Rykman (1981) listed 30 species from eight families. The Sheyenne River downstream from Lake Ashtabula contained 49 species from 10 families. Most of the additions were minnows and suckers.

Red River Valley (16,565 mi², 46 percent)

The Red River Valley is the flat bed of glacial Lake Agassiz (Figures 6 and 21). The shape of the valley is the result more of the glacial lake plain rather than the result of the river that presently drains and erodes its surface. Therefore, the floodplain is poorly defined and high-water inundation can spread several miles wide over cultivated fields and through municipalities. Land altitude changes only 350 feet from the headwaters near Wahpeton, North Dakota, to the Canadian border. Although the area is quite flat there is little standing water most of the year. A vast network of drainage ditches and channelized streams reduces the accumulation of standing water and provides for rapid runoff of precipitation and snowmelt.

The predevelopment vegetation of this ecoregion was tall bluestem prairie (big and little bluestem, switch grass, and Indian grass) which covered the river valley (Kuchler, 1964). Primarily cottonwood, willow, and elm grew along the stream courses. Oak savanna developed in the southwestern part of the region in the sandy areas around the lower Sheyenne River.

At present (1993), nearly all the land in the region is agricultural. About 80 percent of the region is used for dry-land farming, but some livestock production

occurs. The principle crops are spring wheat, sugar beets, barley, sunflowers, potatoes, corn, rye, soybeans, and flax. A few stands of trees grow along the water courses and as windbreaks, but little if any natural vegetation remains. Farming practices have reduced or eliminated almost all riparian and floodplain habitat. Cultivated fields extend to the stream banks leaving only a narrow band of riparian grasses, trees, and shrubs. Some riparian aquatic macrophytes are evident at the stream banks, mostly grasses, reeds, sedges, and cattails.

The streams and rivers of the western half of the Red River Valley are, for the most part, slow flowing, meandering, and highly turbid with large sediment loads of fine silt. Most are little more than conduits for their upstream basins delivering water, dissolved materials, and sediment to the Red River after traversing the flat valley with relatively small gain in discharge. Lack of precipitation and relatively high potential evapotranspiration cause many of the western tributaries to the Red River to stop flowing or go dry.

The types and relative amounts of various habitats change from the upstream areas (outside of the Red River Valley) to the valley plain. Upstream areas where riffles, runs, pools, bends, and woody debris are common, are more diverse. On the valley plain, the streams lose gradient and contain mostly runs, bends, and woody debris. Substrates reflect the loss of gradient and are primarily sand, clay, and silt with some fine organic detritus deposited in long pools or the downstream shallow sides of bends. Woody debris provide significant habitat for aquatic invertebrates in the lower reaches of the rivers. Loss of habitat diversity is not the only constraint to invertebrate communities in the Red River Valley streams. In a North Dakota study of aquatic mollusks, Cvancara (1983) found a decrease in the number of species associated with increased chloride concentration in the lower reaches of the Forest, Park, and Turtle Rivers.

Biological communities in the upstream reach of the Turtle River have been described by Neel (1985). He characterized five algal communities associated with various habitats; three in riffles and at the head and tail of pools, one on sandy bottoms under low velocity, and a fifth in still water areas. Diatoms were the most wide spread group in all habitats while filamentous green algae were dominant at various times in other habitats. Composite benthic macro-invertebrate samples identified 133 taxa in 16 orders and 58 families. The caddisfly genera *Cheumatopsyche* and *Hydropsyche* represented 51 percent of the total. Corixid water bugs and Elmids water beetles ranked next in abundance and accounted for 8 percent and 7 percent, respectively. Community composition of

macro-invertebrates in the Turtle River was comparable within similar habitats to that of the Forest River (Stoaks, 1975). The fish community of the upper Turtle contained 13 species, five of which were Cyprinids (minnows), and three Ictalurids (catfishes). There was only one piscivore, the northern pike whereas most of the other species could be considered benthic omnivores and insectivores. No abundance data were available (Neel 1985).

A recent fish survey of the rivers in the Red River Valley ecoregion indicated the western tributaries contained fewer species than the eastern tributaries to the Red River (Peterka, 1991). The survey included six rivers in the western half of the ecoregion: the Pembina, Tongue, Park, Forest, Turtle, and Goose Rivers. The maximum number of species collected at one location was 10. Total species number for the rivers ranged from 12 (Pembina and Tongue Rivers) to 18 (Park River), and in all cases insectivorous minnows were the most abundant trophic group and piscivores were the least abundant.

The eastern tributaries to the Red River vary in size and discharge; ranging from the relatively small Buffalo and Wild Rice Rivers to the large Red Lake River which contributes about 33 percent of the flow of the Red River at Emerson, Manitoba. The upland areas of these tributaries to the Red River are in other ecoregions, and contributions from upstream (both water and biota) depend on the source. Once these streams are in the valley and on the glacial lake bed, they are physically similar.

On the valley floor, these rivers are slow flowing and meandering except where they have been channelized. The banks are eroded and subject to slumping; tend to be steep, and have a narrow strip of riparian vegetation, which is mostly grasses, cottonwood trees, willows and other woody shrubs. Aquatic plants (cattails, reeds, sedges, and grasses) grow in shallow areas but are limited in the mainstream primarily by depth or high turbidity which greatly reduces light penetration.

The Minnesota Department of Natural Resources (Minn. DNR) has conducted biological surveys of several of the rivers in the eastern region: the Otter Tail in the southern part of the region, the Red Lake in mid-region, and the Red River (Hanson *et al.*, 1984; Renard *et al.*, 1983; and Renard *et al.*, 1986, respectively). Data from these studies are used to characterize the biological communities within the eastern portion of this ecoregion.

The portion of the Otter Tail River within the Red River Valley ecoregion is on the glacial lake bed flowing from approximately Fergus Falls, Minnesota, west to its confluence with the Bois de Sioux River at Breckenridge, Minnesota. This reach of the river is

downstream of Orwell Dam. The river upstream from Fergus Falls is comprised of pools and riffles. Progressing downstream of Fergus Falls, sinuosity and turbidity increase with the loss of riffle and pool habitats; substrates change from rubble with gravel and some boulders to mostly sand and some gravel; and Secchi disc readings decrease from 3.0 to 0.7 feet.

Hanson *et al.* (1984) found 49 species of fish throughout the Otter Tail River which flows through three ecoregions. The fish community within the Red River Valley ecoregion, the most downstream or lower part of the river, contained 37 species (about 75 percent of all species found in the river). Fish community diversity or species richness is reduced in this lower reach compared to the entire river. The fish community of the lower river was dominated by benthic omnivores. Carp and suckers comprised 50 percent of the individuals captured. Piscivores were rare.

Qualitative and quantitative samples of benthic invertebrates were made at Breckenridge in a sand substrate, 20 miles upstream on a gravel and sand substrate, and downstream of Orwell Dam in a rubble and gravel substrate. Both the numbers of taxa and individuals increased upstream with the change in substrate type. The sand substrate contained primarily midges (Chironomidae), while in the gravel and sand substrate caddisflies (Hydropsychidae) and true flies (Diptera) were about equally represented at 35 percent and 29 percent of the specimens collected, respectively. In the rubble and gravel substrate caddisflies (Hydropsychidae) represented 69 percent of the benthic macroinvertebrate community.

The Red Lake River is the largest tributary to the Red River in the United States. Originating at a flood control dam at Lower Red Lake, the river flows through an extensive wetland-bog area in the Red Lake Indian Reservation. The river has little gradient (0.8 ft./mile) and has been channelized in this upper reach (sinuosity of 1.3). From High Landing, Minn. to Thief River Falls, Minnesota, the river meanders through agricultural and pasture land. There is little riparian area; agricultural land use extends to the river banks. Downstream of Thief River Falls the river changes character. The gradient increases to 5.1 ft/mi and riffle areas are abundant. The river banks are as much as 80 feet high. The substrate in this erosional section is primarily rubble, gravel, sand, and boulders. Downstream of Crookston, Minnesota, the gradient ranges from 0.9 to 2.2 ft/mi and the river again is slow flowing and meandering through agricultural land. There are seven low-head dams on the river, two of which are non-functional and two of which are in the Red Lake Indian Reservation. The remaining three dams are located at Thief River Falls, Crookston, and East Grand Forks.

Renard *et al.* (1983) identified 16 species of emergent aquatic macrophytes and 19 species of floating submerged plants. The frequency of occurrence and abundance of aquatic macrophytes decreased in areas of high gradient and downstream of Crookston where high turbidity and depth prevented light penetration. Downstream of Crookston the same survey identified only four species of submerged plants and four species of emergent plants.

The fish community of the Red Lake River contained 38 species in 13 families. Twenty-five species (66 percent) were common to both the Red Lake River and the lower reaches of the Otter Tail within the ecoregion. As in the Otter Tail River, carp and suckers accounted for approximately half the specimens sampled (46 percent). The decrease in gradient and concurrent habitat types in conjunction with other sources of disturbance downstream of Crookston is evidenced by the presence of only 22 species.

As previously mentioned, the Red River is formed by the confluence of the Otter Tail and Bois de Sioux Rivers at Breckenridge, Minnesota, and Wahpeton, North Dakota. Low slope and high suspended solids loads from tributaries have produced a slow flowing, highly turbid river with either a sand/silt substrate or a hard clay bottom. Riffle areas with rock or gravel bottoms are rare but may be found just downstream of Breckenridge, Minnesota, in the area of maximum gradient.

Riparian vegetation is rare in the upstream areas. Agricultural fields extend to the banks of the river, although a small, narrow strip of grasses and trees may be found on the banks. Aquatic vegetation is also limited due to the high turbidity levels. In the upstream areas there are beds of river pondweed and occasional stands of smartweed and sedges along the river banks in shallows.

Renard *et al.* (1986) list 50 species of fish in 14 families collected from the Red River by several different studies, and their survey found 36 species in 12 families. Fish community composition was correlated to physical characteristics of the river. Those areas with greater gradient and consequently more coarse substrates generally contained greater numbers of fish. Carp and suckers were dominant species as in other rivers comprising about 40 percent of the fish community. Two members of the family Hiodontidae, the mooneye and goldeye which had been only minor species in the other rivers, represent 11 percent of the community. These are species of large rivers and apparently replace certain of the suckers (Catostomidae) under highly turbid conditions with fine substrates. The proportion of piscivores and opportunistic piscivores is larger in the Red River than in its tributaries (11 percent), due to the

increased abundance of channel catfish (5 percent), an opportunistic piscivore.

The Red River supports a trophy fishery for channel catfish. The larger individuals are entirely predatory. Their primary prey species are the mooneye and goldeye. Although both walleye and channel catfish have been stocked in the river previously, the current (1992) management of the fishery in both the United States and Canada focuses on the catfish.

North-Central Hardwood Forests (3,410 mi², 10 percent)

This ecoregion is a transition zone between the flat Red River Valley ecoregion and the Northern Lakes and Forests ecoregion. The topography is varied, containing both hilly areas and smaller plains as compared to the other ecoregions. The upland areas are forested with a complex mosaic distribution of conifers and hardwoods, depending on the saturation levels of the soils and the amount of prior logging that has occurred. In the non-forested areas agricultural activities are less intense than in the Red River Valley. Livestock pastures, hay fields, and row crops such as potatoes, snap beans, peas, and corn predominate. This ecoregion has the greatest density of lakes, and the streams usually flow through several small lakes before entering the Red River Valley. The middle reaches of the Otter Tail River flow through 18 lakes in this region.

Streams tend to be small headwater types with relatively high gradients (2.7 to 9.5 ft/mi) where they flow between lakes. Substrates are variable but gravel, sand, and rock predominate in the flowing runs. Riffles, pools, and runs are abundant.

Many of the larger lakes have been developed for year-round and summer homes and the region is a recreational center. Where housing development has not occurred, the riparian vegetation consists of cattails, wild rice, rushes, sedges, grasses, and woody species such as box elder, willows, and American elm.

Aquatic macrophytes are abundant in the clear lakes and connecting rivers. A Minnesota DNR biological survey identified 27 species of emergent and 25 species of submerged aquatic plants in the Otter Tail River (Hanson *et al.*, 1984). Addition of suspended particulates further reduces plant communities and the abundance of plants as the river approaches the Red River Valley.

Fish communities of this ecoregion as represented by the upper Otter Tail River are a mixture of both lotic (rivers or streams) and lentic (lake or pond) species. Sunfishes tend to be more abundant, as do bullheads, whereas the number of sucker species

tends to be lower. The biotic community is a mosaic both lotic and lentic communities because the bas trophic organization of the two systems is different, as are the habitats. The energy base in a lentic system is derived from autotrophic production, photosynthesis and primary production, whereas lotic systems tend to be fueled by organic carbon from external sources.

The survey by Hanson *et al.* (1984) also sample aquatic invertebrates in the Otter Tail River in this ecoregion. The substrate was gravel with aquatic plants. The mayflies (Ephemeroptera) comprised 11 percent, Diptera were 32 percent, and caddisflies (Trichoptera) were 27 percent of the sample. Hydropsychid caddisflies were 76 percent of all Trichoptera. The abundance of this group is not unusual because they are net spinners and feed on drifting organic matter and other small plants and animals captured in their nets. The combination of lake and stream conditions contribute an abundant supply of items to drift.

Northern Lakes and Forests (1,159 mi², 3 percent)

This ecoregion is a small part of the Red River basin located on the eastern border. Although it is relatively small, it contains the head waters of the Otter Tail, Wild Rice, and Clearwater Rivers. The topography of the area is comprised of steep rolling hills interspersed with pockets of wetlands, bogs, lakes, and ponds. The streams between the interconnecting lakes have moderate gradients up to 5.0 ft/mi. The land is mostly forested with conifers, but prior logging and controlled burning have contributed to the replacement of the original conifers with hardwoods such as quaking aspen and birch. The nutrient poor soils have inhibited agriculture in the area. The few areas that are not forested support some beef and dairy cattle and feed grains and forage. Many of the lakes sustain recreational uses.

The Minnesota DNR survey of the Otter Tail River found aquatic vegetation in upper reaches of the Otter Tail similar to the aquatic vegetation in the North-Central Hardwood Forest ecoregion. The combination of lotic and lentic environments provides physical and chemical conditions for an abundant and diverse aquatic macrophyte community and extensive riparian vegetation. Species composition is comparable between the two ecoregions.

The fish communities of these upper reaches, comprised of smaller headwater systems of lakes, ponds, and streams, reflect their mixed habitats. Species richness in the upper reaches is less than farther downstream where the rivers are larger. In the upper reaches of the Otter Tail, the Minnesota DNR survey

found 21 species from 6 families. The number of sunfish and bullheads was comparably higher in most segments sampled due to the large amount of lake and pond systems versus the amount of stream habitat where more riverine types like minnows were more abundant. The fish communities in this area were similar to those of the North Central Hardwood Forests ecoregion due to the similarity of physical features.

Northern Minnesota Wetlands (3,354 mi², 10 percent)

This is a vast area of wetlands, peat bogs, and marshes. The Roseau River, which flows across the northern part of the ecoregion into Canada, is the dominant stream in this ecoregion. The land is very flat with stream gradients ranging from 0.48 ft/mi at the Canadian border to only 0.16 ft/mi in the river channel adjacent to the old bed of the drained Roseau Lake. About 38 miles of the river channel have been straightened or widened. There is an extensive network of drainage ditches. Ditch morphology varies from shallow, broad grassy swales to large, well defined Judicial ditches which can be as much as 10 feet deep.

Most of the land is considered wet prairie, covered by marsh vegetation. Agriculture in the area is limited by the extent of the wet peatlands. Of the few crops grown, most are small grains. The major agricultural use is for livestock and hay.

Low stream gradient and riparian vegetation reduce the amount of sediment in the streams. Substrates vary from cobble and boulders to gravel and sand. Larger, coarse bed materials are more common here than in the other ecoregions. Aquatic vegetation can be found in small, dense stands but is rare. Submerged macrophytes are mostly pondweeds. Emergent species include sedges, rushes, and cattails. These are limited in distribution to low areas by cut-off oxbows and the shallow portions of bends. The riparian zone can be extensive where the gradient is minimal and banks are low as in most of the region.

From 1975 to 1977, the Minnesota DNR surveyed the fish and wildlife resources of the Roseau River (Enblom, 1982). The results of that survey are used to characterize the fish community of the Roseau River. Substrates were mostly sand and gravel but clay bottoms were found in two of the sectors. Riffles and pools were common except near dams. The survey showed 22 species of fish from eleven families. Insectivores and omnivores were poorly represented. The fish community of the Roseau River was also lacking in sunfishes, and the number of minnow

species was low compared to streams in the other ecoregions.

Although agriculture has been a major factor affecting land use in some parts of the ecoregion, it is still the least disturbed aquatic environment within the entire Red River basin.

IMPLICATIONS OF ENVIRONMENTAL SETTINGS FOR WATER QUALITY

The physical, chemical, hydrological, and biological characteristics that comprise the environmental setting of in the Red River basin affect the water quality. The availability of mineral and organic materials to the hydrologic system is a factor affecting the overall water quality in the basin. The dissolution of these available materials and resulting concentrations in water is linked to residence time, energy, and transport associated with the hydrologic system. Materials dissolved into or removed from the water can be from natural or human factors. Implications of major natural and human factors are described in this section in the context of how the environmental setting affects the regional water quality.

Natural Factors

Temperature, color, and sediment concentration are among the physical properties of water important to most users and aquatic biota. Ground water generally is uniform in temperature within the glacial drift aquifer system (roughly equivalent to the average annual air temperature), is colorless, and is free of sediment. In contrast, the large annual variability of air temperature affects surface water temperature, which varies annually from 0°C in the winter to almost 32°C in summer in some of the smaller streams. Surface water can be colored, especially in streams that drain the organic-rich peatlands area. Natural sediment concentrations in streams and lakes are highly variable across the basin and in time. Sediment concentrations are small in the forested and wetland areas of the basin (Figure 9). Sediment concentrations are generally greater in streams that have steeper gradients such as the moraine and drift prairie areas. The silty stream banks of the Red River Valley Lake Plain and Lake-washed Till Plain also are highly susceptible to erosion and subsequent sedimentation of streams that drain these areas. Sediment concentrations and load generally are larger during spring runoff and during summer storms than during other times of the year.

A summary of all of the available chemical data on water in the Red River basin is beyond the scope of this report. A general description of the occurrence and distribution of selected constituents is given based on summaries provided by Maclay *et al.* (1972) for the Minnesota part of the basin and by Winter *et al.* (1984) for the North Dakota part.

Concentration of dissolved chemical constituents in surface waters are generally low during spring runoff and after thunderstorms. At times of low flow, when water in streams is largely from ground-water seepage, the water quality more reflects the chemistry of the glacial-drift aquifer system.

Water in the Red River generally has dissolved-solids concentrations less than 600 mg/L and mean values range from 347 mg/L near the headwaters to 406 mg/L at the international boundary near Emerson, Manitoba (Winter *et al.*, 1984). Calcium and magnesium are the principal cations and bicarbonate is the principal anion along most of the reach of the Red River, which indicates that carbonate materials (calcite and dolomite) are available and soluble in glacial drift and associated soils in the basin. Dissolved-solids concentrations generally are lower in the Minnesota tributaries than in the tributaries draining the western part of the basin. However, the annual loading of chemical constituents from each side of the basin are fairly-well balanced as a result of the larger contribution of streamflow from the eastern side (Figure 13).

Except during low flow conditions stream water for most of the North Dakota tributaries, generally is suitable for crop irrigation based on specific conductance and sodium-adsorption ratio. Boron concentration, in excess of the U.S. Environmental Protection Agency (1986) criterion for irrigation use of 750 $\mu\text{g/L}$, has occurred at the 90th percentile only at the Sheyenne River near Kindred, North Dakota (Winter *et al.*, 1984).

Little information is available on fluvial sediment for streams of the Red River basin. Sediment transported by the streams is derived from sheet and wind erosion of glacial drift and lake deposits. Bimonthly sediment samples collected over the past few years from the Red River at Emerson, Manitoba, contained sediment concentrations ranging from 20 mg/L (during winter) to 270 mg/L (during summer-storm runoff). More than 98 percent of the suspended sediment commonly is silt size or finer.

The quality of water in glacial drift is quite variable and depends on the position of the sampling point within the ground-water flow system. Ground water in the surficial aquifers commonly is a calcium bicarbonate type with low dissolved solids, and therefore tends to be suitable for most uses. However, water from deeper in the glacial drift tends to be more

mineralized and variable. Dissolved solids concentrations in glacial drift aquifers ranges from 200 to over 4,500 mg/L, but generally is between 300 and 700 mg/L. Water from glacial-drift aquifers beneath the Minnesota part of the Red River basin varies from a calcium-magnesium bicarbonate type to a sodium bicarbonate type with a median dissolved solids concentration of about 550 mg/L (Ruhl, 1987). Ground water in recharge areas in the surficial aquifers generally has dissolved solids concentrations less than 500 mg/L with calcium and bicarbonate as the dominant ions. As the ground water moves down-gradient, dissolved-solids concentration increases, and ions in the water become dominated by magnesium and sulfate.

Water in the deepest bedrock aquifers (Cambrian-Ordovician, Mississippian, and Lower Cretaceous aquifers) is characterized by dissolved-solids concentrations in excess of 1,000 mg/L, which limits these units as sources of water for domestic, municipal, or irrigation uses. Downey (1986) reports that brines (dissolved-solids concentrations in excess of 100,000 mg/L) may be present in the Cambrian and Ordovician rocks beneath the northwestern part of the Red River basin. Major ions in ground water have been associated with the Cambrian-Ordovician and Lower Cretaceous aquifers based on limited data. Ruhl and Adolphson (1986) reported that water sampled from the Red River-Winnipeg aquifer (part of the Cambrian-Ordovician regional aquifer) near the Red River Valley is predominantly a sodium chloride type with dissolved solids ranging from 5,000 to 57,000 mg/L. Major ions in the Cretaceous aquifers beneath the southern part of the Red River basin in Minnesota varies from sodium chloride type to calcium-magnesium sulfate type with dissolved solids ranging from 1,000 to 3,000 mg/L (Woodward *et al.*, 1986).

Water in the Upper Cretaceous and Tertiary bedrock aquifers commonly has dissolved-solids concentrations above 1,000 mg/L with sodium and bicarbonate as the primary ions (Winter *et al.*, 1984). This water is used for some domestic purposes, but the high sodium and salinity levels generally makes it unsuitable for irrigation purposes.

The highly saline water from the regional bedrock aquifers may have a significant effect on the quality of shallower ground water and surface water near low areas of the Red River Valley Lake Plain (Downey, 1986). Maclay *et al.* (1972) reported chloride concentrations above 1,000 mg/L in water sampled from wells less than 100 feet deep located within 15 miles of the Red River in extreme northwestern Minnesota. Ground-water salinity becomes a water-quality concern when dilution by streamflow is reduced or when the head in shallow aquifers is reduced. Upward leakage of saline ground water into streams of this area

has been observed, especially during low-flow conditions. The International Red River Pollution Control Board (1990) reported a strong historic relation between increased chloride concentration and low-flow conditions during late fall and early winter in the Red River at Emerson, Manitoba. Chloride and sulfate concentrations exceeding 100 mg/L are common during these base-flow conditions. Saline seeps to wetlands and depressions also could affect the health and types of natural and crop vegetation in the western part of the Red River Valley Lake Plain.

The spatial distribution for natural leakage of the deeper saline ground water into shallower ground water and streams is not well understood. U.S. Geological Survey data and surveys indicate that leakage of saline ground water to the surface occurs along tributaries to the Red River in northeastern North Dakota. A number of wells completed over the past 50 years in the bedrock aquifers flowed freely into wetlands and streams. Many of these flowing wells still exist within the watersheds of the Park, Forest, and Turtle Rivers and discharge water with dissolved solids concentrations ranging from 3,000 to more than 11,000 mg/L (M.L. Strobel, U.S. Geological Survey, oral communication). The effect of this point discharge on overall stream quality is not known. Water-quality reconnaissance surveys of stream base flow in 1991 indicated that leakage of saline ground water directly into the Red River is small relative to the dissolved solids load contributed by the tributaries of northeastern North Dakota (Cowdery and Brigham, 1992).

A few trace metals, iron and some nutrients also are present naturally in waters of the Red River basin. Although data are sparse, selenium at levels that slightly exceed the Federal primary drinking water standard of 10 µg/L (U.S. Environmental Protection Agency, 1986) have been sampled in wells and streams (Winter *et al.*, 1984). Selenium is available from the Cretaceous rocks (Pierre Shale) beneath the basin. Arsenic has been detected in ground water in excess of 50 µg/L in four areas in the extreme southwestern part of the Red River basin (Moody *et al.*, 1986) which could, in part, be from natural leaching of geologic materials. Dissolved iron concentration in ground water from glacial drift aquifers commonly exceeds 300 µg/L. Nitrate-nitrogen concentration in ground water sampled from the Red River basin generally are less than 1 mg/L according to ambient ground-water monitoring in Minnesota (Wall and Montgomery, 1991) and U.S. Geological Survey data (Moody *et al.*, 1986). Naturally occurring radionuclides in ground water may also be important considering the bedrock geochemistry, but data are not sufficient to substantiate this hypothesis.

CONTAMINATION POTENTIAL FROM HUMAN ACTIVITY

Contamination of natural waters is the introduction into the water of substances which alter its natural quality. Water-quality impairment can be measured by usefulness to humans and other biota. Many chemical, physical, and biological processes can affect the fate and transport of contaminants as they enter the environment via the hydrologic system. Describing the effectiveness of such processes or developing a quantitative relation between contamination sources and measured chemical constituents in water is beyond the scope of this report. A qualitative description of the distribution of potential major contamination sources and water-quality implications is provided below.

Based on related research, chemical inputs to surface waters of the Red River basin are possible from atmospheric sources. For example, mercury has been measured in precipitation in northeastern Minnesota, less than 200 miles east of the Red River basin. Sorensen *et al.* (1990) and Glass *et al.* (1991) report wet-deposition rates of mercury ranging between 10 and 15 mg/m²/y. Other studies have shown that most of the mercury accumulating in lake sediments in pristine areas of Minnesota is deposited from the atmosphere either directly on the lake surface or via overland runoff in the lake catchment (Swain *et al.*, 1992, and Fitzgerald *et al.*, 1991). Although the chemical concentrations are very low, deposition over years into surface-water bodies may be significant. Atmospheric deposition and accumulation of other compounds onto the Red River basin are possible, but their significance has not been quantified.

Given that about three-fourths of the land area in the Red River basin is used for growing crops and grazing livestock, agricultural activities probably will contribute the most significant nonpoint sources of contaminants to surface and ground waters. Soil type, land slope, and climatological factors affect grazing or cropping patterns and tillage practices. Applications of fertilizer and pesticides is dependent on crop type, crop rotation, soil type, and the individual farmer.

Erosion and runoff are processes that are affected by soil type, land slope, climatological factors, and tillage practices. These processes affect the movement of contaminants to surface and ground waters. Sediment erosion by wind and water can be increased by cultivation practices and by livestock that trample streambanks. Nitrate-nitrogen and pesticide concentrations also can increase locally in surficial aquifers beneath cropland that is fertilized, particularly where irrigated. Nitrogen and phosphorous in surface runoff from cropland fertilizers and nitrogen from manure

can contribute nutrients to lakes, reservoirs, and streams. For the period 1970 to 1989, the mean concentration of total phosphorous in the Red River at Emerson, Manitoba, was 0.23 mg/L based on 3,883 samples (Chako and Ronmark, 1990). However, nitrate and other nitrogen species are not a widespread problem regionally in the basin; this might suggest that denitrification is a factor or that the fine-grained soils common in most of the basin are retaining the nitrogen. A number of farmers practice conservation practices that can effectively reduce sediment and chemical loadings to the hydrologic system.

Pesticides are applied to the crops before, during, and after the growing season, especially within the Red River Valley Lake Plain. Some of the more persistent pesticides like atrazine, have been detected in the Red River. However, few data are available to conclusively state widespread presence of pesticides and their break-down products in Red River basin aquifers or streams.

Silviculture is not a major activity compared to other agricultural activities in the basin, but it can be a nonpoint source of contamination. Forest cutting followed by extensive burning of earlier timber development may have left charcoal in lake sediments and altered bottom chemistry in streams. Many of the pine/spruce forests were replaced with aspen and birch and rejuvenated by natural regrowth. Although some pesticides are associated with forest management, increased sediment yields probably is the primary pollutant related to silviculture.

Activities associated with urbanization and food processing are other major candidates for contamination sources in the Red River basin. Urban runoff and treated effluent from municipalities is discharged into streams. These point discharges contain some quantity of organic compounds from storm runoff, including turf-applied pesticides. The largest releases of treated-municipal wastes are from the population centers along the Red River and its larger tributaries (Figure 8).

Solid-waste disposal and leaking underground storage tanks also are associated with the urbanized areas. Sanitary landfills and leaking storage tanks can leak a broad spectrum of toxic chemicals slowly into the hydrologic system. On a regional scale, such as the size of the Red River basin, these facilities function as point sources of contamination.

A partial inventory of industrial waste conducted in the late 1960's suggested that a primary source of contamination was from food processing in sugar-beet refining, potato processing, poultry and meat packing, and dairy processing (Souris-Red-Rainy River Basins Commission, 1972). Sugar-beet and potato processing plants, most of which are located along the Red River, produce wastes on a seasonal basis, usually during

times of low streamflow. Most food-industry wastes are treated by oxidation ponds or lagoons because waste release to streams during low-flow conditions is unauthorized by states in an effort to control bacteria growth and depletion of dissolved oxygen in the receiving streams. Dairy processors commonly are connected to municipal waste-treatment systems. Bacteria are not a significant problem in surface waters of the Red River basin, but bacteria counts do increase downstream of major population centers.

Cadmium, lead, and mercury have been found in streams at concentrations that exceed U.S. Environmental Protection Agency (1986) interim primary drinking-water standards (Winter *et al.*, 1984). Geochemical sources of these constituents probably do not exist in the basin, and the occurrence of these trace metals may be related to individual contamination events from urbanized or industrial locations. Mercury and polychlorinated biphenyls (PCB's) have been detected in tissues of game fish (catfish and walleye) at levels sufficient to evoke consumption advisories for humans in the Red River and Red Lake River (Minnesota Department of Health, 1991).

Water use can affect water quality. For example, large ground-water withdrawals from glacial-drift aquifers can induce upward leakage of more saline ground water from underlying bedrock aquifers or contaminated water from nearby streams; thereby reducing the quality of the shallow ground water. Irrigation applied beyond soil-moisture capacity can increase leaching of soil and agricultural chemicals to the water table. Return flows from irrigation also may increase salinity to surface and ground water in the dryer western part of the Red River basin. Treated return flows from public supply or self-supplied industrial uses can increase nutrients and salinity and decrease dissolved oxygen to streams at point discharges.

Dams and drainage ditches can alter the residence time of water in subbasins affecting the amount of sediment, biota, and dissolved constituents carried by water. These structures also can have a significant effect on the habitat of aquatic biota that alters populations and community structure. Water-control activities also could effect the salinity of surface-water systems. For example, proposed diversion of water from the Missouri River basin through the Devils Lake closed basin (Figure 1) into the Sheyenne River (North Dakota State Water Commission, 1991) might, at times, increase salinity of the Sheyenne River.

Networks of transportation arteries and pipelines exist throughout the basin. These systems can indicate the potential locations of toxic-waste spills into the environment as point discharges of contamination to water.

Recreational access to fishing and wildlife commonly have very small effects on water quality. However, introductions of new species in aquatic systems for recreation (fishing) can cause direct competition with the existing components of the aquatic communities. Fisheries management activities have encouraged the alteration of aquatic systems through an increased harvest of selected species and stocking of forage and additional game species.

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SELECTED REFERENCES

- Anderson, J. L. and D. F. Grigal, 1984. Soils and Landscapes of Minnesota. Agricultural Experiment Station, University of Minnesota, 8 pp.
- Anderson, J. R., 1967. Major Land Uses in the United States. In: National Atlas of the United States of America. U.S. Geological Survey, 1970, Washington, D.C., pp. 158-159.
- Armstrong, C. A., 1980. Ground-Water Resources of Dickey and LaMoure Counties North Dakota. North Dakota State Water Commission County Ground-Water Studies 28, Part III, 61 pp.
- Armstrong, C. A., 1981. Supplement to Predictive Modeling of Effects of the Planned Kindred Lake on Ground-Water Levels and Discharge, Southeastern North Dakota. U.S. Geological Survey Open-File Report 81-646, 15 pp., plates.
- Armstrong, C. A., 1982. Ground Water Resources of Ransom and Sargent Counties, North Dakota, Part III. North Dakota Geological Survey Bulletin 69 and North Dakota Water Commission County Ground-Water Studies 31, 51 pp.
- Baker, C. H., Jr., 1966. The Milnor Channel, an Ice-Marginal Course of the Sheyenne River, North Dakota. U.S. Geological Survey Professional Paper 550-B, pp. B77-B79.
- Baker, C. H., Jr., 1967. New Observations on the Sheyenne Delta of Glacial Lake Agassiz. U.S. Geological Survey Professional Paper 575-B, pp. B62-B68.
- Baker, C. H. Jr., and Q. F. Paulson, 1967. Geology and Ground Water Resources Richland County, North Dakota, Part III. North Dakota Geological Survey Bulletin 46 and North Dakota Water Commission County Ground-Water Studies 7, 45 pp.
- Bayer, T. N., 1959. The Subsurface Bedrock Stratigraphy of Northwestern Minnesota. Masters of Science thesis, Minneapolis, University of Minnesota, 77 pp.
- Bidwell, L. E., T. C. Winter, and R. W. MacLay, 1970. Water Resources of the Red Lake River Watershed, Northwestern Minnesota. U. S. Geological Survey Hydrologic Investigations Atlas HA-346.
- Blair, D. E., 1989. The Synoptic Climatology of the Red River Basin. Ph.D. Thesis, University of Manitoba, p. 369.
- Bluemle, J. P., 1977. Geologic Highway Map of North Dakota. North Dakota Geological Survey, Educational Series 11, Miscellaneous Map 19.
- Braidech, T. E. and D. J. Munro [Editors], 1987. Red River Toxic Profile Study. Prepared for the International Red River Pollution Board, 43 pp.
- Chacko, V. T. and T. H. Ronmark, 1990. Water Quality Data Summary, Red, Assiniboine, and Roseau Rivers. Environment Canada, Water Quality Branch, 115 pp.
- Clayton, L., S. R. Moran, J. P. Bluemle, and C. G. Carlson, 1988. Geologic Map of North Dakota. North Dakota Geological Survey.
- Cowdery, T. K. and M. E. Brigham, 1992. Baseflow Dissolved-Solids Loads to Streams of the Red River of the North basin, South Dakota, North Dakota, and Minnesota. 37th Annual Midwest Ground Water Conference Program with Abstracts, October 1-16, 1992, p. 38.
- Cvancara, A. M., 1983. Aquatic Mollusks of North Dakota. North Dakota Geological Survey Report of Investigation No. 78, 14 pp.
- Dominion Ecological Consulting Ltd., 1991. The Red-Assiniboine River Basin Initiative Planning Report, April 22-24, 199 Workshop in Winnipeg, Canada. Prepared for Environment Canada, Regina, May 31, 1991 Discussion Draft, 54 pp., appendices.
- Downey, J. S., 1969. In: Geology of Northeastern North Dakota. D. T. Pederson J. R. and Reid (Editors). North Dakota Geological Survey Miscellaneous Series 39, p. 12.
- Downey, J. S., 1971. Ground-Water Resources of Walsh County Northeastern North Dakota. U.S. Geological Survey Hydrologic Investigations Atlas Ha-341, scale 1:126,720.
- Downey, J. S., 1973. Ground-Water Resources, Nelson and Walsh Counties, North Dakota. Part III of North Dakota Geological Survey Bulletin 57 and Part III of North Dakota State Water Commission County Ground-Water Studies 17, 67 pp.
- Downey, J. S., 1984. Geohydrology of the Madison and Associated Aquifers in Parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1273-G, 4 pp.
- Downey, J. S., 1986. Geohydrology of the Bedrock Aquifers in the Northern Great Plains in Parts of Montana, Wyoming, North Dakota and South Dakota. U.S. Geological Survey Professional Paper 1402-E, 87 pp., plates.
- Downey, J. S. and C. A. Armstrong, 1977. Ground Water Resources of Griggs and Steele Counties, North Dakota. North Dakota State Water Commission County Ground-Water Studies 21, Part III, 33 pp.
- Downey, J. S. and Q. F. Paulson, 1974. Predictive Modeling of Effects of the Planned Kindred Lake on Ground-Water Levels and Discharge, Southeastern North Dakota. U.S. Geological Survey Water-Resources Investigations Report 30-74, 22 pp., plates.
- Eddy, S. and J. C. Underhill, 1974. Northern Fishes. University of Minnesota Press, Minneapolis, Minnesota, 414 pp.
- Enblom, J. W., 1982. Fish and Wildlife Resources of the Roseau River. Minnesota Department of Natural Resources Special Report No. 130, 95 pp., plates.
- Fandrei, G. S., S. Heiskary, and S. McCollar, 1988. Descriptive Characteristics of the Seven Ecoregions in Minnesota. Minnesota Pollution Control Agency, Division of Water Quality, 140 pp.
- Fitzgerald, W. F., R. P. Mason, and G. M. Vandal, 1991. Atmospheric Cycling and Air-Water Exchange of Mercury Over Mid-Continental Lacustrine Regions. Water, Air, and Soil Pollution 56:745-767.
- Glass, G. E., J. A. Sorensen, K. W. Schmidt, G. R. Rapp, D. Yap, and D. Fraser, 1991. Mercury Deposition and Sources for the Upper Great Lakes Region. Water, Air, and Soil Pollution 56:235-249.
- Gunard, K. T., J. H. Hess, J. L. Zirbel, and C. E. Cornelius, 1990. Water-Resources Data - Minnesota, Water Year 1988, Volume I, Great Lakes and Souris-Red-Rainy River Basins. U.S. Geological Survey Water-Data Report, MN-88-1, 130 pp.
- Hanson, S. R., P. A. Renard, N. A. Kirsh, and J. W. Emblom, 1984. Biological Survey of the Otter Tail River. Minnesota Department of Natural Resources Special Report No. 137, 101 pp., plates.
- Harkness, R. E., N. D. Haffield, and G. L. Ryan, 1986. Water-Resources Data - North Dakota, Water Year 1986. U.S. Geological Survey Water-Data Report ND-86-1, 399 pp.

- Hirsch, R. M., W. M. Alley, and W. G. Wilber, 1988. Concepts for a National Water-Quality Assessment Program. U.S. Geological Survey Circular 1021, 42 pp.
- Hobbs, H. C. and J. E. Goebel, 1982. Geologic Map of Minnesota, Quaternary Geology. Minnesota Geological Survey State Map Series S-1.
- Horton, R. E., 1945. Erosional Development of Streams and Their Drainage Basins. Hydrophysical Approach to Quantitative Morphology: Geological Society of America Bulletin 56:275-370.
- Hynes, H. N. B., 1970. The Ecology of Running Waters. University of Toronto Press, Toronto, Ontario, 555 pp.
- International Red River Pollution Board, 1990. Thirtieth Progress Report to the International Joint Commission - Red River. International Red River Pollution Board, October 1990, 115 pp.
- Karl, T. R. and W. E. Riebsame, 1984. The Identification of 10-Year to 20-Year Temperature and Precipitation Fluctuations in the Contiguous United States. Journal of Climate and Applied Meteorology 23:950-966.
- King, P. B. and H. M. Beikman, 1974. Geologic Map of the United States. U.S. Geological Survey, scale 1:2,500,000.
- Koch, N. C., 1975. Geology and Water Resources of Marshall County, South Dakota - Part I: Geology and Water Resources. South Dakota Geological Survey Bulletin 23, 76 pp.
- Kuchler, A. W., 1964. Potential Natural Vegetation of the Conterminous United States. American Geographical Society Special Publication 36, 116 pp., plus map.
- Kuehne, R. A., 1962. A Classification of Streams, Illustrated by Fish Distribution in an Eastern Kentucky Creek. Ecology 43:608-614.
- LaBaugh, J. W., T. C. Winter, V. Adomaitis, and G. A. Swanson, 1987. Hydrology and Chemistry of Selected Prairie Wetlands in the Cottonwood Lake Area, North Dakota. U.S. Geological Survey Professional Paper 1431, 26 pp.
- Laird, W. M., 1944. The Geology and Ground-Water Resources of the Emerado Quadrangle. North Dakota Geological Survey Bulletin 17, 35 pp.
- Lawrence, S. J., 1989. Water-Resources Appraisal of the Lake Traverse Indian Reservation in South Dakota. U.S. Geological Survey Water-Resources Investigations Report 88-4031, 42 pp.
- Laycock, A. H., 1957. Precipitation and Streamflow in the Mountain and Foothill Regions of the Saskatchewan River Basin. Prairie Provinces Water Board Report No. 6, Regina Saskatchewan, p. 48.
- Leahy, P. P., J. S. Rosenshein, and D. S. Knopman, 1990. Implementation Plan for the National Water-Quality Assessment Program. U.S. Geological Survey Open-File Report 90-174, 10 pp.
- Lissey, A., 1971. Depression-Focused Transient Groundwater Flow Patterns in Manitoba. Geological Association of Canada Special Paper 9, pp. 333-341.
- MacLay, R. W., L. E. Bidwell, and T. C. Winter, 1969. Water Resources of the Buffalo River Watershed, West-Central Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-307.
- MacLay, R. W. and G. R. Schiner, 1962. Aquifers in Buried Shore and Glaciofluvial Deposits Along the Gladstone Beach of Glacial Lake Agassiz Near Stephen, Minnesota. U.S. Geological Survey Professional Paper 450-D, pp. 170-172.
- MacLay, R. W., T. C. Winter, and L. E. Bidwell, 1969. Water Resources of the Mustinka and Bois de Sioux Rivers Watershed, West-Central Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-272.
- MacLay, R. W., T. C. Winter, and L. E. Bidwell, 1972. Water Resources of the Red River of the North Basin, Minnesota. U.S. Geological Survey Water-Resources Investigation Report 72-1, 127 pp.
- MacLay, R. W., T. C. Winter, and G. M. Pike, 1965. Water Resources of the Middle River Watershed, Northwestern Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-201.
- MacLay, R. W., T. C. Winter, and G. M. Pike, 1967. Water Resources of the Two Rivers Watershed, Northwestern Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-237.
- McAndrews, J. H., 1966. Postglacial History of Prairie, Savanna, and Forest in Northwestern Minnesota. Memoirs of Torrey Botany Club 22(2):72 pp.
- McDonald, M. G., and A. W. Harbaugh, 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. U.S. Geological Survey Techniques of Water Resources Investigations, Book 6, Chapter A1, 586 pp.
- Miller, J. E. and D. L. Frink, 1984. Changes in Flood Response of the Red River of the North Basin, North Dakota-Minnesota. U.S. Geological Survey Water-Supply Paper 2243, 103 pp.
- Minnesota Agricultural Statistics Service, 1991. Minnesota Agriculture Statistics 1991. St. Paul, Minnesota, 99 pp.
- Minnesota Department of Health, 1991. Minnesota Fish Consumption Advisor. Minnesota Department of Health, P.O. Box 59040, Minneapolis, Minnesota, 60 pp.
- Minnesota Pollution Control Agency, 1990. Minnesota Water Quality, Water Years 1988-1989. Minnesota Pollution Control Agency, St. Paul, Minnesota, 67 pp. and appendices.
- Minnesota Soil Survey Staff, 1983. Soil Associations of Minnesota. Minnesota Agricultural Experiment Station, University of Minnesota, 1 plate.
- Moody, D. W., J. Carr, E. B. Chase, and R. W. Paulson, 1986. National Water Summary 1986 - Hydrologic Events and Ground-Water Quality. U.S. Geological Survey Water Supply Paper 2325, pp. 313-320 and 401-406.
- National Research Council, 1990. A Review of the U.S. Geological Survey National Water-Quality Assessment Pilot Program. National Academy Press, Washington D.C., 153 pp.
- Neel, J. K., Sr., 1985. A Northern Prairie Stream. University of North Dakota Press, Grand Forks, North Dakota, 274 pp.
- North Dakota Agricultural Statistics Service, 1990. North Dakota Agricultural Statistics-Compiler. Ag Statistics No. 59, Fargo, North Dakota, 158 pp.
- North Dakota State Department of Health and Consolidated Laboratories, 1988. North Dakota Nonpoint Assessment Report. North Dakota State Department of Health and Consolidated Laboratories, Bismarck, North Dakota, 60 pp.
- North Dakota State Department of Health and Consolidated Laboratories, 1990. The Status of Water Quality in the State of North Dakota. State Department of Health and Consolidated Laboratories, Bismarck, North Dakota, 73 pp.
- North Dakota State Water Commission, 1991. Executive Summary-Conceptual Water-Management Plan, Devil's Lake Basin. North Dakota State Water Commission Project No. 322, 8 pp.
- Omernik, J. M., 1987. Ecoregions of the United States. Annals of the Association of American Geographers 77:118-125.
- Omernik, J. M. and A. L. Gallant, 1988. Ecoregions of the Upper Midwest States. U.S. Environmental Protection Agency EPA/600/3-88/037, 56 pp.
- Omodt, H. W., G. A. Johnsgard, D. D. Patterson, and O. P. Olson, 1968. The Major Soils of North Dakota. North Dakota State University Agricultural Experiment Station Bulletin 472, 60 pp., 1 map.
- Paulson, Q. F., 1964. Geological Factors Affecting Discharge of the Sheyenne River in Southeastern North Dakota. In: Geological Survey Research 1964. U.S. Geological Survey Professional Paper 501-D, pp. D177-D181.
- Paulson, Q. F., 1983. Guide to Ground-Water Resources of North Dakota. U.S. Geological Survey Water-Supply Paper 2236, 25 pp.
- Peterka, J. J., 1978. Fishes and Fisheries of the Sheyenne River, North Dakota. Annual Proceedings, North Dakota Academy of Science, No. 32 (II), pp. 29-44.
- Peterka, J. J., 1991. Survey of Fishes in Six Streams in Northeastern North Dakota, 1991. Mimeo, 16 pp.

- Pusc, S. W., 1993. The Interaction Between Ground Water and a Large Terminal Lake, Devil's Lake, North Dakota: Hydrogeology of the Devil's Lake Area. North Dakota State Water Commission Water Resources Investigation 13, 95 pp.
- Randich, P. G., 1977. Ground-Water Resources of Benson and Pierce Counties, North Dakota. North Dakota State Water Commission, County Ground-Water Studies 18, Part III, 76 pp.
- Reid, G. K., 1961. Ecology of Inland Waters and Estuaries. Van Nostrand Reinhold Company, New York, New York, 375 pp.
- Renard, P. A., S. R. Hanson, and J. W. Embloom, 1983. Biological Survey of the Red Lake River. Minnesota Department of Natural Resources Special Report No. 134, 76 pp., plates.
- Renard, P. A., S. R. Hanson, and J. W. Embloom, 1986. Biological Survey of the Red River of the North. Minnesota Department of Natural Resources Special Report No. 142, 60 pp., plates.
- Ruhl, J. F., 1987. Hydrogeologic and Water-Quality Characteristics of Glacial-Drift Aquifers in Minnesota. U.S. Geological Survey Water-Resources Investigations Report 87-4224, 3 plates.
- Ruhl, J. F. and D. G. Adolphson, 1986. Hydrogeologic and Water-Quality Characteristics of the Red River-Winnipeg Aquifer, Northwestern Minnesota. U.S. Geological Survey Water-Resources Investigations Report 84-4111, 2 plates.
- Ryckman, L. F., 1981. A Revised Checklist of the Fishes of North Dakota, with a Brief Synopsis of Species Distribution Within the State. North Dakota Game and Fish Department Circular, 18 pp.
- Sanderson, M. E., 1948. Drought in the Canadian North-West. Geographical Review 38(2):289-299.
- Schiner, G. R., 1963. Ground-Water Exploration and Test Pumping in the Halma-Lake Bronson Area, Kittson County, Minnesota. U.S. Geological Survey Water-Supply Paper 1619-BB, 38 pp.
- Shay, C. T., 1967. Vegetation History of the Southern Lake Agassiz Basin During the Last 12,000 Years. In: Life, Land and Water - Proceedings of the 1966 Conference on Environmental Studies of the Glacial Lake Agassiz Region, M. J. Mayer-Oakes (Editor). University of Manitoba Press, Winnipeg, pp. 231-252.
- Sorensen, J. A., G. E. Glass, K. W. Schmidt, J. K. Huber, and G. R. Rapp, Jr., 1990. Airborne Mercury Deposition and Watershed Characteristics in Relation to Mercury Concentrations in Water, Sediments, Plankton, and Fish of Eighty Northern Minnesota Lakes. Environmental Science and Technology 24(11):1716-1731.
- Souris-Red-Rainy River Basins Commission, 1972. The Combined Report - Type I Framework Study, Vol. 1, 216 pp.
- Stoaks, R. D., 1975. Seasonal and Spatial Distribution of Riffle Dwelling Aquatic Insects in the Forest River, North Dakota. Ph.D. Dissertation, North Dakota State University, Fargo, N. Dakota., 162 pp.
- Stoner, J. D., 1991. National Water-Quality Assessment Program - Red River of the North. U.S. Geological Survey Open-File Report 91-151, 2 pp.
- Strobel, M. L., 1990. Characteristics Affecting the Vertical Flow of Ground Water Through Selected Glacial Deposits in Ohio. Unpublished M.S. Thesis, Ohio State University, Columbus, Ohio, 185 pp.
- Sturrock, A. M., T. C. Winter, and D. O. Rosenberry, 1992. Energy-Budget Evaporation from Williams Lake: A Closed Lake in North-Central Minnesota. Water Resources Research 28(6):1605-1617.
- Swain, E. B., D. R. Engstrom, M. E. Brigham, T. A. Henning, and P. L. Brezonik, 1992. Increasing Rates of Atmospheric Mercury Deposition in the Midcontinental North America. Science. 257:784-786.
- Thelin, G. P. and R. J. Pike, 1991. Landforms of the Conterminous United States - A Digital Shaded-Relief Portrayal. U.S. Geological Survey Miscellaneous Investigations Series Map I-2206.
- Thorntwaite, C. W., 1948. An Approach Toward a Rational Classification of Climate. Geographical Review 38(1):55-94.
- Thorntwaite, C. W. and J. R. Mather, 1955. Introductions and Tables for Computing Potential Evapotranspiration and the Water Balance. Publications in Climatology, Laboratory of Climatology, Vol. 8, No. 1, p. 104.
- U.S. Bureau of Census, 1991. Census of Population and Housing, 1990. Public Law (P.L.) 94-171, data from compact disk ROM (Minnesota, North Dakota, and South Dakota), Washington D.C.
- U.S. Department of Agriculture, 1975. Soil Survey of Marshall County, South Dakota, 116 pp.
- U.S. Department of Agriculture, 1977. Soil Survey of Roberts County, South Dakota, 116 p.
- U.S. Department of Agriculture, Soil Conservation Service, 1981. Land Resource Regions and Major Land Resource Areas of the United States. Agricultural Handbook 296, map (scale 1:750,000), 156 pp.
- U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1982. Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1941-70 (Minnesota, North Dakota, and South Dakota). Asheville, North Carolina, Climatology of the United States, No. 81.
- U.S. Environmental Protection Agency, 1986. Quality Criteria for Water 1986. U.S. Environmental Protection Agency Report Number 440/5-86-001, 256 pp.
- Upham, Warren, 1895. The Glacial Lake Agassiz. U.S. Geological Survey Monograph, Vol. XXV, 658 pp.
- Wall, D. B. and B. R. Montgomery, 1991. Nitrogen in Minnesota Ground Water. Minnesota Pollution Control Agency and Minnesota Department of Agriculture, St. Paul, Minn., 280 pp.
- Wiche, G. J., 1991. Evaporation Computed by Energy-Budget and Mass-Transfer Methods and Water-Balance Estimates for Devils Lake, North Dakota, 1986-88. North Dakota State Water Commission Water-Resources Investigation 11, 52 pp.
- Winter, T. C., 1967. Linear Sand and Gravel Deposits in the Sub-surface of Glacial Lake Agassiz. In: Life, Land and Water - Proceedings of the 1966 Conference on Environmental Studies of the Glacial Lake Agassiz Region, M. J. Mayer-Oakes (Editor). University of Manitoba Press, Winnipeg, pp. 141-154.
- Winter, T. C., R. D. Benson, R. A. Engberg, G. J. Wiche, D. G. Emerson, O. A. Crosby, and J. E. Miller, 1984. Synopsis of Ground-Water and Surface-Water Resources of North Dakota: U.S. Geological Survey Open-File Report 84-732, 127 pp.
- Winter, T. C., L. E. Bidwell, and R. W. Maclay, 1969. Water Resources of the Otter Tail River Watershed, West-Central Minnesota. U.S. Geological Hydrologic Investigations Atlas HA-296.
- Winter, T. C., L. E. Bidwell, and R. W. Maclay, 1970. Water Resources of the Wild Rice River Watershed, Northwestern Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-339.
- Winter, T. C. and M. R. Carr, 1980. Hydrologic Setting of Wetlands in the Cottonwood Lake Area, Stutsman County, North Dakota. U.S. Geological Survey Water-Resources Investigations Report 80-99, 41 pp.
- Winter, T. C., R. W. Maclay, and G. M. Pike, 1967. Water Resources of the Roseau River Watershed, Northwestern Minnesota. U.S. Geological Survey Hydrologic Investigations Atlas HA-241.
- Wolf, R. J., 1981. Hydrology of the Buffalo Aquifer, Clay and Wilkin Counties, West-Central Minnesota. U.S. Geological Survey Water-Resources Investigations Report 81-4, 83 pp.
- Woodward, D. G. and H. W. Anderson, Jr., 1986. Hydrogeologic and Water-Quality Characteristics of the Cretaceous Aquifer, Southeastern Minnesota. U.S. Geological Survey Water-Resources Investigations Report 84-4153, 2 plates.