Water-Quality Assessment of Part of the Upper Mississippi River Basin, Minnesota and Wisconsin— Environmental Setting and Study Design

By James R. Stark, William J. Andrews, James D. Fallon, Alison L. Fong, Robert M. Goldstein, Paul E. Hanson, Sharon E. Kroening, and Kathy E. Lee

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Foreword

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policy makers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for a specific contamination problem; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.
- Describe how water quality is changing over time.
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 60 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 60 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch
Chief Hydrologist

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Multiply Inch-Pound Unit	By	To obtain Metric Unit
cubic foot per second (ft^3/sec)	28.32	liter per second
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
foot per day (ft/d)	.3048	meter per day
acre-foot (acre-ft)	1,233	square meter
gallon per minute (gal/min)	.06308	liter per second
cubic foot per second (ft^3/s)	.02832	cubic meter
square mile (mi^2)	2.590	square kilometer
degree Fahrenheit (°F)	(temperature °F - 32)/1.8	degree Celsius

Chemical concentrations: Chemical concentrations of substances in water are given in metric units of micrograms per liter (µg/L). Micrograms per liter is a unit expressing the concentration of chemical constituents in solution as mass (micrograms) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter.

Sea level: in this report sea level refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Use of brand names is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Acronyms used in this report:

MDH—Minnesota Department of Health

MPCA—Minnesota Pollution Control Agency

NASQAN—National Stream Quality Accounting Network

NAWQA—National Water-Quality Assessment Program

RASA—Regional Aquifer-System Analysis

TCMA—Twin Cities metropolitan area

UMIS—Upper Mississippi River Basin study

USEPA—U.S. Environmental Protection Agency

USGS—U.S. Geological Survey

VOC's—volatile organic compounds

Water-Quality Assessment of the Upper Mississippi River Basin Study Unit, Minnesota and Wisconsin—Environmental Setting and Study Design

By James R. Stark, William J. Andrews, James D. Fallon, Alison L. Fong, Robert M. Goldstein, Paul E. Hanson, Sharon E. Kroening, and Kathy E. Lee

Abstract

The Upper Mississippi River Basin is diverse in ways that can control the areal distribution and flow of water and the distribution and concentration of constituents that affect water quality. A review of the environmental setting of the Upper Mississippi River Basin study unit of the National Water-Quality Assessment Program is intended to put water quality in perspective with the geology, soils, climate, hydrology, ecology and historical uses of the land and provides a basis for the sampling design of the study.

The Upper Mississippi River Basin study unit encompasses about 47,000 square miles and includes all of the basin upstream from Lake Pepin. The climate of the study unit is subhumid continental with cold dry winters and warm, moist summers. Average annual precipitation ranges from 22 inches in the western part of the study unit to 32 inches in the east. Annual runoff ranges from less than 2 inches in the west to 14 inches in the northeast.

The physiography of the study unit includes the Superior Upland and the Central Lowland Provinces. The Wisconsin Driftless Area and the Dissected Till Plains are unique physiographic sections of the Central Lowland Province. Hydrogeologic units in glacial deposits include surficial and buried sand and gravel aquifers and confining units. Bedrock aquifers and confining units are part of a thick sequence of sedimentary rocks that can be divided into major aquifers separated by confining units.

The population of the study unit was about 3,640,000 as of 1990 and increased 16 percent between 1970 and 1990. Seventy-five percent of the population lives in the Twin Cities metropolitan area. An average of 413 million gallons of water per day was used—59 percent from ground water and 41 percent from surface water. Land use and land cover in the study unit consists of forested, agricultural, and urban areas. About 63 percent of the land area is agricultural.

The quality of water in streams and ground water are affected by both natural and anthropogenic factors. The quality of water is generally satisfactory for most domestic, public, industrial, and irrigation uses. Most water is of the calcium-magnesium-bicarbonate type.

The initial six-year phase of the Upper Mississippi River Basin National Water-Quality Assessment, lasting from 1994 to 1999, focuses on data collection and analysis in a 19,500 square-mile area in Minnesota and Wisconsin that includes the Twin Cities metropolitan area. The study design focuses on factors that have an influence on or a potential influence on the water quality in that area. The most significant contaminants include nutrients, pesticides, synthetic-organic compounds, and trace metals.

Environmental stratification consists of dividing the study unit into subareas with homogeneous characteristics to assess natural and anthropogenic factors affecting water quality. The assessment of water quality in streams and in aquifers is based on the sampling design that compares water quality within homogeneous subareas defined by subbasins or aquifer boundaries. The study unit is stratified at four levels for the surface-water component: glacial deposit composition, surficial geology, general land use and land cover, and secondary land use. Ground-water studies emphasize shallow ground water where quality is most likely influenced by overlying land use and land cover.

Stratification for ground-water sampling is superimposed on the distribution of shallow aquifers. For each aquifer and surface-water basin this stratification forms the basis for the proposed sampling design used in the Upper Mississippi River Basin National Water-Quality Assessment.

Introduction

The USGS began full scale implementation of the NAWQA Program in 1991. The purposes of the NAWQA Program are to describe the status and trends in the quality of the Nation's water resources and aquatic ecosystems, and to determine factors affecting water quality. Study-unit investigations are significant components of the program. Study units are made up of hydrologic systems that include parts of most major river basins and aquifer systems.

The UMIS study unit includes all of the surface drainage to the Mississippi River Basin upstream from Lake Pepin and encompassing 47,000 mi^2 (fig. 1). The study unit encompasses areas of rich agricultural lands, forests, wetlands, prairies, and a major urban area. The Mississippi River is the principal source of water supply to major municipalities, including the cities of Minneapolis, St. Paul, and St. Cloud. Outside of those municipalities, ground water is the principal source of water for public and domestic water supply. Bedrock aquifers comprised of sedimentary rocks of Cambrian and Ordovician age are the primary sources of ground water for suburban communities surrounding the Twin Cities, whereas unconsolidated glacial deposits are the primary source of water supply for the rest of the study unit.

The Upper Mississippi River Basin was selected as a study unit because water quality of the Mississippi River, the largest river in the Nation, is of national concern. The study unit represents important agricultural and urban areas.

The purpose of the UMIS NAWQA study is to describe the status and trends in quality of the water resources of the study unit and to provide understanding of factors affecting water quality and ecosystem status. The initial six-year phase of the study, lasting from 1994 to 1999, focuses on data collection and analysis in a 19,500-mi^2 study area in Minnesota and Wisconsin that includes the seven-county TCMA. During the first phase of the study, the focus is on the most important water-quality and ecosystem issues, principally the effects of the TCMA on water quality and aquatic ecosystems. The study area includes the UMIS drainage from Lake Pepin upstream to include all of the St. Croix River Basin and to points on the Minnesota (Jordan, Minnesota) and Mississippi (Royalton, Minnesota) Rivers where long-term water-quality data are available.

The study characterizes the geographic and seasonal distribution of water quality, aquatic biota and aquatic habitat conditions in relation to anthropogenic activities and natural features, and focuses on the TCMA. Pesticides, nutrients, volatile organic chemicals, and biological conditions are of specific interest to NAWQA from a national perspective (Gilliom and others, 1995).

The objectives of the UMIS NAWQA study are to:

- Design sampling networks for streams, ground water, and biological communities and habitat to effectively monitor for long-term trends.
- Identify key physical and chemical constituents indicative of water quality in major aquifers.
- Identify key physical and chemical constituents and biological conditions indicative of water quality and ecosystem conditions in streams.
- Identify natural features and anthropogenic activities that affect the concentrations and loads of target constituents measured in streams and in aquatic-biological tissue.
- Describe seasonal variability of selected target constituents in streams and ground water.
- Estimate distribution and annual load of selected physical and chemical constituents in streams.
- Describe relation of water quality to regional land use and land cover.
- Describe long-term trends in the concentrations of target constituents in streams, aquatic-biological tissue, and ground water.

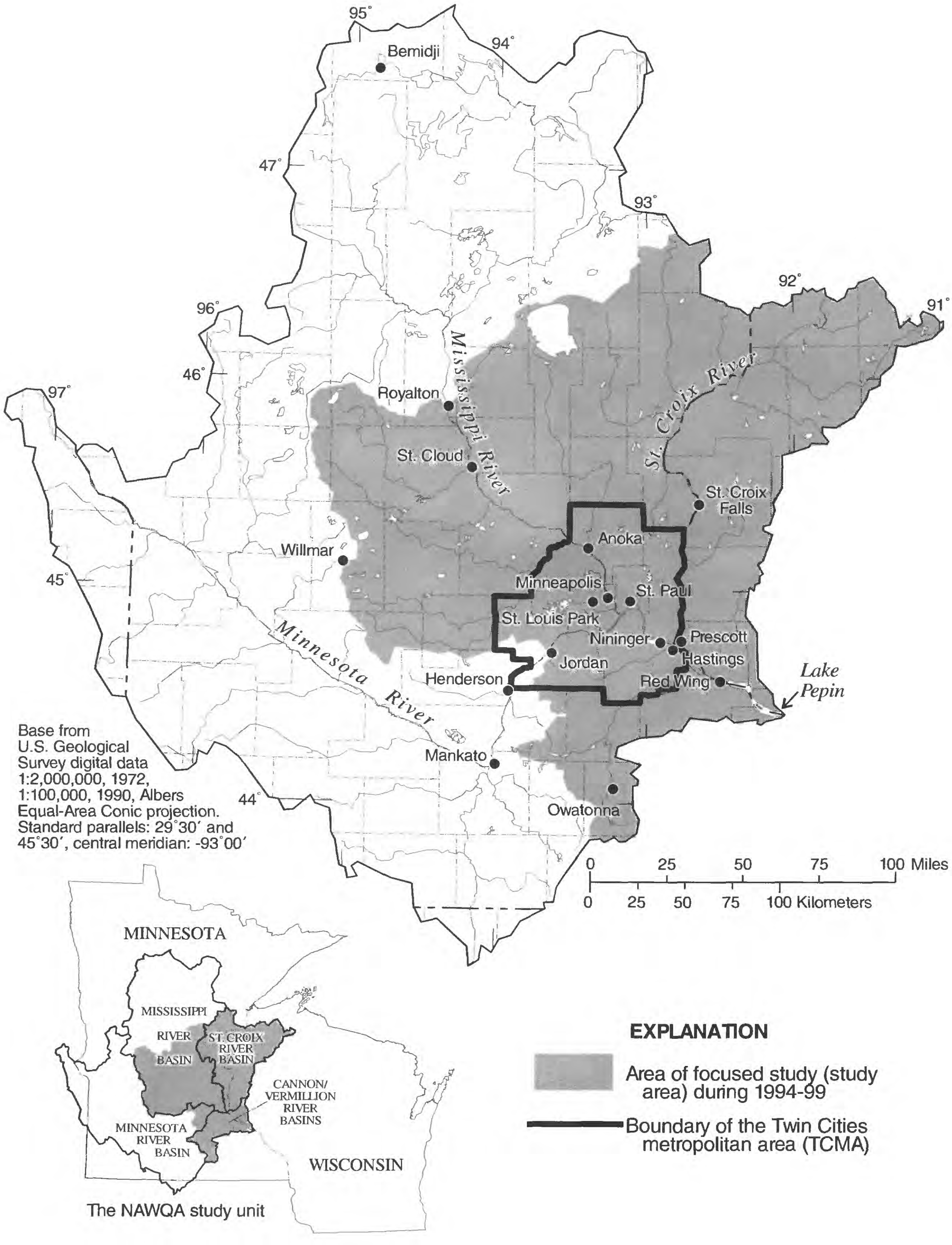


Figure 1.--Location of the Upper Mississippi River Basin study unit, study area, selected towns, and major cities

Purpose and Scope

The purpose of this report is to describe the environmental setting of the UMIS study unit, including the physical, chemical, and aquatic-biological characteristics which affect or are affected by water quality. The report also defines the focused area of study (study area) for the period 1994-99. This report provides baseline and historical information for following reports that will address specific water-quality issues and processes controlling and affecting water quality in the study area, and for reports that integrate the results of the investigations across the Nation (National-synthesis component of the NAWQA Program). This report also describes the design of the study.

Water-Quality Issues

Because both surface and ground water are major sources of water supply in the study unit, prevention of contamination of streams and major aquifers is of concern. Both point- and nonpoint source-contamination of streams and aquifers are important issues in the study unit. Contaminants in surface and ground water include nutrients, pesticides, synthetic-organic chemicals, and trace metals. Cultural eutrophication of Lake Pepin (fig. 2), a natural lake in the Mississippi River downstream from the Twin Cities, is an important local issue (EnviroTech Associates Inc., 1993; Heiskary and Vavricka, 1993; Heiskary and others, 1993; Metropolitan Waste Control Commission, 1993a; Minnesota Pollution Control Agency, 1989a).

The UMIS study-unit personnel receive input from a liaison committee comprised of representatives from Federal, State, and local agencies, universities, and the private sector that have water-resource responsibilities, expertise, and interest. Protection of the Mississippi River as a water supply and prevention of ground-water quality degradation are among the concerns of the liaison committee. Point and nonpoint sources of contamination, sedimentation, human-induced hydrologic change, and degradation of aquatic habitat were also identified as significant water-quality issues.

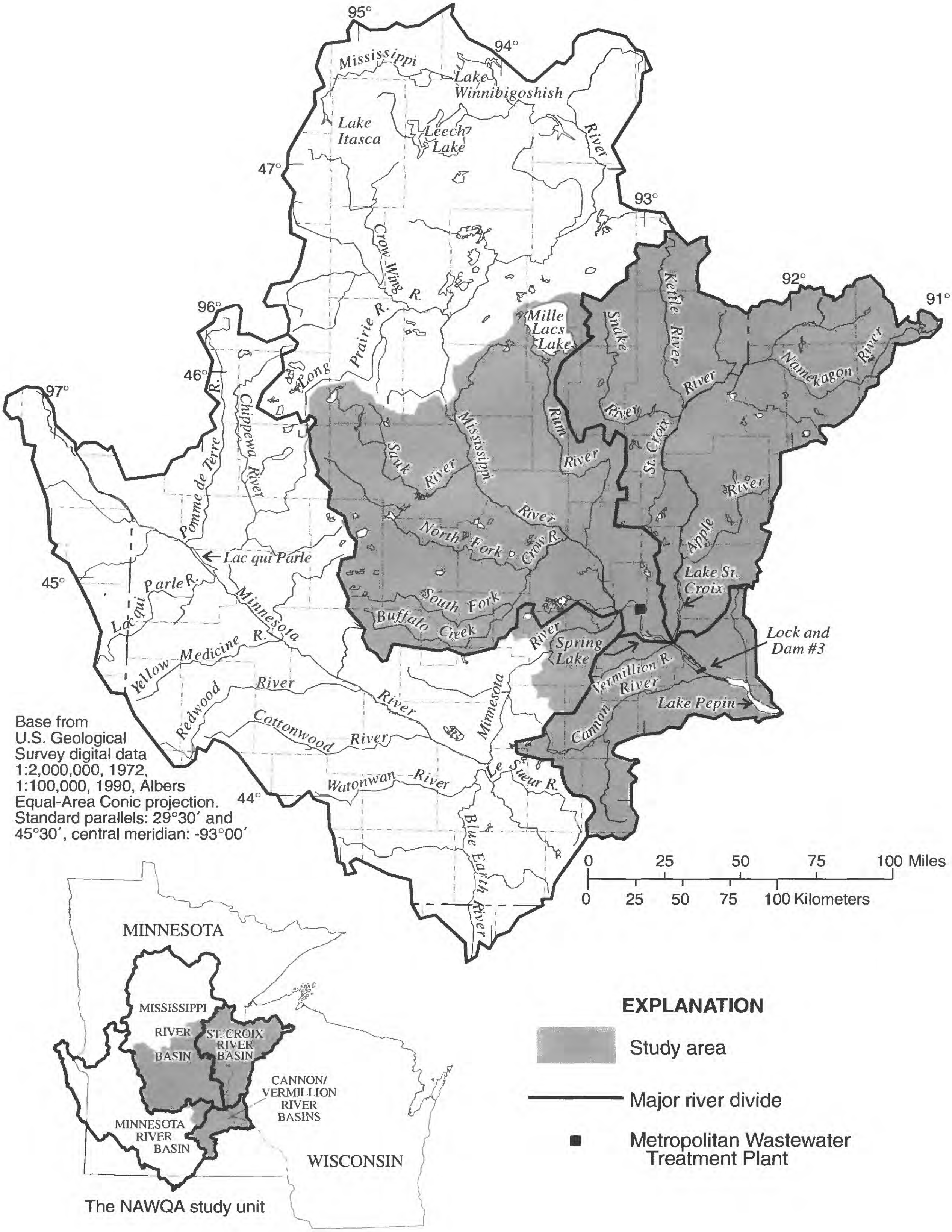


Figure 2.--Hydrography of the Upper Mississippi River Basin study unit.

Previous Studies

The description of the environmental setting of the study unit is based on a review of currently available reports and data from Federal, state, and local agencies. This section describes selected published reports.

General descriptions of surface-water resources of the Upper Mississippi River Basin are presented by Gunard and others (1986) for Minnesota and by Gebert and others (1986) for Wisconsin. The USGS published a series of atlases summarizing the water resources of watersheds in the Minnesota, Mississippi, and St. Croix River Basins. These atlases include information on climate, streamflow, physical features, and surface-water and ground-water resources by watershed. Physical characteristics, including drainage area, stream-order rank, channel length and slope, lake area, and storage area also have been published for subbasins of the Minnesota River in USGS Open-File Reports for the Blue Earth, Chippewa, Cottonwood, Lac qui Parle, Le Sueur, Pomme de Terre, Redwood, and Watonwan Rivers, as well as the upper Minnesota River.

Most interpretive literature about surface water in the study unit deals with extreme hydrologic events or water availability. The 1993 floods in the Mississippi River Basin are summarized in a series of reports that include analysis of precipitation (Wahl and others, 1993) and flood discharge (Parrett and others, 1993; Southard, 1993). Low streamflow has been studied extensively, especially along the Mississippi River reach through the Twin Cities, because of the need for potable water supplies and assimilation of wastewater loads. The drought of 1988 prompted several investigations (Minnesota Department of Natural Resources, 1989; Minnesota Pollution Control Agency, 1989b; Metropolitan Council, 1992).

Two reports summarize the water resources of the TCMA. Norvitch and others (1973) assess supplies of ground water, surface water, and the water quality. A summary was prepared by the Metropolitan Council (1992) in response to limited water supplies during the 1988-89 drought. The report made water management recommendations regarding water use, availability, and quality in the TCMA.

Several reports summarize the surface-water quality of the Upper Mississippi River Basin. Have (1991) describes the spatial and temporal variability in stream-water quality for the Mississippi River from Royalton to Hastings, Minnesota. Payne (1991, 1994) present results of physical and chemical monitoring of the Minnesota River, and Graczyk (1986) describes the water quality of the upper portion of the St. Croix River.

The Minnesota River Assessment Project, a cooperative study by Federal, State, and local agencies coordinated by the MPCA, was conducted during 1989-93 to determine sources of point and nonpoint loading to the Minnesota River and the effects of these loads on water quality and river ecology. Results from the study are compiled in four volumes, each containing several individual reports (Minnesota Pollution Control Agency, 1994a-e). This work includes results from monitoring of the Minnesota River and its tributaries from Lac qui Parle reservoir to Henderson, Minnesota (Payne, 1991 and 1994), and results from monitoring of the lower Minnesota River and its tributaries from Jordan, Minnesota to the confluence with the Mississippi River, using data collected by the Metropolitan Waste Control Commission's River-Water Quality Monitoring Program (Metropolitan Waste Control Commission, 1994b).

Graczyk (1986) describes the stream-water quality in the St. Croix National Scenic Riverway. Troelstrup and others (1993) used data from various agencies to describe water quality in the lower St. Croix River from St. Croix Falls, Wisconsin to the confluence with the Mississippi River. Johnson and Aasen (1989) analyzed dissolved-oxygen data collected by the Metropolitan Waste Control Commission in the Mississippi River from St. Paul to Red Wing, Minnesota that documented improvements in river-water quality coinciding with improvements in wastewater treatment practices.

The Metropolitan Waste Control Commission (1993a) conducted a study of phosphorus in the Mississippi River from Anoka, Minnesota to the downstream part of Lake Pepin during 1990-92. The study evaluated the effect of phosphorus loadings from the Metropolitan Wastewater Treatment Plant, and from other sources, on the water quality of Spring Lake and Lake Pepin, two reservoirs located on the Mississippi River. The study results are presented in a series of 11 reports.

Bailey and Rada (1984) analyzed trace metal (cadmium, chromium, copper, nickel, lead, and zinc) concentrations in bed sediments in the Upper Mississippi River to determine whether trace metals were accumulating in Lake Pepin. Their results suggest that cadmium, copper, lead, and zinc concentrations were significantly greater in sediments within and upstream from Lake Pepin than in sediments downstream from the lake. Wiener and others (1984) analyzed trace metal concentrations in sediment from the Upper Mississippi River to determine their longitudinal distribution in fishes and bed sediment. Concentrations of cadmium, mercury, and lead in bed sediments were generally greater in samples collected downstream of the TCMA.

The geology and hydrogeology of the study unit have been the subject of several comprehensive reports. Kanivetsky (1978 and 1979) and Kanivetsky and Walton (1979) describe the bedrock and Quaternary hydrogeology of Minnesota. Mandle and Kontiz (1992), Siegel (1989), and Young (1992a and 1992b), present results of a study of the Cambrian-Ordovician aquifer system in the Northern Midwest as part of the USGS RASA. Olcott (1992) presents a summary of the ground-water resources of Iowa, Michigan, Minnesota, and Wisconsin. Sims and Morey (1972) present a series of papers describing the geologic setting and origins of rocks and unconsolidated deposits of Precambrian to Cenozoic age in Minnesota. Delin and Woodward (1984) and Woodward (1986) describe the hydrogeologic setting and the potentiometric surfaces of regional aquifers in the Hollandale Embayment area of southeastern Minnesota. Norvitch and others (1973) describe the general hydrologic framework of the TCMA. Schoenberg (1990) describes the geologic and hydrologic setting of the TCMA and describes the development and application of a model to simulate ground-water flow in the aquifer system for the period 1970-79. Hult and Schoenberg (1984) present an analysis of the ground-water hydrology as part of an evaluation of a ground-water contamination site in St. Louis Park.

Maps of potentiometric altitudes have been constructed for many of the principal aquifers in the TCMA by Andrews and others (1995a), the Minnesota Department of Natural Resources, Division of Waters (1961), Reeder (1966), and Schoenberg (1984) for the Prairie du Chien-Jordan and Mt. Simon-Hinckley aquifers; by Norvitch and others (1973) for the St. Peter, Prairie du Chien-Jordan, and Mt. Simon-Hinckley aquifers; and by Larson-Higdem and others (1975) and Palen and others (1993) for the unconsolidated aquifers of glacial and alluvial origins. The Minnesota Geological Survey published a series of detailed hydrogeologic county atlases which include maps of potentiometric altitudes and well yields for major aquifers in five of the seven counties in the TCMA (Balaban, 1989; Balaban and Hobbs, 1990; Balaban and McSwiggen, 1982; Meyer and Swanson, 1992; and Swanson and Meyer, 1990).

This report includes sources of information about surface-water hydrology, hydrogeology, geology, soils, climate, biology, aquatic ecology and water quality (nutrients, pesticides, VOC's, and trace metals). Important sources of information include the Metropolitan Council Environmental Services, Minnesota Department of Agriculture, Minnesota Department of Health, Minnesota Department of Natural Resources, Minnesota Geological Survey, Minnesota Pollution Control Agency, U. S. Geological Survey, University of Minnesota, Wisconsin Geological Survey, and the Wisconsin Department of Natural Resources. Water-quality issues and concerns defined by the study-unit liaison committee and NAWQA National Synthesis topics have guided the literature review. The search and acquisition of existing published information consists of approximately 2,000 citations. Electronic literature data bases searched include Aquatic Sciences and Fisheries Abstracts, Biosis, Compendex Plus, Dissertation Abstracts, Enviroline, Georef, Pollution Abstracts, and Water Resources Abstracts.

Environmental Setting

A review of the environmental setting of the study unit puts water quality in perspective with the climate, physiography, geology, soils, hydrology, topography, vegetation, ecology, anthropogenic factors and historical uses of land (fig. 3). The physical, chemical, hydrological, and ecological characteristics of the study unit are considered part of the environmental setting. The diversity in these characteristics across the study unit influences the areal distribution and flow of water and the distribution and concentration of constituents that affect water quality. This description is not comprehensive, but focuses on factors that can affect water quality or aquatic biology, that can be affected by water quality or aquatic biology, and that improve the understanding of environmental factors related to the quality of water in the study unit.

The study unit is located near the geographic center of North America. From its northern source at Lake Itasca (fig. 2), the Mississippi River flows generally southward through an area of glacial moraines, lakes, lake plains and wetlands. Land-surface altitudes in the study unit range from about 2,100 ft above sea level in the western part of the study unit to 667 ft above sea level at Lake Pepin, where the Mississippi River exits the study unit. The relatively low topographic relief and the gently rolling hills and plains in the study unit are the result of glaciation and the structure of the underlying bedrock. Glaciers and glacial meltwater left moraines, lake plains, and flat plains of outwash sands. Bedrock units include a thick sequence of sedimentary rocks that are present beneath much of the study unit. In the southeastern part where glacial deposits are thin or missing, the local relief is a product of erosion of bedrock units and is generally greater than in the rest of the study unit.

Water quality varies significantly across the study unit and is affected by both natural and anthropogenic factors. Natural factors include climate, physiography, geology, soils, hydrology, topography, vegetation, and aquatic ecology. Differences in water quality across the study unit may be attributable to differences in these natural factors.

The principal anthropogenic factors affecting water quality are agriculture, urban runoff, and municipal and industrial point-source discharges or emissions. Anthropogenic factors, with the exception of agriculture, are concentrated in the TCMA, which contains the highest concentration of population, traffic, and manufacturing facilities. Anthropogenic substances emitted include millions of pounds of VOC's (Andrews and others, 1995b; U.S. Environmental Protection Agency, 1994); nutrients from fertilizers, animal manure, wastewater, and urban runoff (Creason, and Runge, 1992); pesticides applied to cropland, lawns and golf courses, and atmospheric deposition (D.A. Goolsby, U.S. Geological Survey, written commun., 1995).

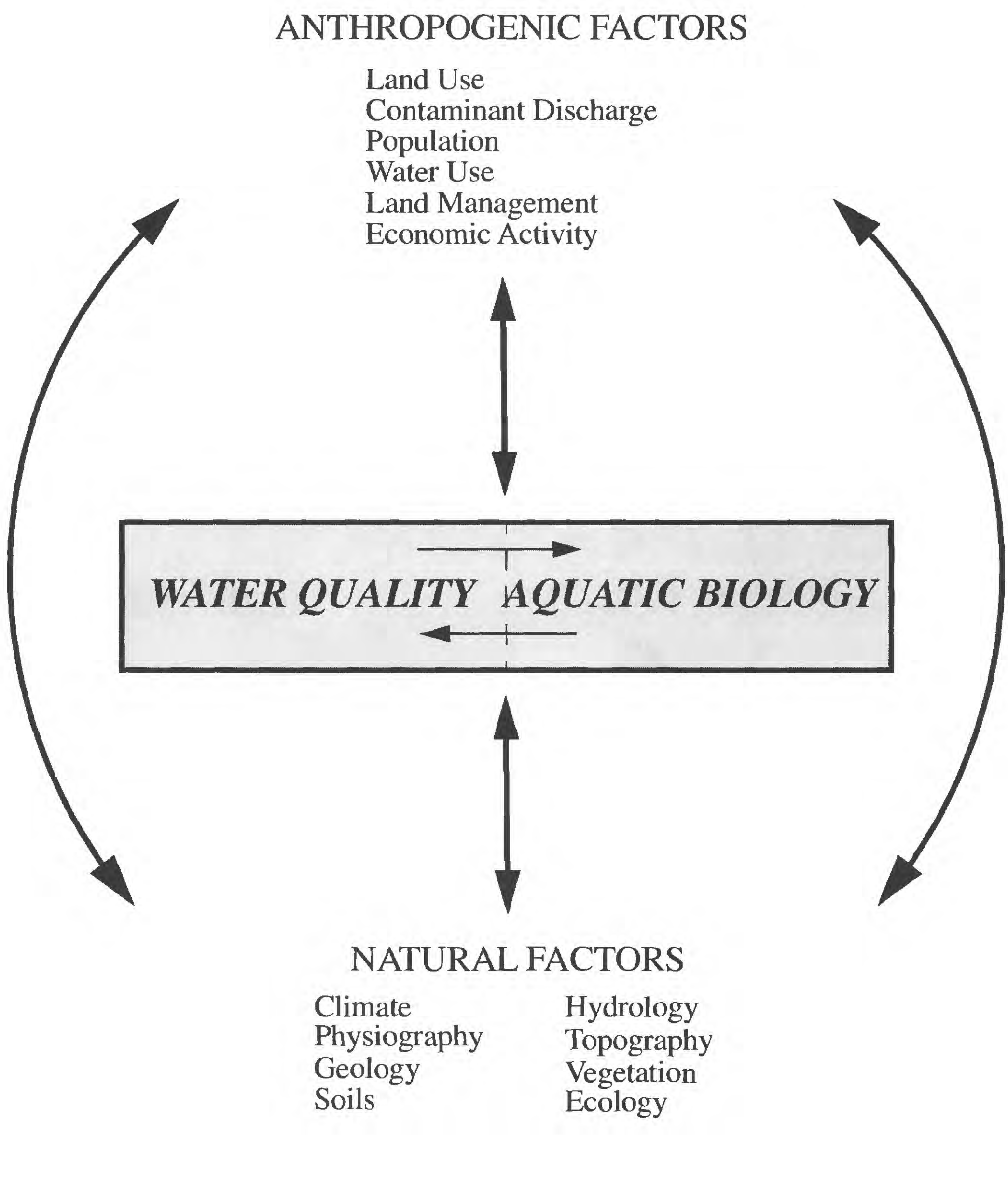


Figure 3.--Selected natural and anthropogenic factors that affect water quality and aquatic biology.

Climate

The climate of the study unit is subhumid continental. Upper-level winds flow from west to east for most of the year with a more southerly component of flow during the spring and summer. The Gulf of Mexico is the main source of moisture, supplying more than 75 percent of the annual precipitation (Carlson and others, 1991). The Pacific Ocean is the second most important source of moisture; however, air masses from the Pacific lose most of their moisture as they pass over the Rocky Mountains. All air masses are affected by evapotranspired water. Approximately 75 percent of the annual precipitation falls during the growing season, which lasts from May to September (Baker and others, 1979). December to February is the driest period, receiving only 8 percent of the annual precipitation (Baker and Kuehnast, 1978).

Annual normal temperatures (1961-90) range from 44°F in the south to 38°F in the north (Baker and others, 1985). In the Twin Cities (Minneapolis-St. Paul International Airport), the average monthly temperature ranges from 11°F in January to 74°F in July (fig. 4). Average monthly temperatures in the north, at Walker, Minn., range from 6°F in January to 68°F in July (fig. 4). The lake ice-out date is early April in the south and late April in the north (Kuehnast and others, 1982). Cold, dry, polar continental air from northwestern Canada dominates winter weather (Carlson and others, 1991). Warm, moist, tropical maritime air from the Gulf of Mexico or warm, dry, tropical continental air from the Southwest dominate the summer weather (Carlson and others, 1991). The weather in the spring and fall is affected by all three sources of air.

Average annual precipitation ranges from 22 inches in the west to 32 inches in the east (fig. 4). February generally is the driest month. The number of days with snow cover ranges from 85 days in the south to 145 days in the north (Kuehnast and others, 1982). June typically is the wettest month. In the winter, cyclonic storms from the northwest bring little precipitation (Krug and Simon, 1991). Cyclonic storms from the southwest in fall, winter, and spring contain significant moisture from the Gulf of Mexico and can produce substantial precipitation amounts (Krug and Simon, 1991). Thunderstorms commonly form during the late spring and the summer.

Mean annual evaporation (annual free-water surface evaporation) ranges from less than 28 inches in the northeast to more than 40 inches in the southwest (fig. 4). Evaporation was estimated using class A pans and multiplying by a pan coefficient to correct for climate conditions (Farnsworth and others, 1982).

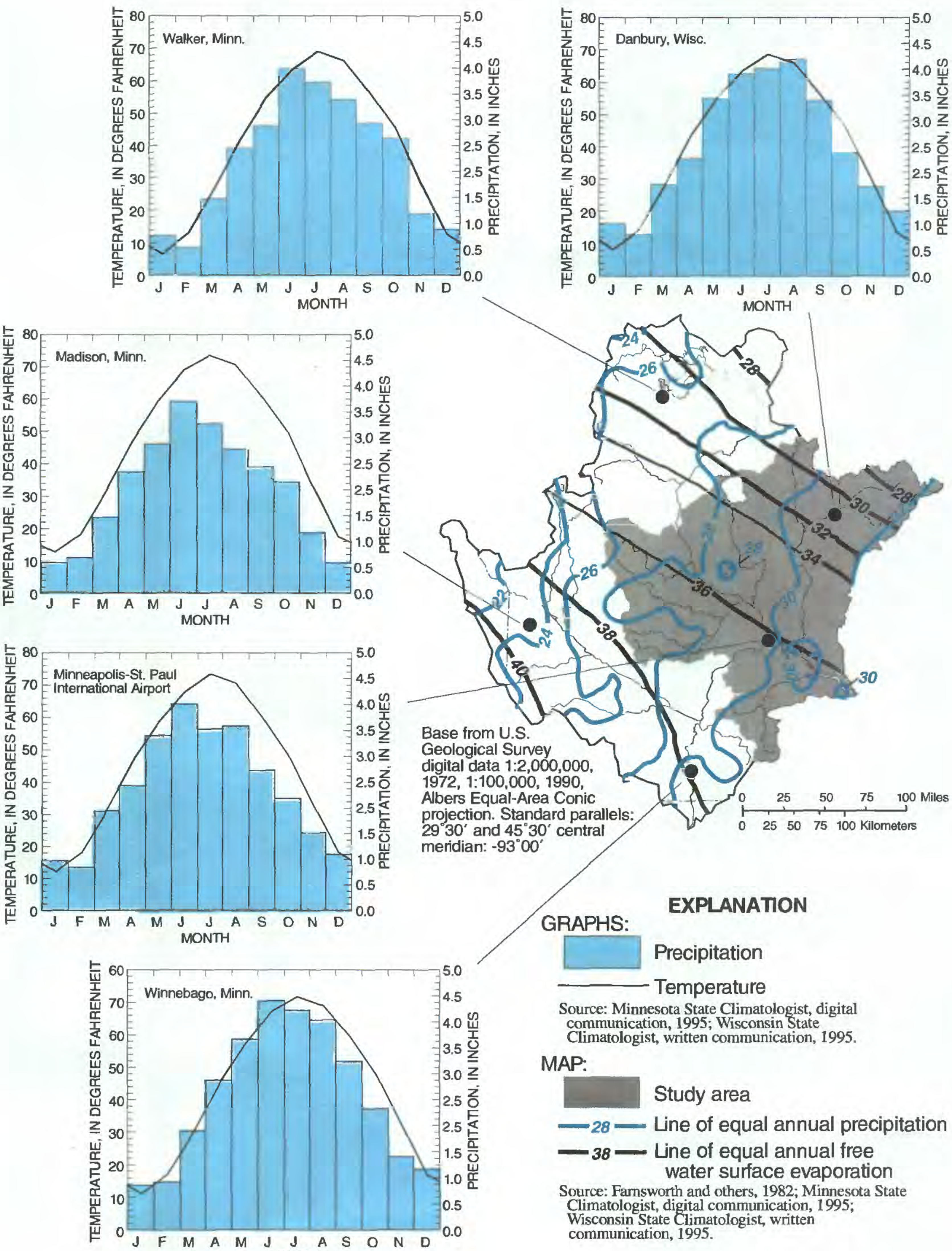
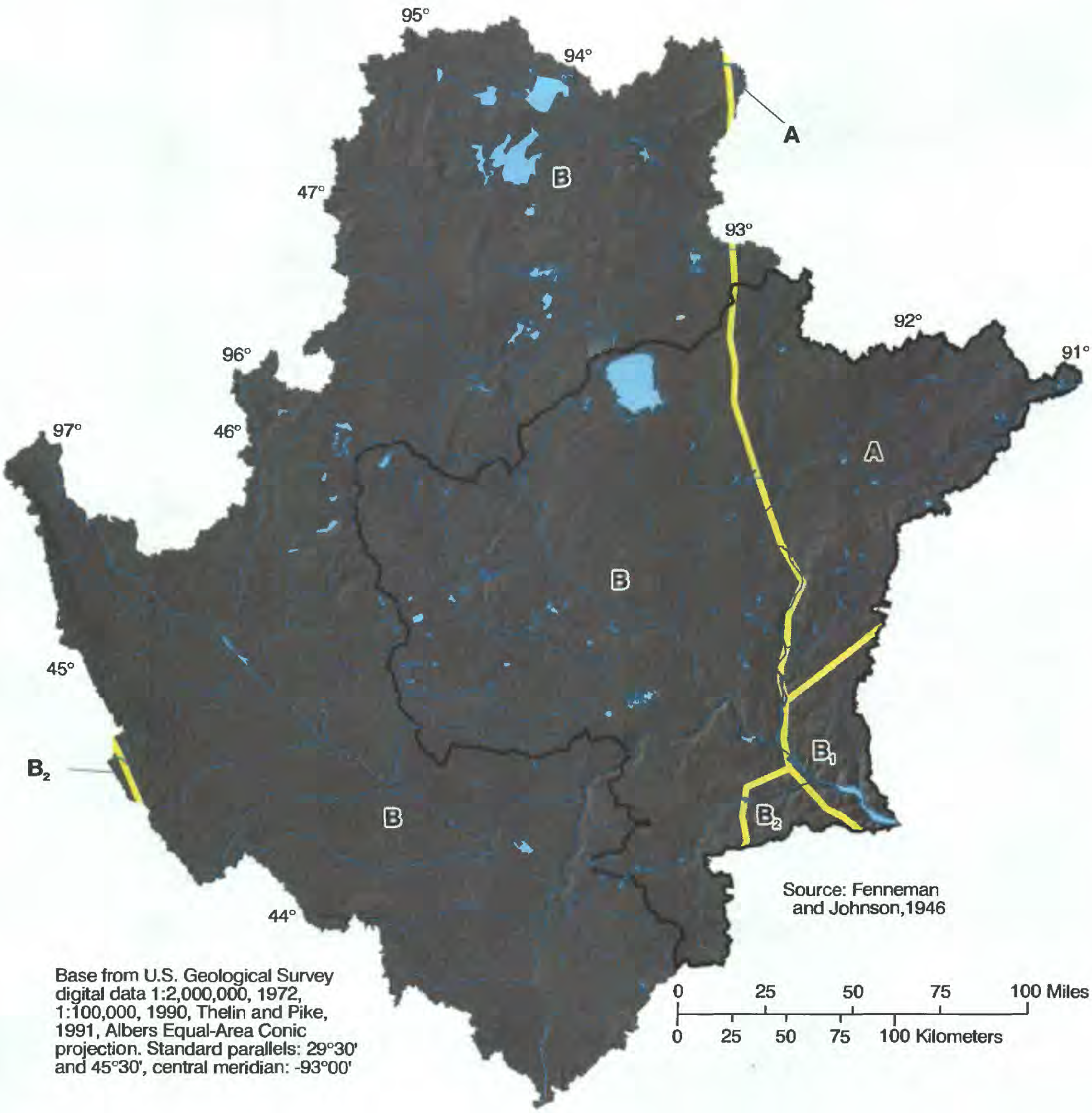


Figure 4.--Mean monthly precipitation and temperature at selected stations and annual precipitation and free water surface evaporation in the Upper Mississippi River Basin study unit, 1961-90.

Physiography

Physiographic provinces include the Superior Upland and the Central Lowland (fig. 5). The Central Lowland, which occupies most of the western three-quarters of the study unit, is characterized by flat-lying to rolling ground moraines and outwash plains. The Superior Upland, which occupies the northeastern part of the study unit, is characterized by flat to hilly moraines and outwash plains. The Wisconsin Driftless Section and Dissected Till Plains Section are unique physiographic sections of the Central Lowland Province which occupy small areas in the southeast, and are characterized by hilly terrain (Fenneman, 1938; Fenneman and Johnson, 1946).



EXPLANATION

Study area boundary

Boundary of physiographic areas

Physiographic areas:

A – Superior Upland Province

B – Central Lowland Province

B_1 – Wisconsin Driftless Section

B_2 – Dissected Till Plains Section

Figure 5.--Physiography in the Upper Mississippi River Basin study unit.

Geology

Hydrologic characteristics and geochemical controls of surface-water and ground-water quality are strongly affected by surficial and bedrock geology. Rocks and unconsolidated deposits in the study unit can be categorized by three general types: crystalline rocks of Precambrian age, stratified sedimentary rocks of Precambrian to Cretaceous age (fig. 6), and unconsolidated Pleistocene- and Holocene-age (Quaternary) deposits. Generalized glacial deposits are shown in figure 7. The formal and informal terms for rock units and hydrogeologic units in the study unit vary slightly between Minnesota and Wisconsin (fig. 8) (Olcott, 1992). In addition, there are minor differences in the ways in which rock units and hydrogeologic units are grouped within a given name or term. In this report terms commonly used in Minnesota are used except as noted.

The study unit is on the southern margin of the Superior Province of the Canadian Shield, a region where igneous and metamorphic rocks of Precambrian age are exposed at or near land surface (Sims and Morey, 1972). In the southeastern one-third, in an area known as the Hollandale Embayment (fig. 6), Precambrian crystalline rocks are unconformably overlain by Cambrian to Ordovician-age sandstones and carbonate rocks with subordinate siltstones and shales (Sims and Morey, 1972). The Twin Cities Artesian Basin, a structural basin beneath the TCMA, contains up to 1,200 ft of Paleozoic formations. Rocks younger than the Galesville Sandstone of Cambrian age are incised by deep channels eroded by pre-glacial and interglacial rivers. These channels are filled with up to 600 ft of unconsolidated sands and gravels of alluvial origin (Schoenberg, 1990).

Four continental glacial advances covered the study unit during the Pleistocene Epoch and left a nearly continuous veneer of less than 100 ft of unconsolidated deposits on bedrock uplands and up to 600 ft of unconsolidated deposits in bedrock valleys and in terminal moraines. Glacial deposits primarily are the result of the last episode of Pleistocene glaciation—the Wisconsinan, that lasted from 110,000 to 10,000 years before the present (Sugden and John, 1976; Wright, 1972).

Unconsolidated glacial deposits can be classified by the origins of the glacial lobes that deposited these materials and by the mode of deposition (fig. 7). During the Wisconsinan glaciation, bedrock in the northeast and northwest was covered with sediments deposited by the Superior, Rainy, and Wadena Lobes. The remaining two-thirds of the study unit is mantled by unconsolidated sediments from the Des Moines Lobe, which advanced from the northwest. The Superior and Rainy Lobes traversed igneous and metamorphic rocks and left glacial deposits that tend to be siliceous and sandy. The Des Moines and Wadena Lobes, which traversed calcareous rocks, sandstone, and shales, left more clay-rich calcareous deposits containing fragments of limestone and shale (Ruhl, 1987). The relatively high altitudes of bedrock units (ranging from 1,100 to 1,300 ft) in southeastern Minnesota and southwestern Wisconsin deflected the Des Moines Lobe during the Wisconsinan glaciation, preventing deposition of unconsolidated sediments (Woodward, 1986). Although the southeastern corner of the study unit is commonly referred to as driftless (lacking deposits of glacial origin), thin deposits of unconsolidated materials of pre-Illinoian age (the Illinoian glacial period commenced at 302,000 years before the present), covered by deposits of loess of Wisconsinan age, overlie bedrock in the southeast (Wright, 1972).

Glacial deposits also can be divided into two types—unstratified and stratified. Unstratified deposits consist principally of till (an unsorted mixture of clay, silt, sand and gravel); stratified deposits consist of surficial sand and gravel (outwash), outwash buried beneath tills, and alluvial, ice-contact and valley-fill deposits (Woodward, 1986). Unconsolidated deposits, thickest in the west, progressively thin towards the northeast and southeast (Woodward, 1986). The largest expanse of glacial outwash is located north of the TCMA. Sands and gravels in this area were deposited by meltwater from the receding Superior Lobe, the Des Moines Lobe, and by glacial meltwater flowing in the channel of the Mississippi River, which migrated across the area during the Holocene Epoch (Wright, 1972; Anderson, 1993).

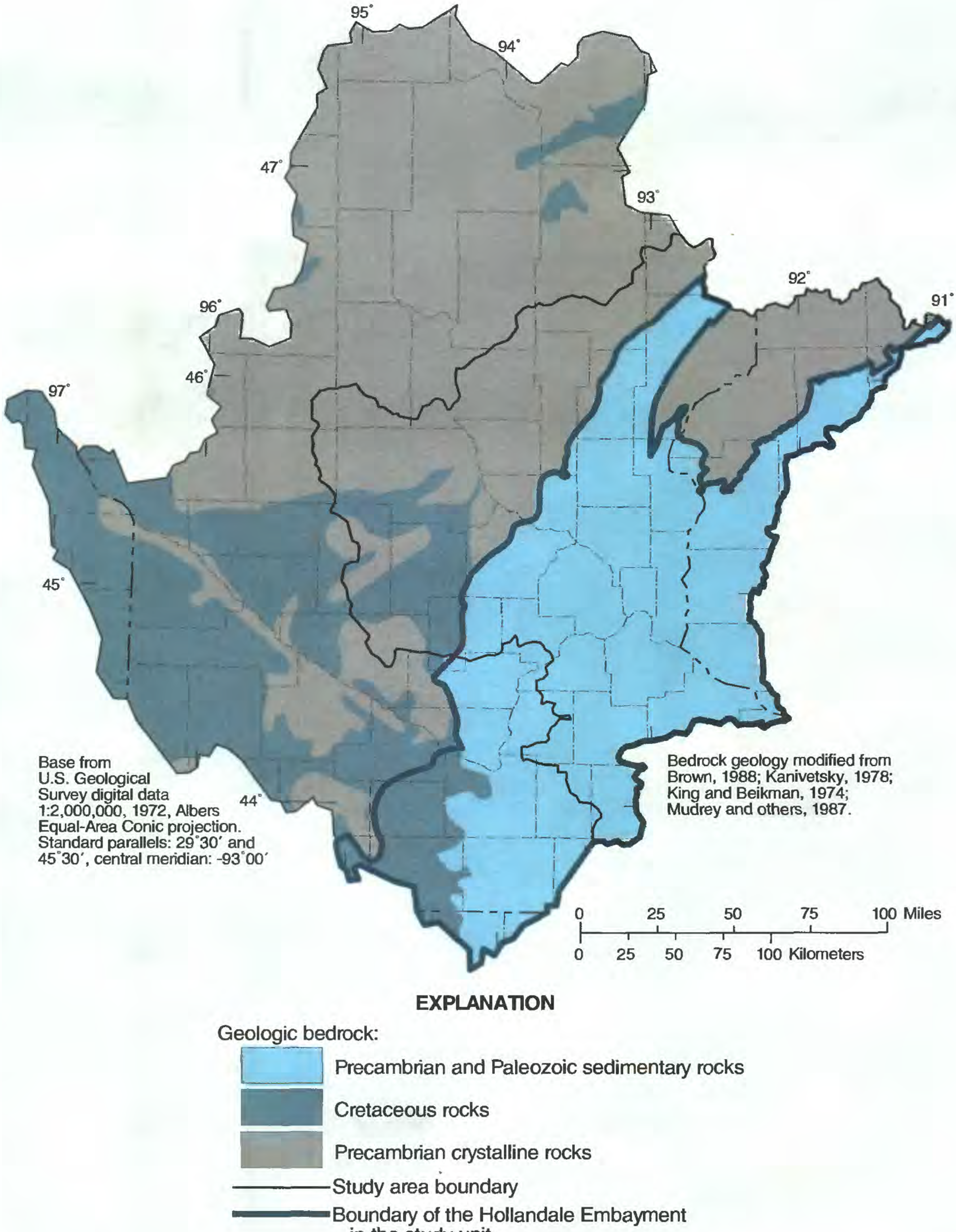


Figure 6.--Generalized bedrock geology in the Upper Mississippi River Basin study unit.

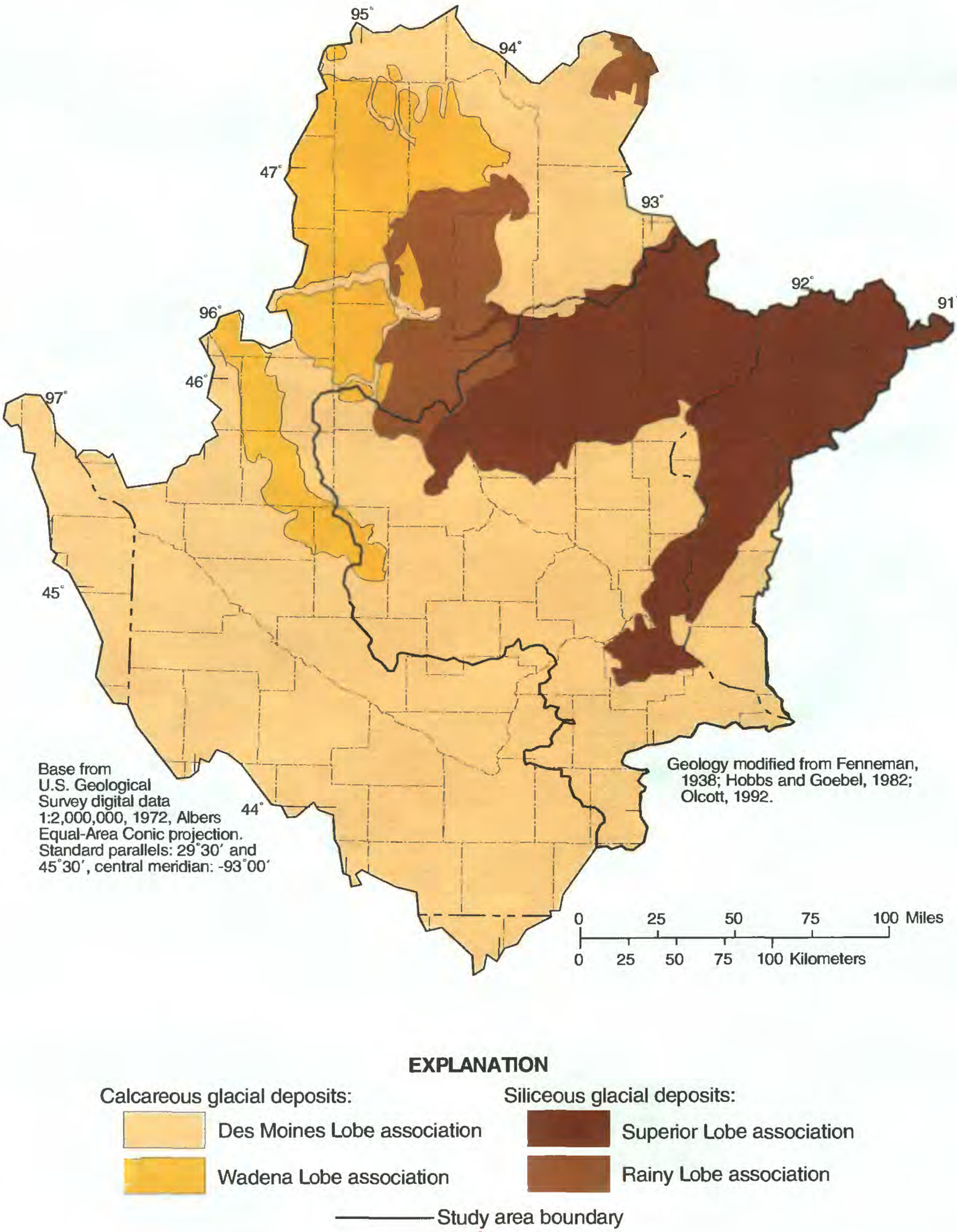
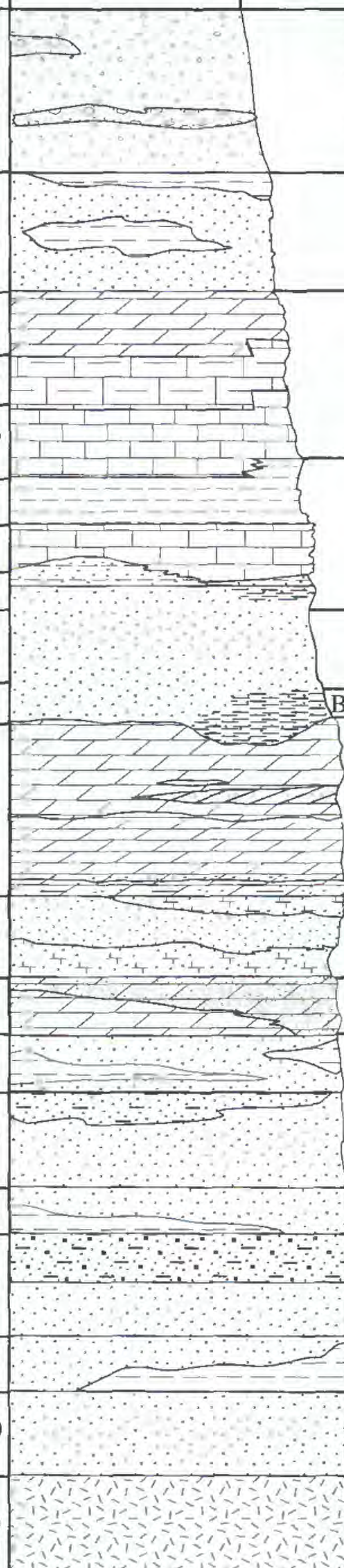


Figure 7.--Generalized glacial-deposit composition in the Upper Mississippi River Basin study unit.

ERATHEM	SYSTEM OR SERIES	FORMATION OR GROUP: MINNESOTA	FORMATION OR GROUP: WISCONSIN	THICKNESS (IN FEET)	GENERAL LITHOLOGY	HYDROGEOLOGIC UNIT: MINNESOTA	HYDROGEOLOGIC UNIT: WISCONSIN
CENOZOIC	QUATERNARY	Drift and alluvium	Drift and alluvium	0-450		Surficial sand and gravel aquifer Till and clay confining units Buried sand and gravel aquifer	Surficial sand and gravel aquifer Till and clay confining units Buried sand and gravel aquifer
MESOZOIC	CRETACEOUS	Carlisle Shale Greenhorn Fm. Graneros Shale Dakota Fm.	--	0-500		Cretaceous aquifers	--
PALEOZOIC	DEVONIAN	Cedar Valley Limestone	--	0-50?		Upper carbonate aquifer	Devonian aquifer
	ORDOVICIAN	Maquoketa Shale	--	0-50?			Maquoketa shale confining unit
		Galena Dolomite	Galena Dolomite	0-110?			Galena-Platteville aquifer
		Decorah Shale	--	0-90		Decorah-Platteville-Glenwood confining unit	
		Platteville Formation	Platteville Formation	0-30			
		Glenwood Shale	Glenwood Shale	0-16			Glenwood confining unit
		St. Peter Sandstone	St. Peter Sandstone	0-130		St. Peter aquifer	St. Peter aquifer
				0-65		Basal St. Peter confining unit	
		Prairie du Chien Group	Prairie du Chien Group	0-335		Prairie du Chien-Jordan aquifer	Prairie du Chien-Trempealeau aquifer
	CAMBRIAN	Jordan Sandstone	Trempealeau Formation	0-130			
		St. Lawrence Formation	St. Lawrence Formation	0-70		St. Lawrence confining unit	St. Lawrence confining unit
		Franconia Formation	Tunnel City Formation	0-200		Franconia-Ironton-Galesville aquifer	Tunnel City-Wonewoc-Eau Claire aquifer
		Ironton Sandstone	Wonewoc Formation	0-100			
		Galesville Sandstone					
		Eau Claire Formation	Eau Claire Formation	0-200		Eau Claire confining unit	
		Mt. Simon Sandstone	Mt. Simon Sandstone	0-200		Mt. Simon-Hinckley-Fond du Lac aquifer	Mt. Simon-Hinckley-Fond du Lac aquifer
PROTEROZOIC	PRECAMBRIAN	Hinckley Sandstone	Bayfield Group				
		Fond du Lac Sandstone		0-650			
		Solor Church Formation	Oronto Group	0-1,100		Undifferentiated PreCambrian sandstone	Undifferentiated PreCambrian sandstone
		Igneous/ metamorphic rocks	Igneous/ metamorphic rocks	UP TO 20,000		Precambrian igneous/ metamorphic aquifers	Precambrian igneous/ metamorphic aquifers

EXPLANATION OF GENERAL LITHOLOGY

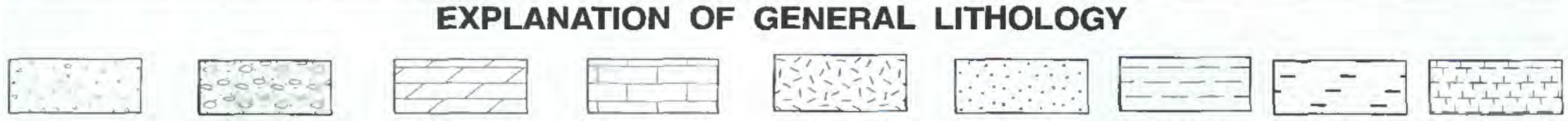


Figure 8.--Generalized hydrogeologic column showing aquifers and confining units in the study unit (modified from Delin and Woodward, 1984; Green, 1977; Olcott, 1992).

Soils

Soil formation is affected by parent materials, climate, relief, living organisms, and time (Anderson and Grigal, 1984). Soils covering the study unit formed since the last glaciers receded. Soil parent materials primarily are glacial deposits except in the southeast where glacial deposits are thin or missing and bedrock is the parent material.

Figure 9 shows the six soil orders in the study unit. Soil orders, the first level of classification for soils, are delineated primarily on the degree of soil horizon development and general characteristics of those horizons (Brady, 1984). Soil orders in the study unit include alfisols, entisols, inceptisols, mollisols, histosols, and spodosols. They are divided into suborders based upon moisture content (or drainage), soil horizon textures, climate, and vegetation (Brady, 1984).

Alfisols, comprised of thin, gray to brown, fertile surface horizons underlain by alluvial clay horizons, cover the northern and eastern parts of the study unit. Alfisols generally form beneath deciduous forests underlain by silty sands. Alfisols generally are present in woodland and mixed woodland and cropland areas underlain by sandy glacial deposits of the Superior, Wadena, and Rainy Lobes. Suborders of alfisols in the study unit include aqualfs (saturated alfisols), boralfs (alfisols of the northern aspen forest), and udalfs (alfisols of moderate saturation) (Anderson and Grigal, 1984; Brady, 1984).

Entisols commonly form on sandy soils in areas of sandy glacial outwash or alluvium. These soils, comprised of recently-formed soils with little soil horizon development, are present in northern and eastern parts of the study unit where unconsolidated sands and gravels were deposited by the Superior, Wadena, and Rainy Lobes. Suborders of entisols include aquents (wet, poorly-developed entisols), fluvents (poorly-drained clayey entisols), and psamments (sandy entisols) (Anderson and Grigal, 1984; Brady, 1984).

Inceptisols, comprised of recently-developed soils with greater degrees of soil horizon development than entisols, are present primarily in the northern part of the study unit, where forests, woodlands, and wetlands are the primary land covers. Suborders of inceptisols in the study unit include aquepts (saturated inceptisols) and ochrepts (inceptisols with thin, light-colored surface horizons) (Anderson and Grigal, 1984).

Mollisols, characterized by a thick, dark, organic-rich, fertile, surface horizon, are present in the south and west. Mollisols generally form on prairies underlain by calcareous sediments such as the calcareous tills and outwash deposited by the Des Moines Lobe. Mollisols are the most productive and intensively cultivated soils in the study unit. Suborders of mollisols include aquolls (saturated mollisols), borolls (cold-climate mollisols), udolls (moist mollisols), and ustolls (intermittently dry mollisols) (Anderson and Grigal, 1984; Brady, 1984).

Histosols consist of yellow-brown to dark black organic-rich soils generally formed in wetlands. They are present primarily in the north. Suborders of histosols include hemists (partially decomposed, peaty histosols), and saprists (highly decomposed histosols) (Anderson and Grigal, 1984).

Spodosols, which consist of soils with light-colored surface horizons and organic and aluminum-rich subsurface horizons, are also present primarily in the northeast. These soils, which are low in natural fertility, are generally formed on sandy, siliceous parent materials primarily covered by coniferous forests. Orthod (leached soils with organic- and aluminum-rich subsurface horizons) is the only suborder of spodosols represented in the study unit (Anderson and Grigal, 1984; Brady, 1984).

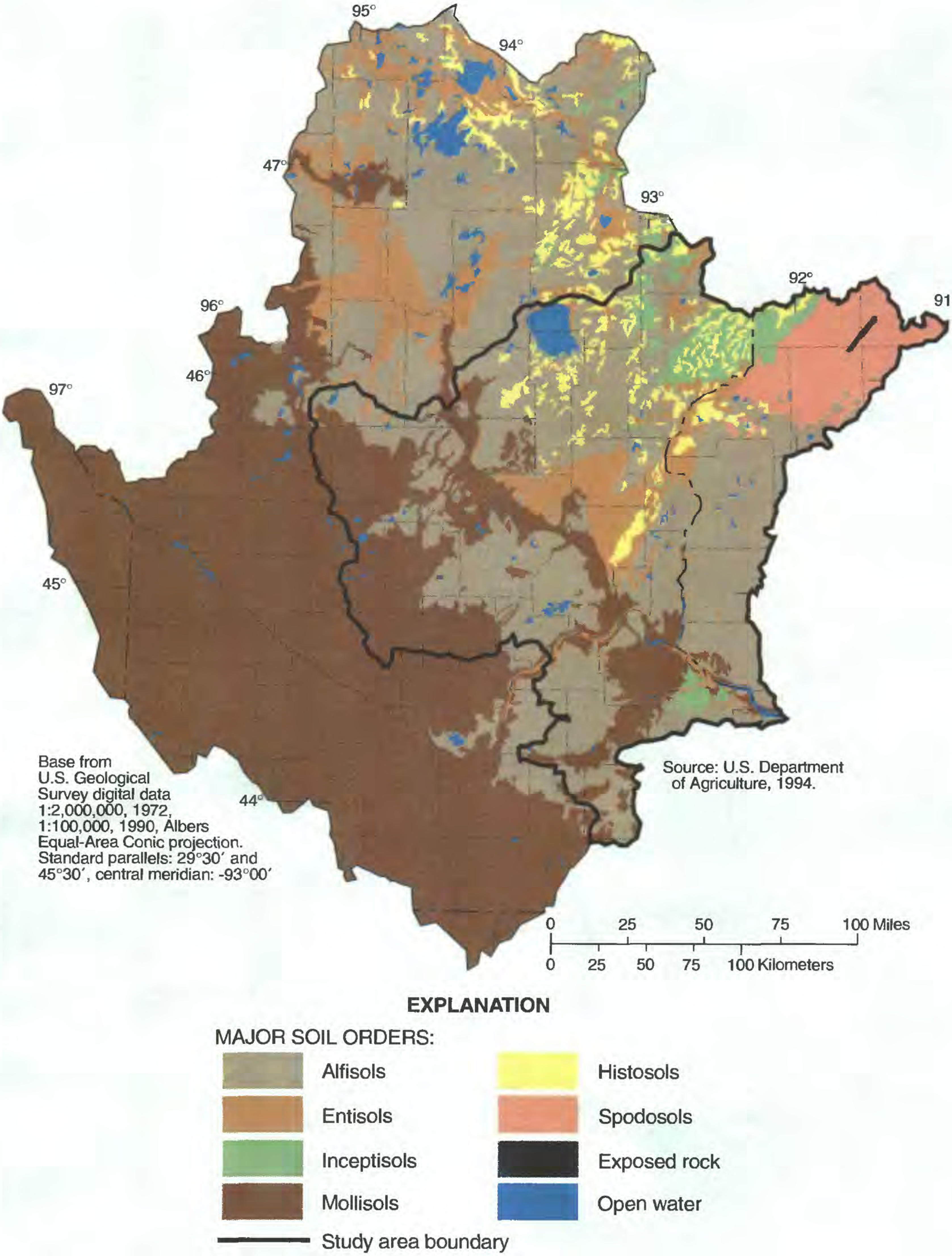


Figure 9.--Generalized soil orders in the Upper Mississippi River Basin study unit.

Hydrologic Setting

From its origin at Lake Itasca to Lake Pepin (fig. 10) the Upper Mississippi River meanders generally southward draining parts of four states and 47,000 mi^2. The river is fed by many small rivers and streams, as well as two major rivers: the Minnesota and the St. Croix. Based on the longest common period of record (1935-93), these two rivers respectively contribute 22 and 26 percent of the mean annual flow (18,600 ft^3/s) of the Mississippi River at Prescott, Wisconsin, station number 05344500 (fig. 10).

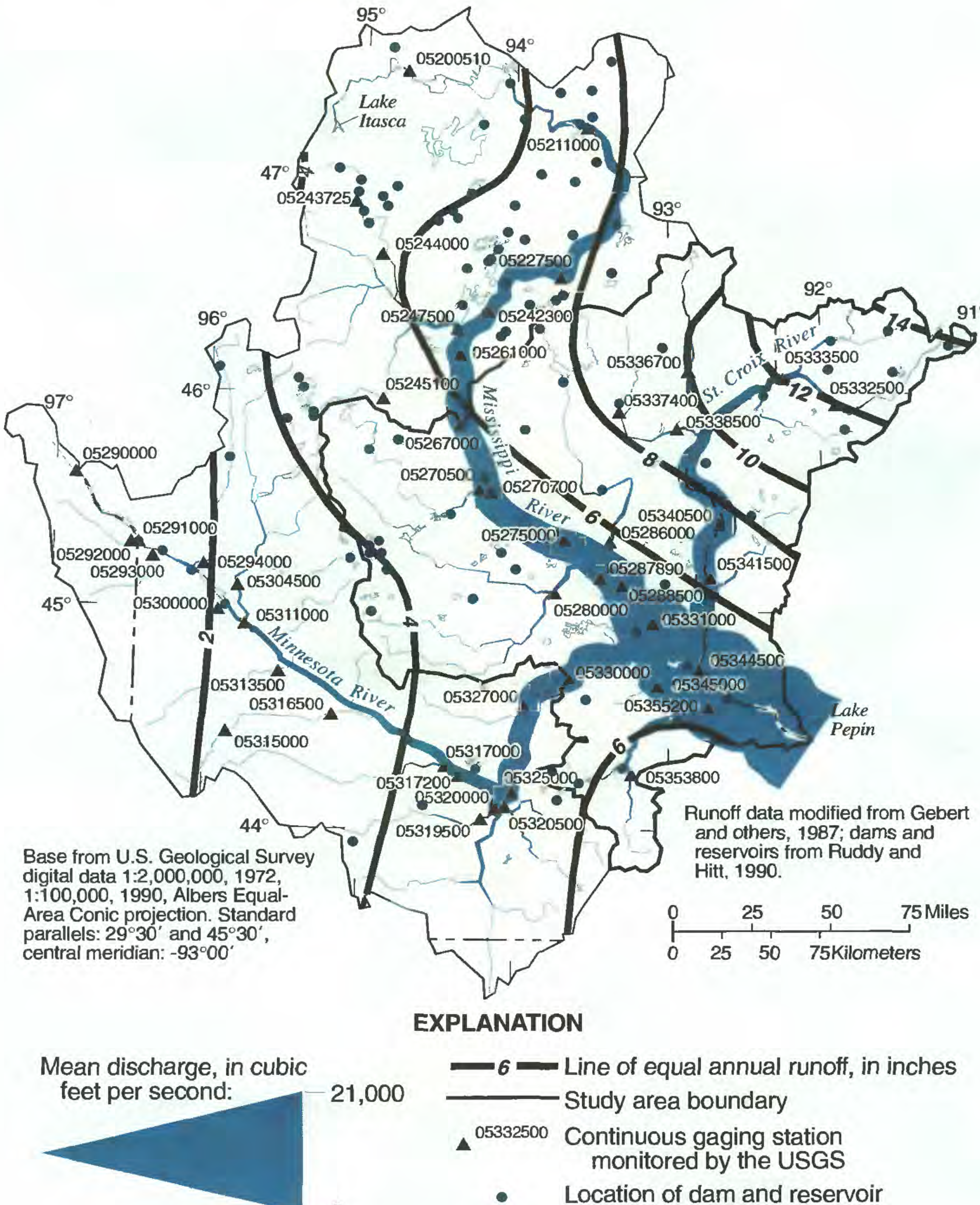


Figure 10.--Mean annual runoff (1951-80), mean annual discharge (1975-93), location of dams and reservoirs, and location of continuous gaging stations in the Upper Mississippi River Basin study unit.

Surface-water hydrology

Average flow of the Minnesota River near Jordan, Minnesota (station number 05330000, about 40 miles upstream from the mouth) is 4,060 ft^3/s. Average flow of the St. Croix River at St. Croix Falls, Wisconsin, station number 05340500, (upstream from its mouth 52 miles) is 4,770 ft^3/s. Downstream of Prescott, the Vermillion and Cannon Rivers contribute most of the remaining streamflow from the study unit. Even though flow contributed by the St. Croix River to the Mississippi River nearly equals that of the Minnesota River, the drainage area of the St. Croix River is only 38 percent as large.

Comparisons of mean annual streamflows normalized for drainage area can be made with mean annual runoff (the depth to which the drainage area would be covered if all runoff were evenly distributed). Across the study unit, mean annual runoff increases from west to east: from less than 2 inches in the headwaters of Minnesota River to more than 14 inches in the upper St. Croix and Namekagon Rivers (fig. 10). The headwaters of the St. Croix River yield the most annual runoff because precipitation is greater than potential evapotranspiration. Conversely, streams in the west yield less runoff because potential evapotranspiration is greater than mean annual precipitation. Other factors that affect runoff include wetlands, lakes and impoundments, and differences in soils, topography, land use, and vegetation.

In addition to annual runoff, other characteristics important to describing streamflow include seasonal and annual variations in flow (Linsley and others, 1982). Seasonal variations in streamflow for the Mississippi River near Anoka, the Minnesota River near Jordan, and the St. Croix River at St. Croix Falls (fig. 11) show that streamflow is generally greatest in spring and early summer as a result of melting snow, rains falling on melting snow, or heavy rains falling on saturated soils. Streamflow varies least during winter when ground-water contributions to streamflow predominate and varies most during late summer and fall when spotty rains and thunderstorms typically occur. Streamflows during most of the year are less than one-fourth of the flows indicated by the average annual flow.

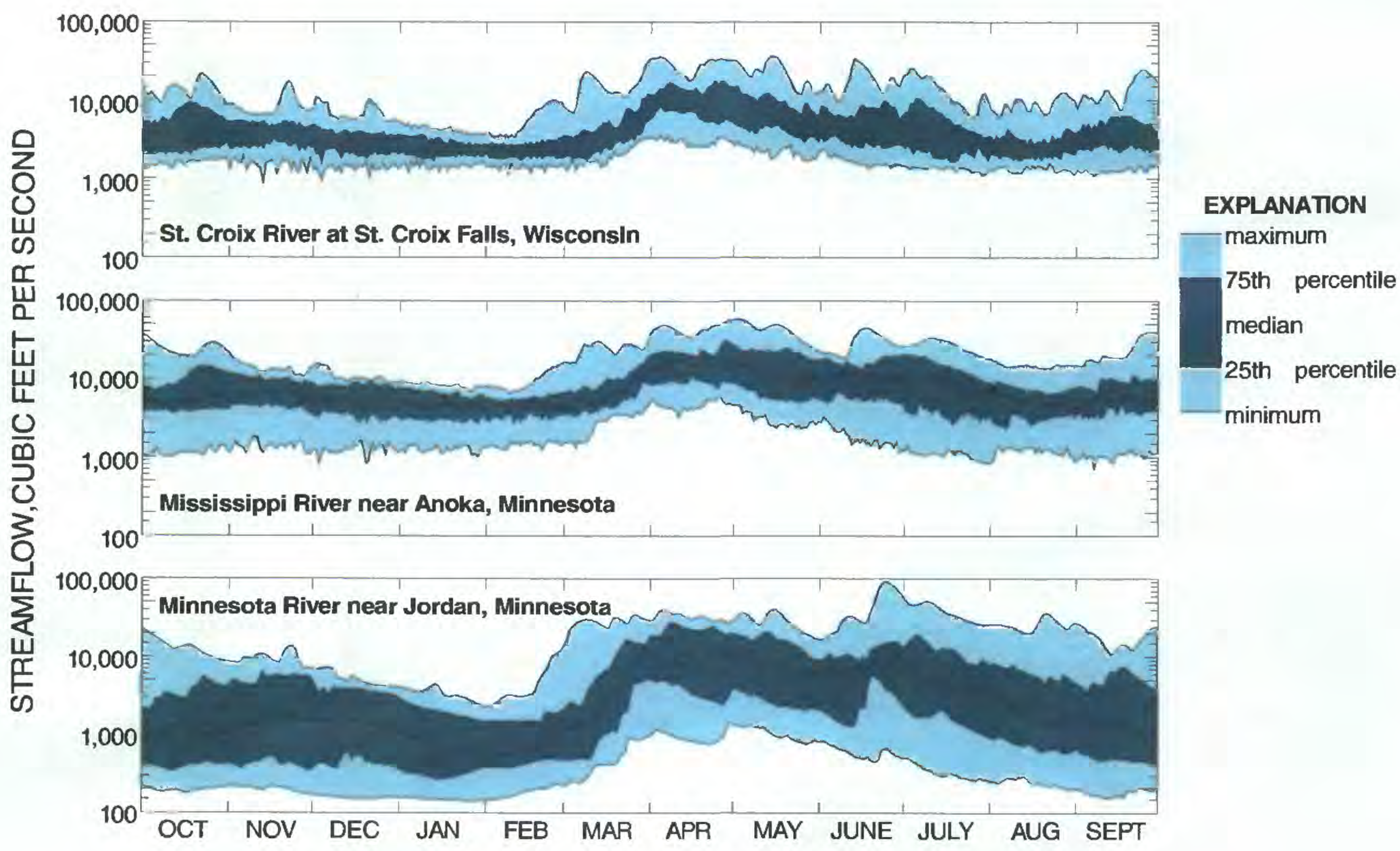


Figure 11.--Hydrographs showing seasonal variations in streamflow at Anoka and Jordan, Minnesota and at St. Croix Falls, Wisconsin, 1975-1993.

Table 1 shows mean annual streamflow coefficients of variation from 1975-93 for streams in the study unit. The larger coefficients of variation found in the Minnesota River Basin most likely result from variable annual precipitation. In contrast, the Mississippi River upstream of Royalton and the St. Croix River have smaller coefficients of variations as a result of more regular annual precipitation and increased storage in lakes and permeable surficial aquifers. Coefficients of variation can be affected by reservoir regulation. Although reservoirs can reduce streamflow variability, most reservoirs in the study unit have residence times of less than one year, so their effects on annual streamflow variation are minimal.

Floods and droughts pose potential threats that test the limits of engineering, agricultural and urban development. The primary causes of flooding include excessive precipitation falling on saturated or impermeable soils, frozen ground or snow, and rapid snowmelt resulting from sudden temperature increases (Engleman, 1983). Table 1 lists annual runoff at selected gaging stations during years in which floods and droughts persisted. The floods of 1965 and 1969 were caused by rapid snowmelt and spring rainfall (Carlson and others, 1991), while the flood of 1993 was caused by excessive summer precipitation (Parrett and others, 1993). Flooding on the St. Croix River has historically been less severe than flooding on the Minnesota and Mississippi Rivers because of the physical characteristics of the basin: greater soil permeability, greater surface-water storage, and restriction of portions of the channel by deep incision in bedrock (Helgesen and others, 1973; Lindholm and others, 1974b; Young and Hindall, 1973).

Droughts frequently persist for periods of time longer than a year. As periods of drought persist, soil moisture becomes depleted and ground-water discharge to streams is reduced resulting in below normal streamflow (Rogers and Armbruster, 1990). Table 1 lists mean annual runoff for selected stations during periods of drought. Annual runoffs listed for 1934 represent the most severe year of drought in the study unit. Annual runoff during 1976 represents the first year of a two-year drought which was second in severity only to the drought of 1934. Severe drought conditions also developed again in 1987-88; flow in the Mississippi River dropped to levels previously reached only in 1934 and 1976.

Lakes, and wetlands are common features over much of the study unit. Natural lakes, ranging in surface area from 10 to 160,000 acres (Walton, 1975), comprise at least 10 percent of the land surface in areas covered by glacial terminal moraines (Borchert and Gustafson, 1980). Lake Pepin formed when sediments from the Chippewa River were deposited in the Mississippi River Valley, constricting and pooling the flow of the Mississippi River (Winter and Woo, 1990). Lake St. Croix (fig. 2) formed from similar processes (Troelstrup and others, 1993).

The drainage patterns in the study unit were unaffected by anthropogenic activities prior to the late 1800's. Since then drainage and channelization has altered the natural drainage, especially in the southwest. Leach and Magner (1992) determined that 80 percent of the wetlands in the Minnesota River Basin had been drained. Anthropogenic activities have transformed a geomorphologically immature land-marsh drainage system into a mature fluvial system.

Wetlands in the northern part of the study unit have not been drained extensively because differences in climate and soils make crop land less productive. However, some wetlands along the Upper St. Croix River are used for commercial cranberry production. Water levels in these wetlands are regulated and concern exists about the effects of these wetlands on water quality of the St. Croix River (Wisconsin Department of Natural Resources, 1994).

Figure 10 shows locations of dams and reservoirs. According to Ruddy and Hitt (1990), of the 102 reservoirs with surface areas greater than 5,000 acre-ft or maximum capacities greater than 25,000 acre-ft, 13 are used primarily for flood control, 12 for hydroelectric production, 8 for recreation, 3 for navigation and 1 for water supply. Pool elevation and discharges from these reservoirs are regulated by various Federal, State, local and private agencies and organizations. Headwater reservoirs of the Mississippi River augment streamflow for navigation during periods of low flow on the Lower Mississippi River.

Table 1.—Streamflow characteristics for selected gaging stations in the Upper Mississippi River Basin study unit
[--, data not available]

Gaging station name (stations listed in downstream order)	Gaging station number (fig. 10)	Drainage area (square miles)	Mean annual streamflow, 1975-93 (cubic feet per second)	Mean annual runoff, 1975-93 (inches)	Coefficient of variation of mean-annual streamflow, 1975-93	Flood years			Drought years		
						Annual runoff in inches, water years					
						1965	1969	1993	1934	1976	1988
Mississippi River near Aitkin, Minn.	05227500	6,140	2,810	6.21	36.6	7.95	8.16	7.00	--	4.45	3.74
Mississippi River near Royalton, Minn.	05267000	11,600	5,220	6.11	39.6	8.39	7.50	7.60	1.43	3.78	3.10
Crow River at Rockford, Minn.	05280000	2,520	1,140	6.14	68.4	7.86	7.80	12.07	--	2.04	.95
Mississippi River near Anoka, Minn.	05288500	19,100	9,020	6.41	41.0	8.32	8.04	7.93	--	4.17	2.78
Minnesota River near Ortonville, Minn.	05292000	1,160	112	1.31	110.3	1.76	2.84	4.86	--	.30	.08
Pomme de Terre River at Appleton, Minn.	05294000	905	132	1.98	72.8	3.15	3.64	4.51	--	.96	.43
Yellow Medicine River near Granite Falls, Minn.	05313500	653	178	3.70	92.7	4.15	7.71	11.76	--	.53	.87
Redwood River near Redwood Falls, Minn.	05316500	629	208	4.49	95.5	3.61	7.38	17.02	--	.56	.87
Cottonwood River near New Ulm, Minn.	05317000	1,280	501	5.30	92.7	7.14	12.62	19.04	--	.96	1.33
Little Cottonwood River near Courtland, Minn.	05317200	230	71.8	4.24	84.9	--	--	14.08	--	.68	.83
Watonwan River near Garden City, Minn.	05319500	812	400	6.69	90.9	--	--	22.23	--	--	1.24
Blue Earth River near Rapidan, Minn.	05320000	2,430	1,280	7.15	85.3	10.40	13.18	25.24	--	0.79	2.04
Le Sueur River near Rapidan, Minn.	05320500	1,100	623	7.69	78.4	11.16	13.32	25.06	--	0.89	2.66
Minnesota River at Mankato, Minn.	05325000	14,900	4,740	4.32	76.7	5.92	7.90	13.56	0.12	.74	1.06
Minnesota River near Jordan, Minn.	05330000	16,200	5,410	4.53	75.8	6.02	8.09	14.18	--	.84	1.10
Mississippi River at St. Paul, Minn.	05331000	36,800	13,900	5.13	50.7	7.37	8.29	10.65	--	2.59	2.02
Kettle River near Sandstone, Minn.	05336700	863	682	10.7	40.8	--	--	12.79	--	7.30	5.02
St. Croix River at St. Croix Falls, Wisc.	05340500	6,240	4,920	10.7	31.6	11.14	13.08	10.79	3.80	9.11	6.03
Mississippi River at Prescott, Wisc.	05344500	44,800	20,900	6.33	42.0	8.27	8.74	10.84	1.32	3.72	2.65
Straight River near Faribault, Minn.	05353800	442	290	8.91	62.4	--	11.88	23.18	--	1.55	3.87

Surface-water quality

The quality of water in rivers and streams in the study unit is affected by both natural and anthropogenic factors. Natural factors that affect stream-water quality include the climate, ecology, physiography, geology, and soil type. Anthropogenic factors include runoff from agricultural and urban areas and municipal and industrial discharges of wastewater. Construction of locks and dams on the Mississippi River during the 1930's greatly affected water quality by transforming the river from a free-flowing stream into a series of slack-water pools. General water quality is illustrated using data collected from USGS NASQAN stations (1977-94) located at the Mississippi River near Royalton (05267000); Minnesota River near Jordan (05330000); Mississippi River at Nininger (05331570); and the St. Croix River at St. Croix Falls (05340500) (figs. 12 and 13).

Streamflow influences water quality in the study unit. Alkalinity, hardness, dissolved-solids concentrations, and specific conductance generally are inversely related to flow, and concentrations of these constituents are generally greatest during low-flow conditions when most streamflow is from ground water (Cotter and Bidwell, 1968; Have, 1991; Helgesen and others, 1975; Van Voast and others, 1970). Studies (Minnesota Pollution Control Agency, 1989b; Kroening, 1994) have shown that phosphorus concentrations in the Mississippi River navigation pools and in Lake Pepin are greatest during years having extremely low river flow. Water residence time in the navigation pools and in Lake Pepin is greatest during low flow and, combined with elevated nutrient concentrations and reduced suspended-sediment concentrations, enhance phytoplankton development (Minnesota Pollution Control Agency, 1989b).

Alkalinity and dissolved-solids concentrations in streams are controlled by the composition of rocks and soils. Data collected by the USGS (Anderson and others, 1974a, b, and c; Ericson and others, 1974; Helgesen and others, 1975; Lindholm and others, 1974a; Young and Hindall, 1973) and Waters (1977) indicate that alkalinity and dissolved-solids concentrations generally increase from the northeast to the south (fig. 12). Alkalinities range from less than 50 mg/L in the upper St. Croix, Kettle, and Snake River Basins to greater than 200 mg/L in the Minnesota River Basin. Lower alkalinities in the upper St. Croix River Basin are the result of drainage from basins having relatively insoluble siliceous soils and geologic deposits (Waters, 1977). In the Minnesota River Basin, greater alkalinities are due to drainage from basins developed in soils and geologic materials that are rich in carbonates and shale (Lindholm and others, 1974a; Magner and Alexander, 1993). Alkalinities also are high (with a median of approximately 225 mg/L) in the Cannon River, probably due to drainage from limestone bedrock (Waters, 1977). In the Mississippi, Rum, and Crow Wing Rivers, alkalinities generally vary from 100 to 150 mg/L (Waters, 1977). In the Mississippi River at Nininger, below the confluence of the Minnesota and Mississippi Rivers, greater alkalinities and dissolved-solids concentrations occur due to mixing with water from the Minnesota River.

Suspended sediment in the streams is the result of erosion. Erosion can be accelerated by land-cover disturbances from agriculture, construction, aggregate mining, forestry, and stream-bank and bed erosion. Elevated suspended-sediment concentrations adversely affect aquatic life and transport nutrients, trace elements, and organic compounds that are sorbed to particle surfaces. Sediment yield increases from north to south across the study unit (Nielsen and others, 1984). Suspended-sediment concentrations are greater in the Minnesota River (fig. 12) which drains areas with intensive cropland. Suspended-sediment concentrations in the lower parts of the Minnesota River frequently are greater than the turbidity standard of 25 Nephelometric Turbidity Units (NTU) (Metropolitan Waste Control Commission, 1994b). The primary contributors of suspended sediment in the Minnesota River are the tributary watersheds in the central and southeastern portions of the Minnesota River Basin (Payne, 1994).

Suspended-sediment distributions in the Mississippi River are primarily affected by locks and dams and loading from the Minnesota River. At Nininger, suspended-sediment concentrations show an increase because of the suspended sediment contributed by the Minnesota River (Payne, 1994). Farther downstream, data collected by the Metropolitan Waste Water Control Commission (1993b) show average suspended-solids concentrations decrease to approximately 30 mg/L at Lock and Dam 3 (fig. 2) because of deposition in the lower reaches of the navigation pools (Nielsen and others, 1984). At the outlet of the study unit, the Mississippi River is relatively clear because most of the sediment has been deposited in Lake Pepin (Nielsen and others, 1984).

A drinking water standard for nitrate ($NO_2 + NO_3$ as N) of 10 mg/L has been established by the USEPA to protect human health (U.S. Environmental Protection Agency, 1994). Sources of nitrate include fertilizers, animal wastes, and wastewater effluent. Nitrate concentrations in the Minnesota River (fig. 12) are

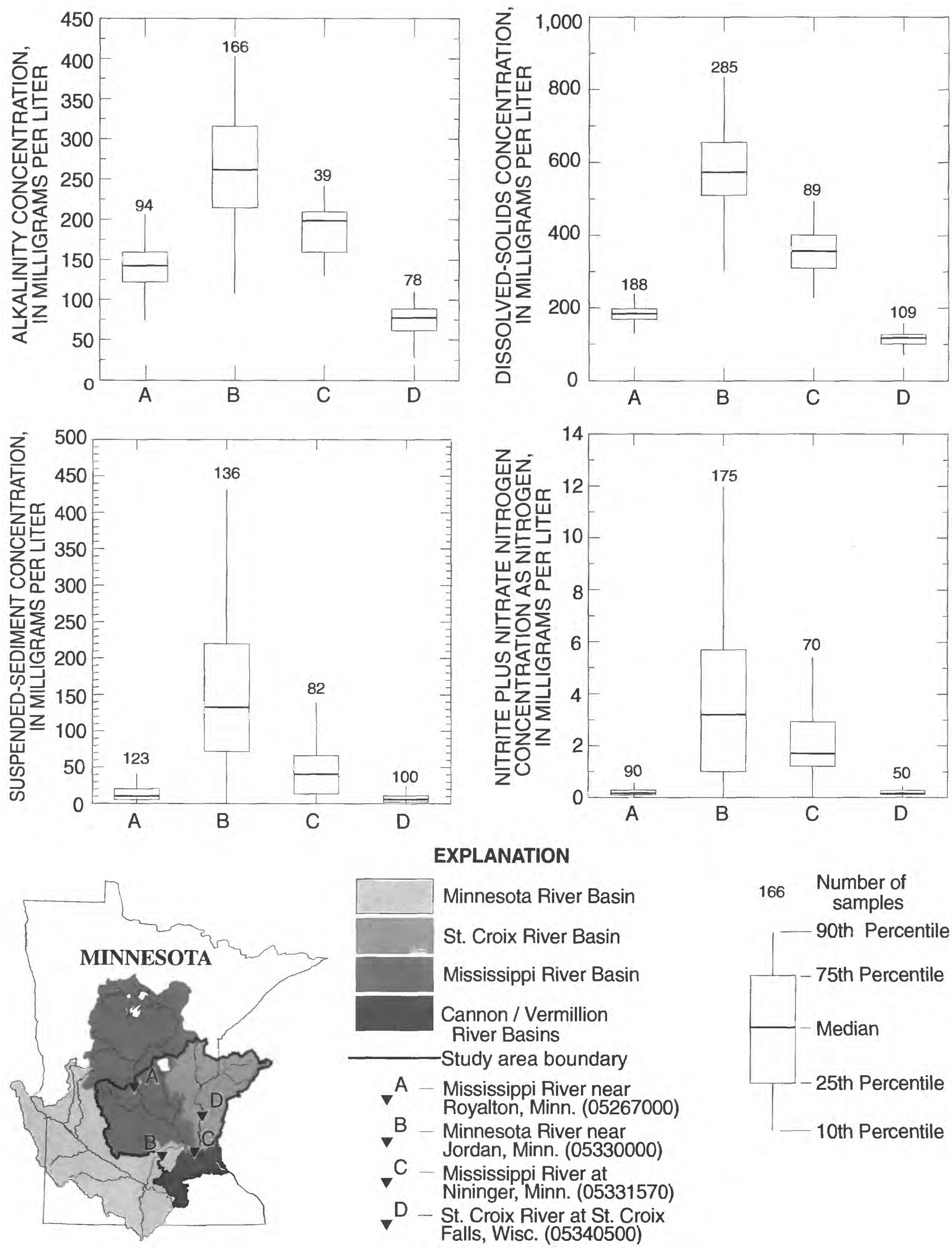


Figure 12.--Generalized water quality at selected sites in the Upper Mississippi River Basin study unit, 1977-94.

elevated over background concentrations and periodically exceed the drinking water standards during spring runoff (Payne, 1994). Tributary watersheds are the primary contributors for nitrate (Payne, 1994). A study of the lower 40 miles of the Minnesota River by the Metropolitan Waste Control Commission (1994b) determined that nitrate concentrations were highest in the tributaries draining extensively tiled watersheds. Concentrations also were elevated in the Mississippi River at Nininger, due to nitrate from the Minnesota River and direct discharges of wastewater effluent, primarily within the TCMA. Nitrate concentrations are low in the St. Croix River and in the Mississippi River above Royalton, both of which drain areas with greater proportions of forested land.

Dissolved oxygen is necessary for the survival of aquatic life. Have (1991) and Graczyk (1986) indicate dissolved-oxygen concentrations in the Mississippi River from Royalton, Minn. to Hastings, Minn. and in the St. Croix River generally exceed the 5 mg/L water-quality standard for the protection of aquatic life (U.S. Environmental Protection Agency, 1986) (fig. 13). Dissolved oxygen concentrations are influenced mainly by water temperature (Have, 1991). Low dissolved-oxygen concentrations, related to blue-green algal blooms, caused fish kills in Lake Pepin during the summer of 1988—an abnormally dry period (Minnesota Pollution Control Agency, 1989b). In the TCMA, point and non-point sources of oxygen-demanding substances also have a significant effect on oxygen concentrations and point and nonpoint sources of oxygen demanding substances have caused violations of the dissolved-oxygen standard in the Mississippi and Minnesota Rivers, primarily below wastewater-treatment-plant outfalls (Johnson and Aasen, 1989; Minnesota Pollution Control Agency, 1985). In the Mississippi River, dissolved-oxygen concentrations typically decrease below the Metropolitan Wastewater Treatment Plant (fig. 2) outfall and begin to increase about twenty miles downstream.

Fecal coliform bacteria in water indicate the presence of sewage or manure. The presence of these bacteria in a stream can also indicate the presence of disease-causing organisms. At the NASQAN sites, fecal bacteria counts are highest in the Minnesota River near Jordan and in the Mississippi River at Nininger (fig. 13). Payne (1994) showed that approximately 40 percent of the samples collected in the Minnesota River Basin exceeded the 200 colonies/100 mL ambient water-quality standard (U.S. Environmental Protection Agency, 1986). Water-quality data collected by the Metropolitan Waste Control Commission (1994a) show that 25 percent of the water samples collected in the Mississippi River just downstream of the Minnesota River and the Metropolitan Wastewater Treatment Plant outfall exceeded the 200 colonies/100 mL water-quality standard.

Trace elements are metals and metalloids which usually are present at concentrations less then 1.0 mg/L. Anthropogenic activities have a strong influence on the presence of many of these trace elements in both stream water and sediment. Industrial societies use large quantities of many elements that would otherwise not be readily available for solution in natural waters. The TCMA is the largest source of trace elements in the study unit. Trace-element data collected in the TCMA during 1992 by the Metropolitan Waste Control Commission (1994a) show concentrations of most constituents, with the occasional exception of total mercury and copper, are generally below ambient or drinking-water quality standards. Data collected by Graczyk (1986) in the St. Croix River Basin show concentrations of iron and manganese at some sites exceeded the Secondary Maximum Contaminant Levels (SMCL's) set by the USEPA for drinking water of 300 μg/L and 50 μg/L, respectively (U.S. Environmental Protection Agency, 1988).

Studies of riverine systems have shown that concentrations of trace elements in bed sediments can be substantially elevated for considerable distances downstream from a major discharge point. A study of the Mississippi River by Wiener and others (1984) determined that concentrations of cadmium, lead, and mercury were generally greater in bed sediment samples from navigation pools 1, 2, and 4 (fig. 13) than in samples taken at other upstream sites. In pools sampled downstream of the study unit, concentrations of cadmium, copper, lead, and zinc in bed sediments are significantly lower than concentrations found in Lake Pepin (pool 4) (Bailey and Rada, 1984).

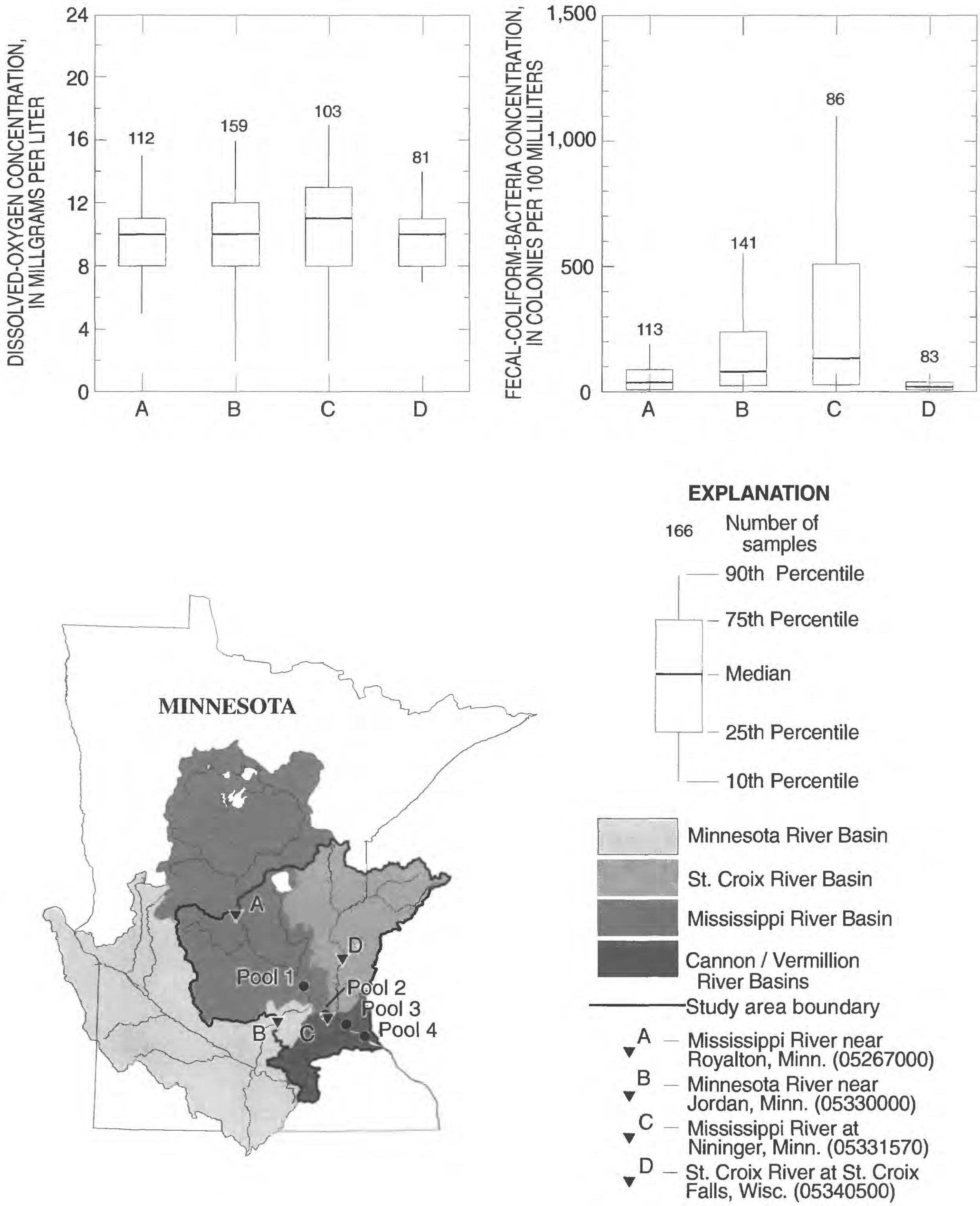


Figure 13.--Generalized water quality at selected sites and location of selected navigation pools on the Mississippi River in the Upper Mississippi River Basin study unit, 1977-94.

Ground-water hydrology

Aquifers, ranging in age from Quaternary to Precambrian, are sources of water in the study unit. Ground water is the source of drinking water to 75 percent of the total population. Ground water is used by 59 percent of the urban population and 98 percent of the rural population (Leete, 1991; Trotta, 1996). Ground water is present in surficial sand and gravel aquifers and in buried sand and gravel aquifers throughout the study unit. In addition, ground water is present in a bedrock aquifer system of Precambrian to Ordovician age in the southeast, in scattered sandstone aquifers of Cretaceous age in the west, and in Precambrian igneous/metamorphic aquifers in the north. Surficial and buried sand and gravel aquifers and aquifers consisting of sedimentary rocks of Precambrian to Ordovician age are the most developed aquifers in the study unit.

Permeable sand and gravel deposited as glacial outwash or as alluvium (surficial and buried sand and gravel aquifers) supply water primarily to shallow domestic wells in the study unit. Glacial meltwaters deposited sand and gravel as much as 600 ft thick along drainage courses in bedrock valleys (Woodward, 1986). Surficial sand and gravel aquifers, which cover about one-third of the study unit (fig. 14), consist primarily of glacial outwash, but also include alluvium and ice-contact, valley-train and terrace deposits (Ruhl, 1987). The Anoka Sand Plain aquifer (fig. 14) is a major surficial sand and gravel aquifer comprised of glacial outwash covering 1,700 mi^2 of the central part of the study unit. Water-table altitudes of surficial sand and gravel aquifers are highly variable, as are well yields, which range from 10 to 1,000 gal/min (Delin and Woodward, 1984).

Buried sand and gravel aquifers consist of lenses or layers of sand and gravel that are overlain by clay or till. Buried sand and gravel aquifers generally are located in areas where unconsolidated materials exceed 100 ft in thickness. Buried sand and gravel aquifers are located primarily in the west and north (Ruhl, 1987), although localized buried sand and gravel aquifers are also located locally in the east.

The principal bedrock aquifers in the study unit consist of sedimentary rocks deposited in a depression known as the Hollandale embayment in the eastern portion of the study unit (fig. 15). The bedrock hydrogeologic system of the Embayment can be divided into several aquifers separated by confining units. The principal aquifers are, in descending order, the St. Peter, the Prairie du Chien-Jordan, the Franconia-Ironton-Galesville, and the Mt. Simon-Hinckley-Fond du Lac (fig. 15). The bedrock aquifers in order of decreasing use, are the: 1) Prairie du Chien-Jordan, 2) Mt. Simon-Hinckley-Fond du Lac, 3) Franconia-Ironton-Galesville, and 4) St. Peter (Norvitch and others, 1973). Major confining units in the Embayment include the Decorah-Platteville-Glenwood, the basal St. Peter, the St. Lawrence and the Eau Claire. Precambrian igneous and metamorphic bedrock underlies these bedrock units and the entire study unit. In some of the western and northern parts of the study unit where more productive sand and gravel or bedrock aquifers are not present, Cretaceous aquifers or aquifers composed of Precambrian igneous/metamorphic rocks supply limited quantities of water (Woodward and Anderson, 1986; Anderson, 1986).

Where not overlain by confining glacial tills or by younger bedrock confining units, bedrock aquifers in the study unit are recharged by leakage from overlying sand and gravel aquifers. Permeability in these bedrock aquifers ranges from primary in aquifers composed of sandstone, to secondary associated with fractures, solution cavities, and joints in aquifers composed of carbonate, igneous, and metamorphic rocks. Water in bedrock aquifers as deep as the Franconia-Ironton-Galesville aquifer generally discharge to major rivers. Water in the deeper Mt. Simon-Hinckley-Fond du Lac aquifer, generally flows laterally toward cones of depression centered around major pumping centers in Minneapolis and St. Paul (Andrews and others, 1995a).

In the southwestern part of the study unit, discontinuous sandstone aquifers of Cretaceous age (fig. 15) supply up to 25 gal/min of water to domestic and agricultural wells (Woodward and Anderson, 1986; Adolphson and others, 1981). Relatively high concentrations of dissolved solids, chloride, and sulfate, low well yields, and depth below land surface limit the use of these aquifers to areas where overlying sand and gravel aquifers are thin or are of low hydraulic conductivity (Woodward and Anderson, 1986).

The Upper Carbonate aquifer, composed of up to 250 ft of the Galena Dolomite and Maquoketa Shale of Ordovician age, and the Cedar Valley Limestone of Devonian age, is present only in the south. The Upper Carbonate aquifer yields water from fractures, joints and solution channels in carbonate rocks (Ruhl and Wolf, 1984). Measured hydraulic conductivities in this aquifer range from 3 to 40 ft/d, and yields from wells completed in this aquifer are highly variable, ranging from 100-500 gal/min (Delin and Woodward, 1984; Kanivetsky and Walton, 1979).

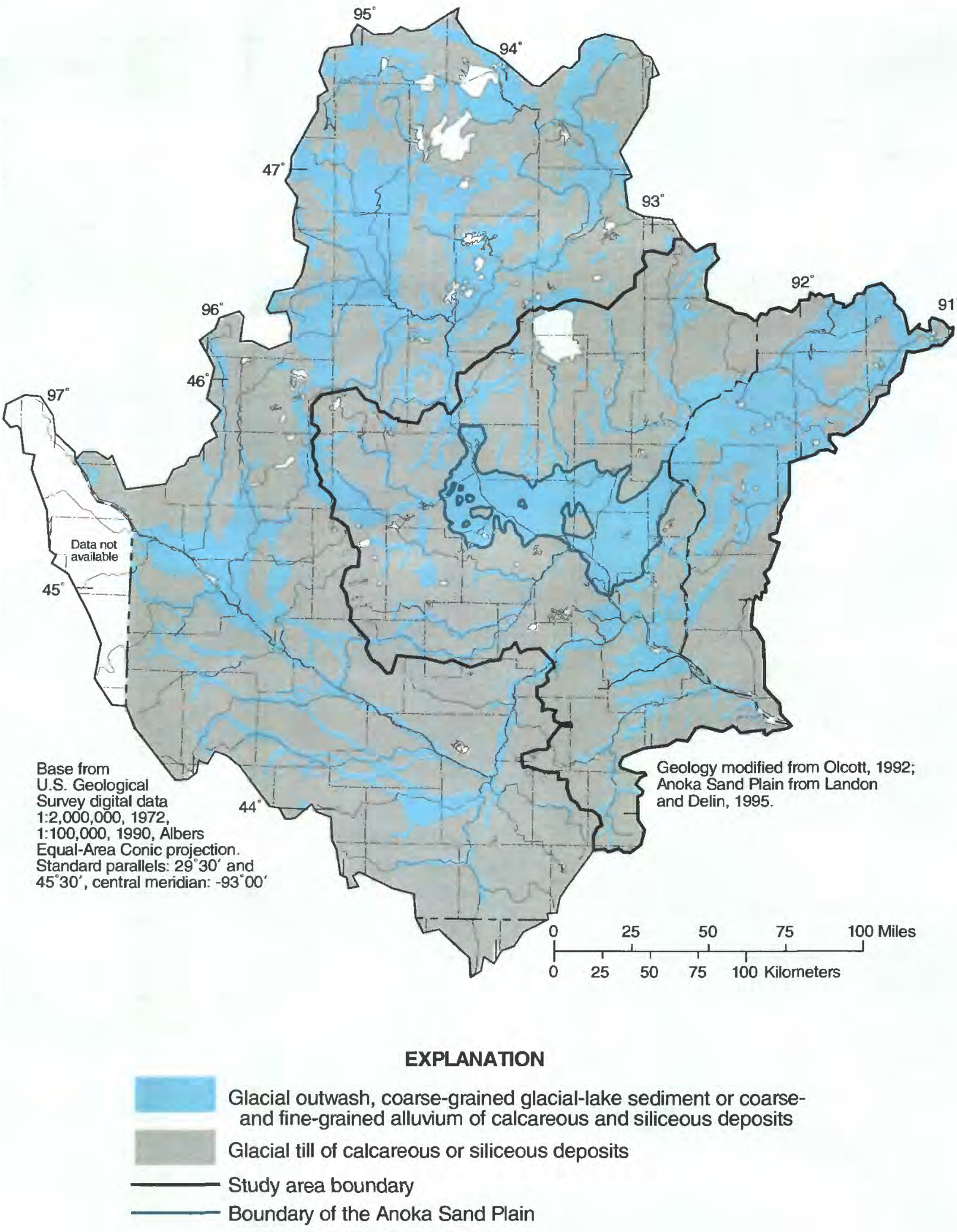


Figure 14.--Surficial geology in the Upper Mississippi River Basin study unit.

Although it is part of the Decorah-Platteville-Glenwood confining unit, the Platteville Formation, composed of up to 20 ft of thin-to medium-bedded dolomitic limestone and dolomite, interbedded with thin shale beds, is a local source of limited supply of water for domestic use in the study unit in areas where overlying aquifers are not sufficient sources of water. Wells completed in this aquifer range from 200-500 gal/min (Kanivetsky and Walton, 1979).

The St. Peter aquifer is composed of the upper part of the St. Peter Sandstone (fig. 15). The St. Peter Sandstone consists of an average of 100 ft of fine- to medium-grained, well sorted, massive, poorly-cemented yellow or white quartz sandstone, underlain by 5-80 ft of sandy shale (Ruhl and Wolf, 1983). Wells completed in the St. Peter aquifer yield from 100-250 gal/min (Kanivetsky and Walton, 1979). The St. Peter aquifer is not heavily developed in the study unit because of its limited extent and larger yields obtainable from underlying aquifers.

The Prairie du Chien-Jordan aquifer, the primary source of ground water for public water supplies in the TCMA, consists of up to 350 ft of sandy dolomite and sandstone of the Prairie du Chien Group of Ordovician age and the Jordan Sandstone of Cambrian age. Wells completed in this aquifer yield up to 1000 gal/min (Kanivetsky and Walton, 1979). The Prairie du Chien-Jordan aquifer is used for supplemental water supplies for St. Paul and is the principal source of water for suburban communities in the TCMA, supplying approximately 75 percent of the ground water withdrawn in the area (Metropolitan Council, 1992).

The Franconia-Ironton-Galesville aquifer (fig. 15) is composed of the Franconia Formation and the Ironton and Galesville Sandstones of Cambrian age. These formations consist of up to 300 ft of very-fine to coarse-grained silty sandstone and sandstone interbedded with shale, dolomitic sandstone, and dolomitic siltstone (Adolphson and others, 1981). The Franconia Formation is composed of generally fine-grained, lower-conductivity siltstones. Yields of wells completed in the Franconia-Ironton-Galesville aquifer range from 250-500 gal/min (Kanivetsky and Walton, 1979). The Franconia-Ironton-Galesville aquifer is an important source of water beyond the extent of the Prairie du Chien-Jordan aquifer in the study unit (Adolphson and others, 1981). The Franconia-Ironton-Galesville aquifer is most intensely developed in the north and northwestern parts of the Hollandale Embayment and adjacent to the Mississippi and Minnesota Rivers in the TCMA (Delin and Woodward, 1984).

The Mt. Simon-Hinckley-Fond du Lac aquifer consists of up to 850 ft of the Fond du Lac and Hinckley Sandstones of Precambrian age and the Mt. Simon Sandstone of late Cambrian age. The relatively great thickness and the high quality of water make the Mt. Simon-Hinckley-Fond du Lac aquifer an important source of water in the study unit, supplying 7 percent of ground water withdrawals in the TCMA, primarily for industrial uses (Metropolitan Council, 1992). Because the aquifer is confined by the overlying Eau Claire confining unit in the TCMA, pumping from this aquifer has caused cones of depression in the potentiometric surface as deep as 200 ft around pumping centers (Schoenberg, 1990; Andrews and others, 1995a). Yields to wells completed in this aquifer are typically about 500 gal/min, but are locally as high as 2,000 gal/min (Adolphson and others, 1981).

Precambrian igneous/metamorphic aquifers include igneous, metasedimentary and undifferentiated rocks (Anderson, 1986). The aquifer provides limited water supplies to domestic and public wells where overlying glacial deposits are thin or of low permeability in the northern and western portions of the study unit. Aquifers composed of these Precambrian-age rocks generally yield from 1 to 25 gal/min to wells completed in fractures and weathered regolith, but yields as high as 150 gal/min are obtained locally (Anderson, 1986; Adolphson and others, 1981).

Using base-flow analysis and ground-water modeling, Schoenberg (1990) estimated regional recharge rates of 6-8 in./yr to surficial sand and gravel aquifers, 4-6 in./yr to unconfined bedrock aquifers, and 0.4-2.0 in./yr to confined bedrock aquifers. Water moves through sand and gravel and bedrock aquifers in the study unit in complex regional and local flow systems. In surficial sand and gravel aquifers, ground water flows from topographically high areas to low-lying wetlands and streams. Potentiometric-surface altitudes measured in the Prairie du Chien-Jordan aquifer indicate that water in this aquifer flows from its northern, southern, and western limits toward the incised valleys of the Mississippi, Minnesota, and St. Croix Rivers (Andrews and others, 1995a). Water in the Mt. Simon-Hinckley-Fond du Lac aquifer similarly flows from its areas of subcrop toward cones of depression caused by withdrawals in the TCMA (Andrews and others, 1995a).

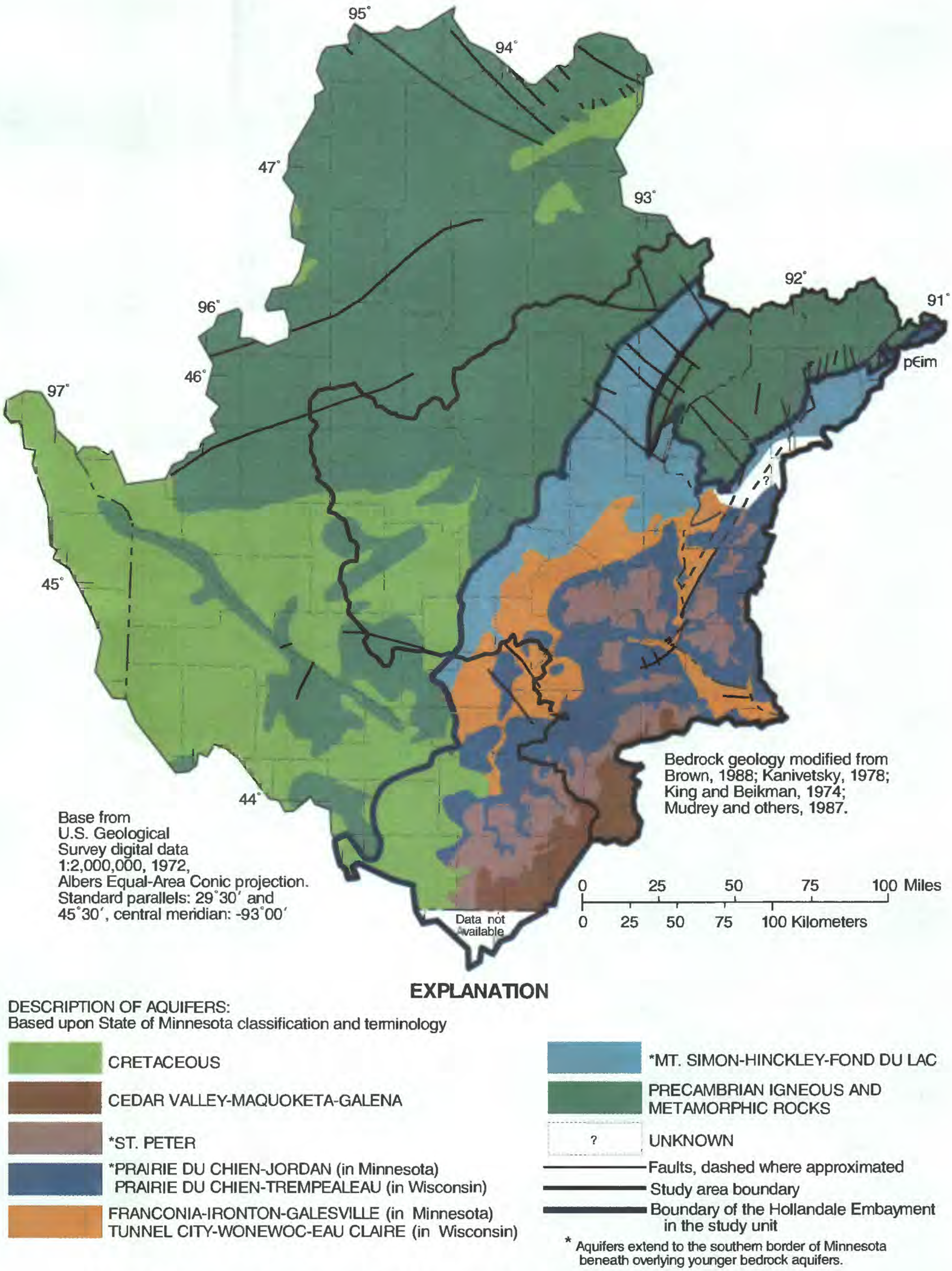


Figure 15.--Bedrock hydrogeology of the Upper Mississippi River Basin study unit.

Ground-water quality

The quality of ground water in the study unit is generally satisfactory for most domestic, public, industrial, and irrigation uses (Kanivetsky, 1986). Except for the Cretaceous aquifers, ground water generally contains less than 1,000 mg/L of dissolved solids (fig. 16). Freshwater generally extends to depths of about 1,000 ft in the center of the Hollandale Embayment and in the TCMA. Most of the ground water in the study unit is of the calcium-magnesium-bicarbonate type (Adolphson and others, 1981). However, naturally present saline water (exceeding 1,000 mg/L dissolved solids) is common in Paleozoic rocks below depths of about 1,000 ft in the south, near Lake Pepin. Concentrations of iron and manganese commonly exceed 300 µg/L and 50 µg/L, respectively, which are the SMCL's for these constituents in drinking water (U.S. Environmental Protection Agency, 1994). Concentrations of sulfate in water from Cretaceous and sand and gravel aquifers in southwestern Minnesota commonly exceed the USEPA's SMCL of 250 mg/L.

Water in surficial sand and gravel aquifers is generally a calcium-magnesium-bicarbonate type (Adolphson and others, 1981), and generally is suitable for most uses. Dissolved-solids concentrations in water from those aquifers range from about 225 to 575 mg/L (fig. 16). Water in the buried sand and gravel aquifers is also generally of the calcium-magnesium-bicarbonate type. Dissolved-solids concentrations in the buried sand and gravel aquifers generally range from about 150 to 225 mg/L (fig. 16).

Water in the Upper Carbonate, St. Peter, Prairie du Chien-Jordan, Franconia-Ironton-Galesville, Mt. Simon-Hinckley-Fond du Lac, and Precambrian igneous and metamorphic aquifers are generally of a calcium-magnesium-bicarbonate type (Anderson, 1986; Ruhl and others, 1983; Ruhl and others, 1982; Ruhl and Wolf, 1983; and Wolf and others, 1983). Dissolved-solids concentrations in those aquifers typically range from 300 to 400 µg/L (fig. 16).

Water from Cretaceous aquifers is generally more mineralized than water from other aquifers in the study unit, commonly containing 800 to 1,450 mg/L dissolved solids (fig. 16). Water quality in the Cretaceous aquifers has considerable areal variation. Relatively high sodium concentrations (100-1,000 mg/L) are present in water in these aquifers (Woodward and Anderson, 1986). In part of southeastern Minnesota, sodium-chloride type water is present in this aquifer below depths of 1,000 feet. In the southwest, where the aquifer is overlain by and receives recharge from rocks of Cretaceous age, the water sometimes contains objectionable concentrations of magnesium and sulfate.

Ground-water quality in the study unit has been locally degraded by contaminants. Major sources of contamination, according to the MPCA (1986), include (1) spills or improper disposal of industrial or manufacturing chemicals, (2) leachate from solid-waste landfills, (3) spills and leaks from petroleum storage areas and pipelines, and (4) feedlots and agricultural chemicals. A total of 132 sites have been identified as priority sites for remediation by the MPCA and the USEPA (Right to Know Network, electronic communication, 1995). Thirty-six of those sites are listed on the National Priorities List, and 6 sites at two U.S. Department of Defense facilities are listed for remediation by the Installation Remediation Program (Right to Know Network, electronic communication, 1995).

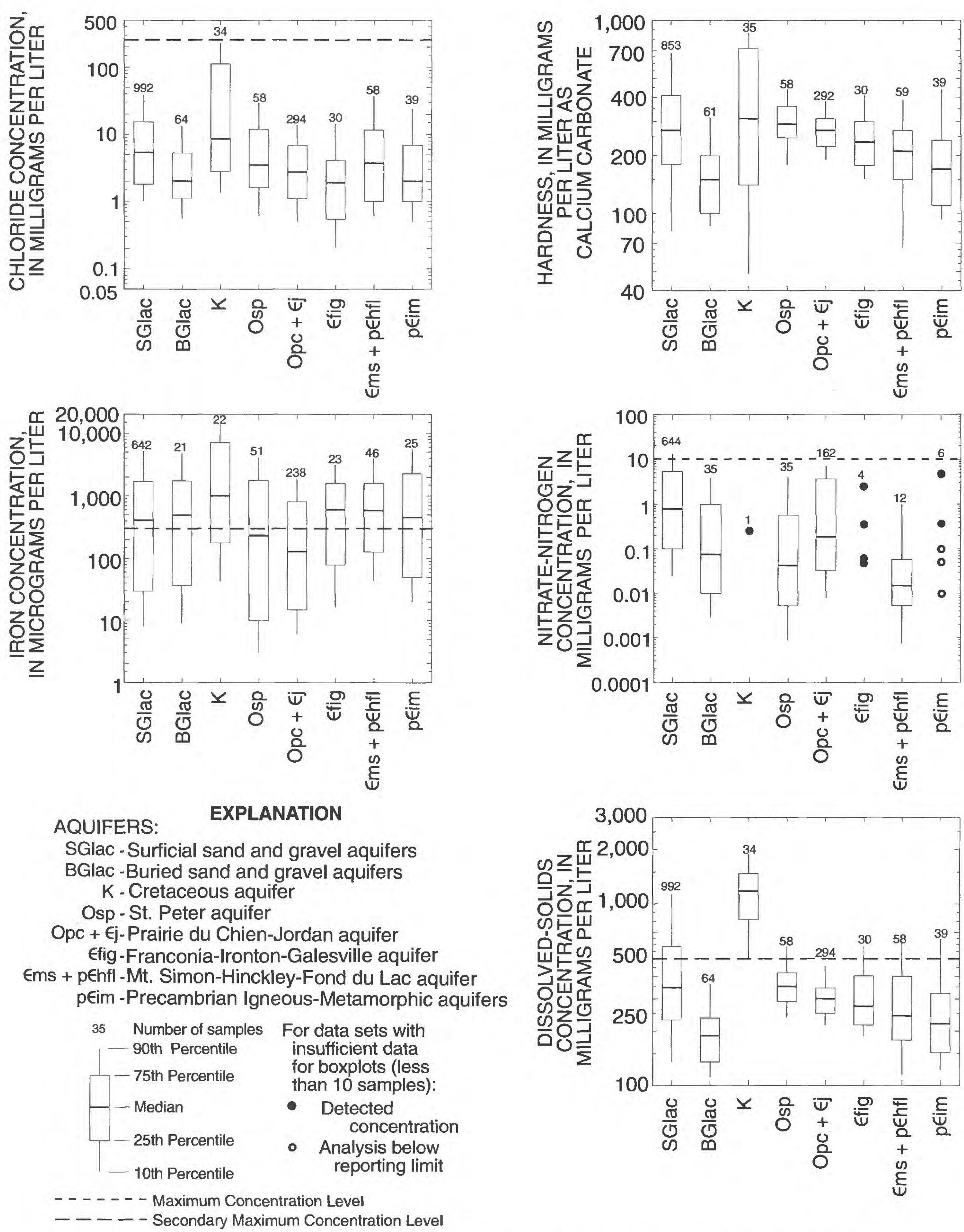


Figure 16.--Generalized water quality for major aquifers within the Upper Mississippi River Basin study unit.

Ecological Setting

Omernik and Gallant (1988) have classified ecoregions as areas with common ecological settings that have relatively homogeneous features including potential natural vegetation, geology, mineral availability from soils, physiography, and land use and land cover. The study unit contains parts of five ecoregions, including, from north to south: the (1) the Northern Lakes and Forests, (2) the North Central Hardwood Forests, (3) the Northern Glaciated Plains, (4) the Western Corn Belt Plains, and (5) the Driftless Area (fig. 17). The Driftless Area ecoregion comprises about 1 percent of the study unit and is not characterized in this section.

The Northern Lakes and Forests ecoregion extends over 31 percent of the study unit, and is characterized by rolling glacial till plains; broad, flat glacial basins; and sandy outwash plains. Forested land in this ecoregion is a mix of second-growth northern hardwoods and coniferous species. The area contains numerous lakes and ponds, many of which are sources of streams. Within the ecoregion, approximately 75 percent of the land is forested and 10 percent is open water or marsh (Fandrei and others, 1988).

The North Central Hardwood Forests ecoregion extends across 31 percent of the study unit and is transitional area between the Northern Lakes and Forests ecoregion to the north and Northern Glaciated Plains and Western Corn Belt Plains ecoregions to the south. Wet forested areas contain coniferous species also common in the Northern Lakes and Forests ecoregion, whereas dry forested prairie areas contain maple/basswood forests, which are common to the south and west. The North Central Hardwood Forest ecoregion is characterized by flat glacial lake and glacial outwash plains and moraines. Lakes are numerous, primarily in the northern and western part of the ecoregion. Approximately 50 percent of the land is cultivated and another 15 percent is forested (Fandrei and others, 1988).

The Western Corn Belt Plains and the Northern Glaciated Plains ecoregions comprise 23 and 14 percent of the study unit, respectively, and are characterized by rolling plains composed of glacial till, loess, and by flat ridge tops, all characterized by silty textured soils. These ecoregions were covered by tall grass prairie prior to European settlement and are now used for agriculture. Over 80 percent of the land is cultivated and about 10 percent is either pasture or open (Fandrei and others, 1988). Dominant crops raised in these ecoregions include corn, soybeans, small grains, and hay grown for livestock forage.

Biological communities form in response to chemical and physical environments, as well as to interactions between species. Major changes in the physical aquatic habitats in streams in the study unit are caused by construction of the locks and dams and to changes in land use (Holland-Bartels, 1992). Construction of locks and dams in the Mississippi River has decreased floodplain backwater and slough habitats and has increased main channel and channel margin habitats (Mueller, 1993). Loss of riparian vegetation and channel straightening in the Minnesota River Basin has reduced habitat, modified hydrologic conditions, and changed water quality.

Fish in streams of the study unit are primarily warm- and cool-water species derived from the lower Mississippi River refugium during late Pleistocene and early Holocene periods (Underhill, 1989). Waterfalls at St. Anthony Falls on the Mississippi River and St. Croix Falls on the St. Croix River (fig. 17) physically separate the fish fauna of each of these two rivers into upper and lower reaches. There are approximately 70 species of fish found in the Mississippi River above St. Anthony Falls and about 120 species below the falls. In the St. Croix River there are about 75 species above St. Croix Falls and about 90 species below (Becker, 1983; Eddy and Underhill, 1974; Underhill, 1989). The Minnesota River basin has 84 native species of fish (Becker, 1983; Eddy and Underhill, 1974; Underhill, 1989).

The aquatic invertebrate community that has received a great deal of attention is mollusks. The study unit has experienced a loss of mollusk species due to commercial exploitation, loss and modification of habitat, water pollution, siltation, and introduction of exotic mussel species (Zebra mussels, *Dreissena polymorpha*) (Mueller, 1993; Williams and others, 1993). There are two Federally-listed endangered mollusk species in the lower St. Croix and Mississippi Rivers—the Higgin's Eye Pearly mussel (*Lampsilis higginsi*) and the Winged Maple-Leaf mussel (*Quadrula fragosa*) (Federal Register, 1992).

Algae in the Upper Mississippi River are composed of most of the major algal groups, including diatoms, green algae (filamentous and unicellular forms), and blue-green algae. Williams (1972) found that a centric, filamentous diatom (*Melosira ambigua*) was the most common species in the river during the spring and fall.

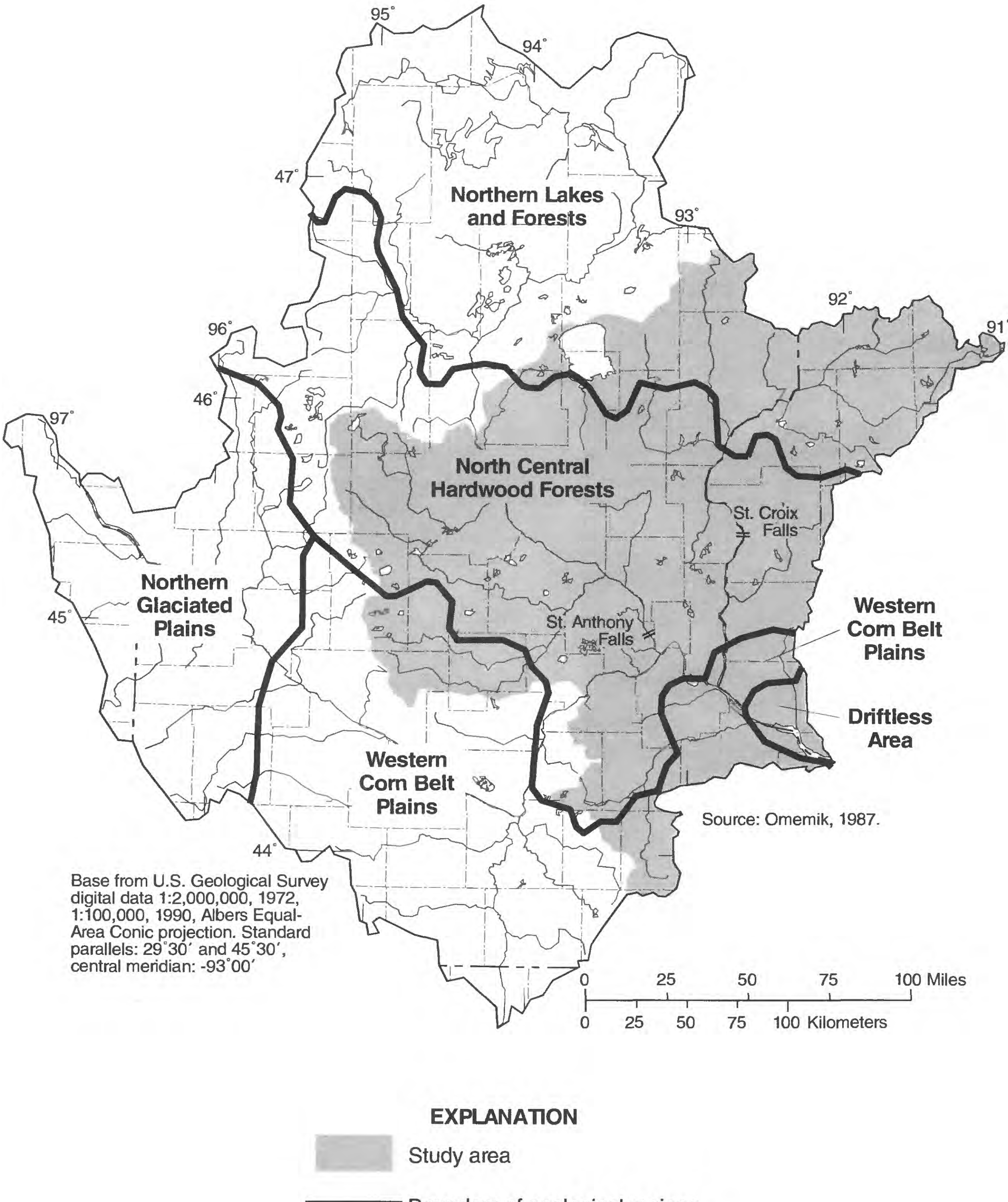


Figure 17.--Ecological regions in the Upper Mississippi River Basin study unit.

Anthropogenic Setting

The TCMA is the center of population and economic activity in the study unit. The TCMA is the historic distribution and transportation center of the Upper Midwest and dominates trade in Minnesota and neighboring states. Land use and land cover in the study unit are diverse and tend to exist in parallel bands that include intensive cropland in the southwest, forests and woodlands in the northeast, and an intervening transitional area. The use of the land is determined by a variety of features including topography, geology, precipitation, soils, and human settlement patterns.

Population

The population of the study unit in 1990 was about 3,640,000, an increase of 16 percent between 1970 and 1990 (U.S. Bureau of Census, 1991). Seventy-five percent of the population reside in the TCMA (fig.18, table 2). Thirty-five percent of the population is in Hennepin and Ramsey Counties, where Minneapolis and St. Paul are the principal cities. Two-thirds of the population growth occurred in the nine counties that surround Hennepin and Ramsey Counties (fig. 18). Counties in Wisconsin and in the northern portions of the study unit in Minnesota had moderate population growth between 1970 and 1990. Much of this growth is due to either TCMA suburban growth, or is a direct reflection of the growth in seasonal homes and tourism in those counties (Borchert and Gustafson, 1980). The population of rural counties in the study unit, particularly in the Minnesota River Basin, decreased 13 percent during the same period (fig. 18). Decreases in rural county population have been occurring since the Depression and World War II. Improvements in personal mobility and farm-machinery technology have allowed for increased productivity with fewer workers, resulting in a steady increase in farm size and a decline in farm population (Borchert and Gustafson, 1980).

Table 2.—Population of principal communities in the Upper Mississippi River Basin study unit

Community	Population		
	1970 (Minnesota Department of Transportation, 1977)	1980 (Minnesota Department of Transportation, 1983)	1990 (U.S. Bureau of Census, 1991)
Twin Cities metropolitan area	1,873,531	1,985,873	2,291,181
Minneapolis, Minnesota*	434,400	370,951	368,383
St. Paul, Minnesota*	309,866	270,230	272,235
Bloomington, Minnesota*	81,970	81,831	86,335
St. Cloud, Minnesota	42,223	42,566	48,812
Mankato, Minnesota	30,895	28,651	31,477
Owatonna, Minnesota	15,341	18,632	19,386
Wilmar, Minnesota	13,632	15,895	17,531
Anoka, Minnesota*	14,773	15,634	17,192
Faribault, Minnesota	16,595	16,241	17,085
Hastings, Minnesota*	12,195	12,827	15,445
Red Wing, Minnesota	12,834	13,736	15,134
Northfield, Minnesota	10,235	12,562	14,684
Stillwater, Minnesota*	10,208	12,322	13,882
New Ulm, Minnesota	13,051	13,755	13,132
Brainerd, Minnesota	11,667	11,489	12,353

* Principal communities included in the Twin Cities metropolitan area.

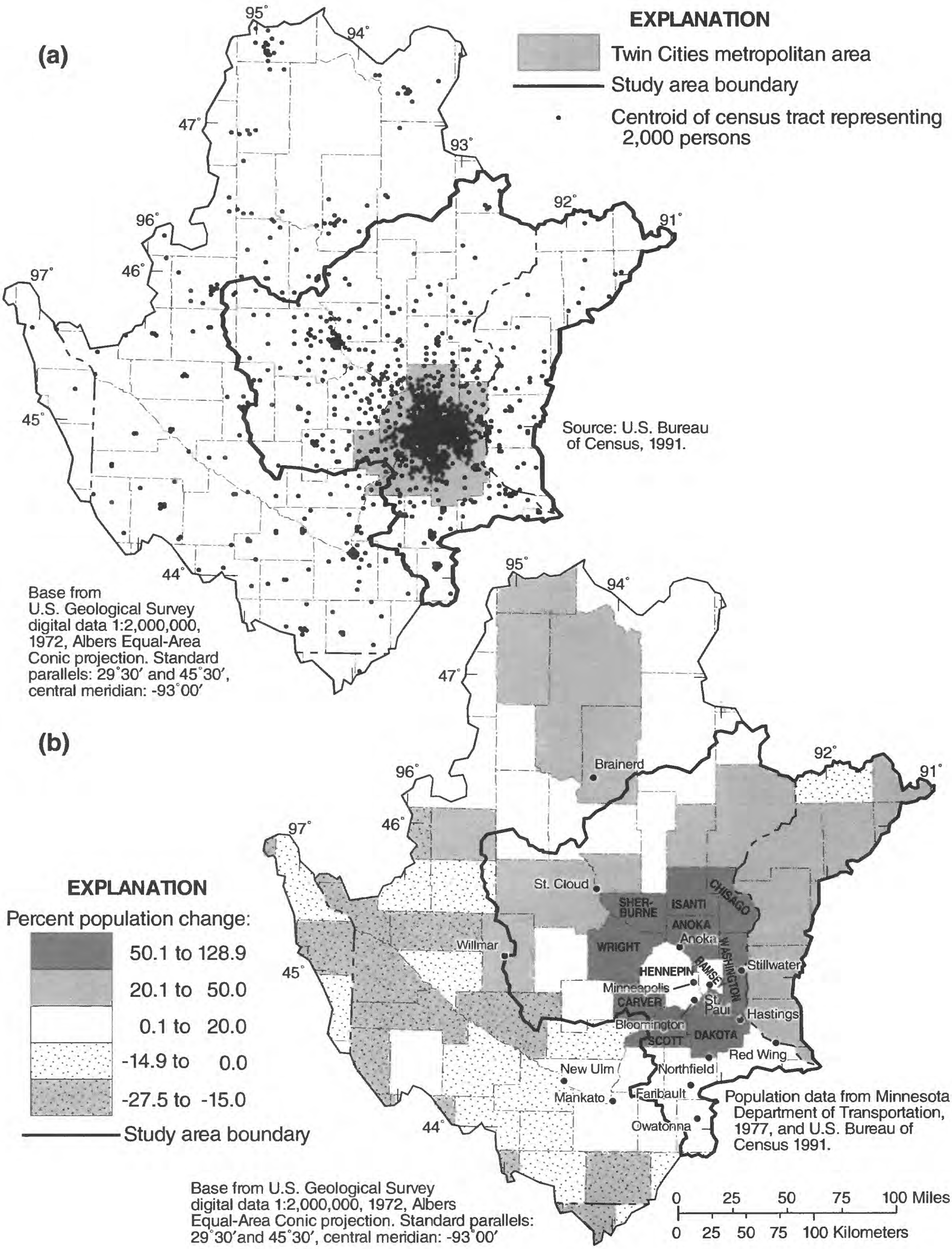


Figure 18.--(a) 1990 population density and (b) population change from 1970 to 1990, by county in the Upper Mississippi River Basin study unit.

Land cover, land use, and economic activity

Climate variants across the study unit (Borchert and Yaeger, 1968) help dictate the primary land uses and land covers, which can be generalized in three zones: an agricultural zone across the southwestern one-third; a forested zone across the northeastern one-third; and a transitional zone in between (fig. 19). The U.S. Geological Survey's land use and land cover data (U.S. Geological Survey, 1990) using the Anderson classification system (Anderson, 1967) indicates about 63 percent of the study unit as agricultural and range land (cropland, pasture). The remaining land use and land cover consists of forests (about 22 percent), water and wetlands (about 13 percent), urban land (about 2 percent), and other categories (less than 1 percent).

Most agricultural land (fig. 19) in the study unit occurs where there are dark, organic-rich, prairie or mollisol soils. Cropland is confined primarily to the Minnesota River Basin where over 80 percent of land is in farms and in some counties can be 95 percent or more (Minnesota Agricultural Statistics Service, 1994). According to the agricultural census of 1994 (Minnesota Agricultural Statistics Service, 1994), crops in the study unit include, in order of decreasing acreage planted in 1993: corn, soybeans, all hay, wheat, and oats. There are distinct geographic patterns to the crops raised. Corn and soybeans are planted primarily in the Minnesota River Basin and are concentrated in the eastern part of the basin. Wheat is also planted primarily in the Minnesota River Basin yet is concentrated in the western part of the basin. Hay and oats are planted in the less fertile agricultural regions of the transitional zone.

The forested zone in the northeast is colder and wetter than the other zones. Soils tend to be rockier and less well drained. Forests, woodlands and wetlands dominate this zone. Aspen and birch forests are the principal forests with large areas of maple, basswood, pine, and oak (Borchert and Gustafson, 1980). Wetlands and peat bogs associated with histosol soils are scattered throughout the zone (fig. 19).

Between the rich agricultural soils of the southwest and the more rocky and less fertile soils of the forested zone in the northeast is a transitional zone that stretches from the rough, stream-dissected till plains of the southeast northwestward along the hummocky, terminal glacial moraines. Cropland is limited in this zone due to rocky, marginally fertile soils on steep terrain, and is strongly associated with livestock production. Historically, this area has been cleared for cultivation but major erosion problems and lower crop yields have led to a decline in cropland. Pastureland is now the most important land use in this zone. Hay and oats are the principal crops and are used to feed livestock. Dairy cows are the predominant livestock. Approximately 400,000 head, or about 80 percent of the cattle in the study unit are in this transitional zone. Poultry production tends to be concentrated in this zone, and has nearly doubled from about 50 million chickens and turkeys in 1983 to 90 million in 1993 (Minnesota Agricultural Statistics Service, 1994). To a lesser extent, beef cattle and horses also graze the hillier lands of the transitional zone. Other important livestock production in the study unit includes hogs in the south and sheep in the drier rangelands of the southwest.

The overwhelming majority of the urban land is concentrated in the southeastern part of the study unit. The Twin Cities metropolitan area, located near the confluence of the Mississippi, Minnesota and St. Croix Rivers, comprises nearly 80 percent of all urban land in the study unit (fig. 19). Other major urban communities include St. Cloud, Mankato, Faribault and Owatonna. These urban centers are the dominant location of most industry, trade, and nodes in various transportation systems in the study unit.

Another important land use is mining. Although sand and gravel mining occurs throughout the study unit, these mining operations tend to be small and do not show on figure 19. Large iron ore mining operations are present in the north-central part. The southern part of the Mesabi Iron Range, the nation's largest iron ore producer during World War II, extends into the study unit. Much of the natural hematite iron ore deposits are now depleted and most iron is extracted from more siliceous taconite ores.

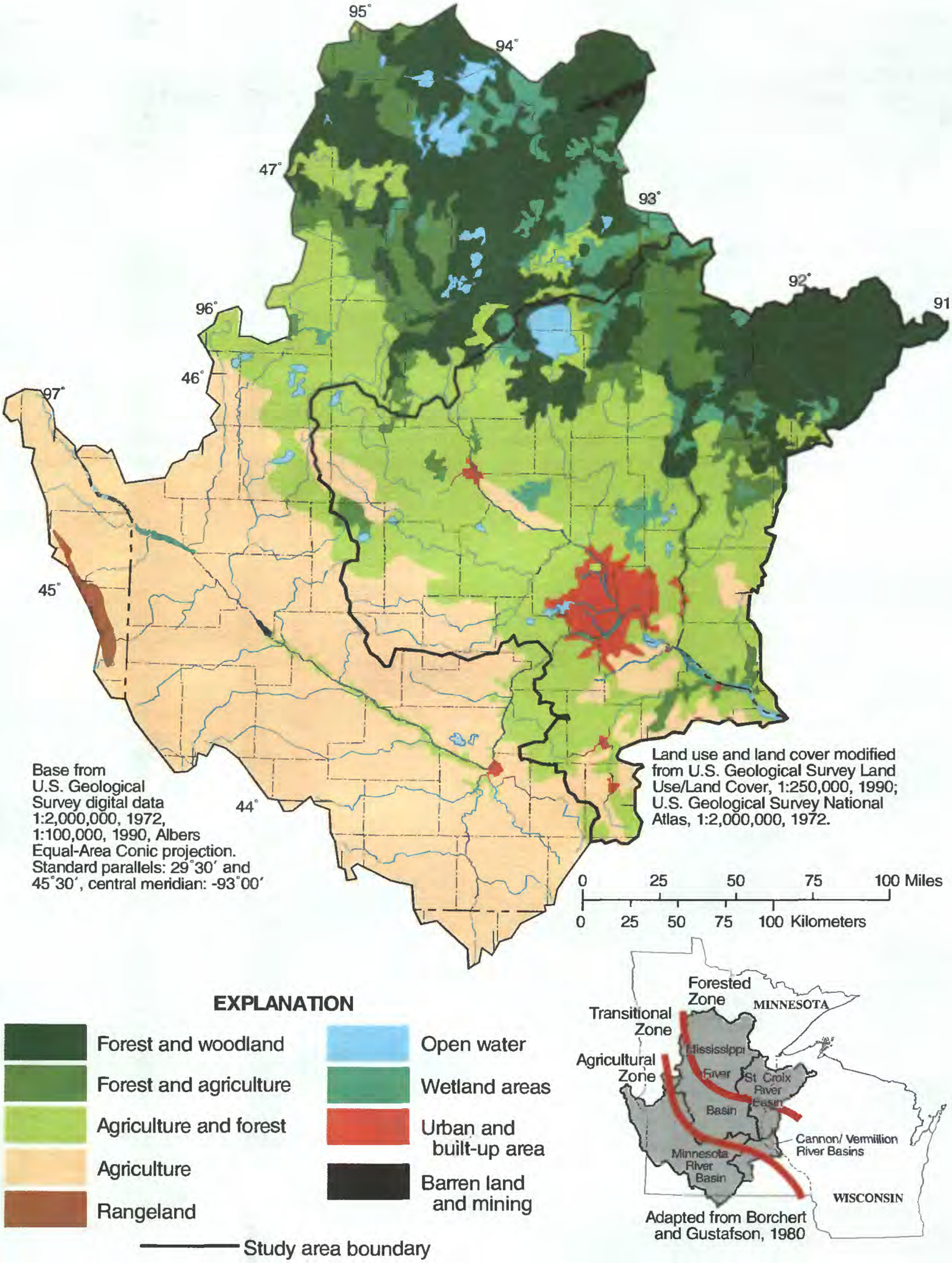


Figure 19.--Land use and land cover in the Upper Mississippi River Basin study unit.

Water use

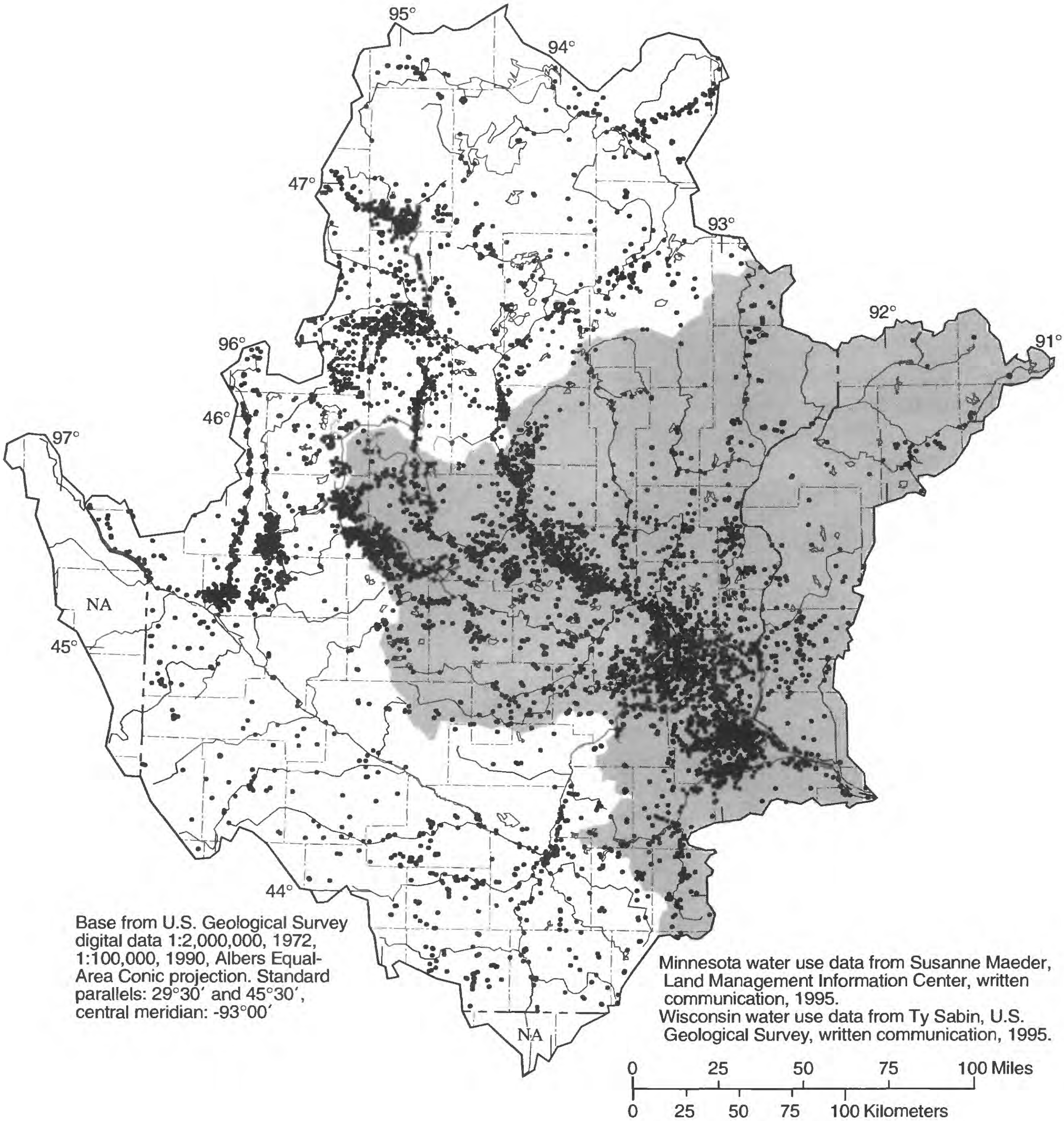
Water use data have been compiled from the USGS, National Water-Use Information Program data base (Site-Specific Water Use Data System) SWUDS and from state regulatory agencies (table 3). This data base contains data collected by the Minnesota and Wisconsin Departments of Natural Resources. Surface water accounted for 75 percent of all water withdrawals in 1990 in the study unit. Power generation plants were the largest surface-water users and accounted for most of the surface water withdrawn. Public supply accounted for about 8 percent of surface water withdrawn. Ground water accounted for 25 percent of all water withdrawals in 1990. Public supply accounted for 36 percent of ground-water use (table 3). Domestic wells and irrigation each account for about 21 percent of ground water use.

Public water supplies served about 2,410,000 people in 1990 (fig. 20). An average of 413 million gallons of water per day were used—59 percent from ground-water and 41 percent from surface water. Public supplies for Minneapolis, St. Paul, and St. Cloud are mainly from the Mississippi River. Ground water is the source for most other public water supplies, including many TCMA suburbs. Domestic use accounts for 85 percent of the total public supply water use. The remaining 15 percent is used for industry (about 7 percent), commercial (about 4 percent), thermoelectric (less than 1 percent), and public use and loses (about 4 percent). Average per capita use for public supplies in the study unit is 112 gal/d (gallons per day). About 1,240,000 people in the study unit use private domestic wells. Average per capita use for domestic self supplied water is 97.5 gal/d.

Consumptive water use in thermoelectric power plants average 18 percent of withdrawal. Public supplies and domestic self supplies combined have a consumption rate of about 30 percent. Water used for livestock and irrigation have high consumption rates, 98 and 90 percent, respectively.

Table 3.—Reported water use in the Upper Mississippi River Basin study unit, 1990 (in million gallons per day)

Category	Ground water	Surface water	Total
Public supply	243	170	413
Domestic self supplied	145	0	145
Commercial self supplied	43.5	12.6	56.1
Industrial self supplied	58.7	34.7	93.4
Livestock	36.3	6.22	42.6
Irrigation	141	12.3	153
Mining	2.35	60.3	62.7
Thermoelectric self supplied	1.29	1735.29	1740
Other	1.42	4.95	6.37
Total	673	2040	2710



EXPLANATION

Study area

• Location of point of withdrawal based on permitting programs

NA Data not available

Figure 20.--Location of major water users in the Upper Mississippi River Basin study unit.

Stratification and Study Design

Water quality in the study unit is affected by natural and anthropogenic factors and systems. The principal natural factors include climate, physiography, geology, soils, topography and aquatic biology. The principal anthropogenic factors include agriculture, urban runoff and municipal and industrial point-source discharges. Agricultural activities contribute significant nonpoint sources of contaminants to surface and ground water. Sediment erosion by wind and water are increased by cultivation practices and by livestock trampling streambanks. Streambanks of the Minnesota River Basin are particularly susceptible to erosion and subsequent sedimentation in streams that drain these areas. Nitrate-nitrogen and pesticide concentrations can locally increase in surficial aquifers and in streams where cropland is fertilized. An important anthropogenic factor in the study unit is the TCMA. Point and nonpoint sources in the TCMA have a substantial affect on water quality. Atmospheric deposition also is a route for the introduction of chemicals into waters of the study unit. A wide variety of commonly used pesticide compounds are deposited in precipitation falling over the TCMA (D. Goolsby, U.S. Geological Survey, written commun., 1995).

The study design for the assessment of water quality focuses on natural and anthropogenic factors that have an influence or a potential influence on water quality (Gilliom and others, 1995). Protection of rivers and aquifers from contamination is a general concern in the study unit because both surface and ground water are major sources of water supply. Bedrock aquifers are the most important sources of ground water in the TCMA. Most suburbs use ground water from those aquifers as their source of water supply. The most significant contaminants in surface and ground water in the study unit include nutrients, pesticides, synthetic-organic chemicals, and trace metals.

Stratification

Environmental stratification consisted of dividing the study unit into subareas (strata) with homogeneous natural and anthropogenic characteristics to assess water quality. The sampling design is based on comparing water quality within and between strata where boundaries are defined on the basis of subbasins or aquifer boundaries. The stratification process included dividing the study unit into subareas based on a combination of physical features and superimposing the drainage-basin and aquifer boundaries on the strata. The process of stratification resulted in a wide range of strata combinations (fig. 21). Most sampling sites are selected from a single stratum.

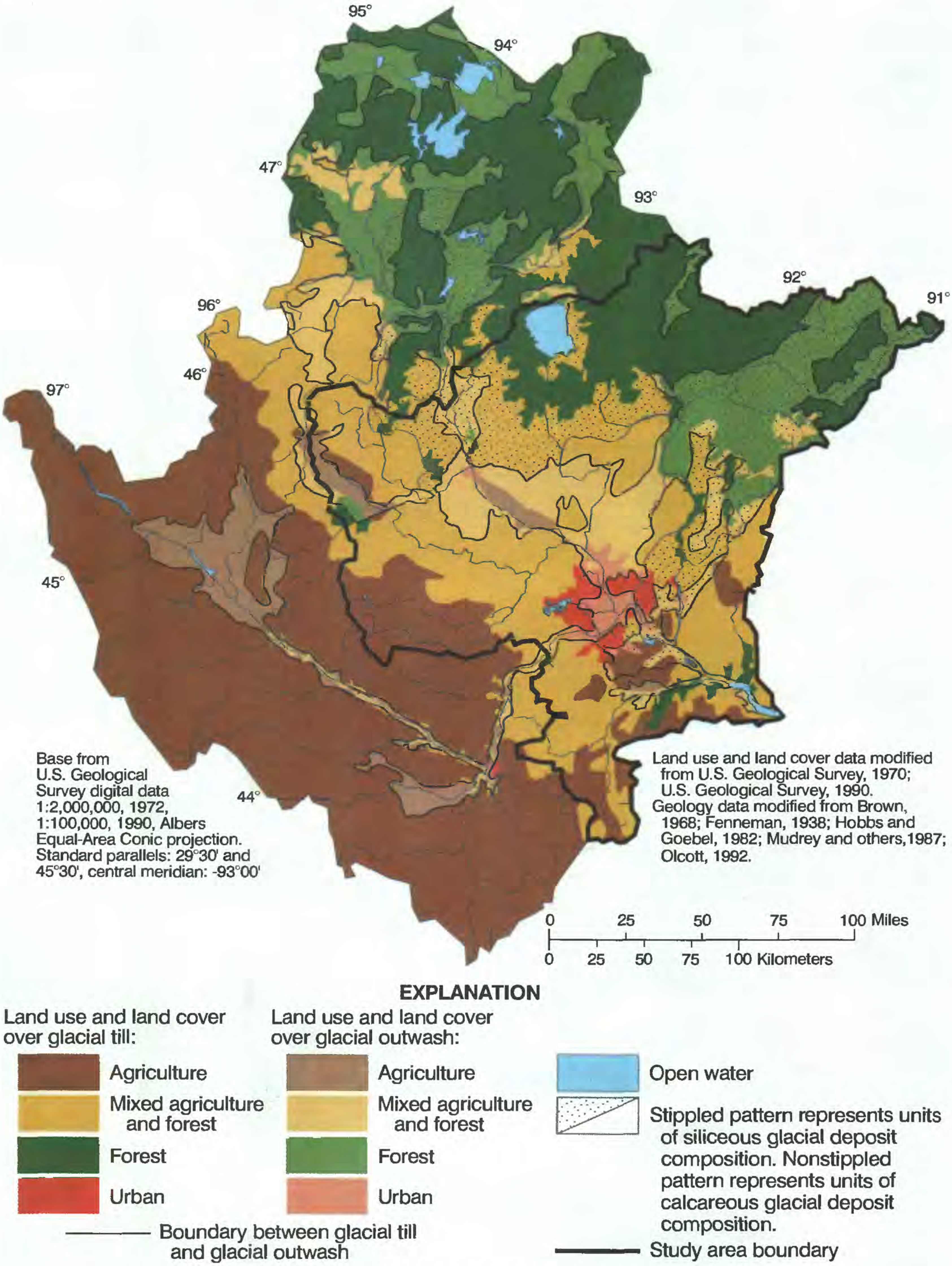


Figure 21.--Basis for stratification for the Upper Mississippi River Basin study unit.

Stratification for surface-water component

The study area was stratified at four levels for the surface-water component: (1) glacial deposit composition (dominant physiographic source area), (2) surficial geology, (3) general land use and land cover, and (4) secondary land use (fig. 22).

The first level of stratification was based on the areal distribution of deposits from glacial lobes that correlate to soil mineralogy, texture, and permeability. Glacial deposits may be classified as consisting predominantly of calcareous (Des Moines and Wadena Lobes) or siliceous (Superior and Rainy Lobes) deposits (Hobbs and Goebel, 1982). The Superior and Rainy Lobes advanced from the northeast and reached a terminus southwest of the present course of the Mississippi River (Wright, 1972). The Des Moines and Wadena Lobes advanced from the west and northwest, overriding Superior Lobe deposits in some places. A small part of the study unit (less than 5 percent), near the downstream boundary, was untouched by Wisconsinan glaciation and stratification of these areas is based on physiographic sections (the Wisconsin Driftless Section and Dissected Till Plains Section of the Central Lowland Province). The Wisconsin Driftless Section is dominated by bedrock. The Dissected Till Plains consist of relatively impermeable loess-covered tills from late- and pre-Wisconsinan glaciations.

Surficial geology was divided into two strata including till plains and moraines (fine-grained deposits) and outwash and alluvium (coarse-grained deposits) for each of the dominant types of glacial deposit compositions. It was assumed the texture of surficial deposits has an influence on the hydrology, water quality and aquatic biology of streams draining those areas. Land use and land cover were divided into five strata: (1) forest, (2) mixed agriculture and forest, (3) agriculture, (4) urban, and (5) wetland and lakes. Land use and land cover include relatively undisturbed forested areas in the north, intensely cultivated areas in the southwest and south, and a major urban area in the southeast. Between the agricultural and forested areas lies an area of mixed agriculture and forest. The mixed agriculture and forest area is not a focus of study-unit sampling efforts because of the heterogeneity of these areas. Secondary land-use strata of residential and industrial land were delineated for the urban areas.

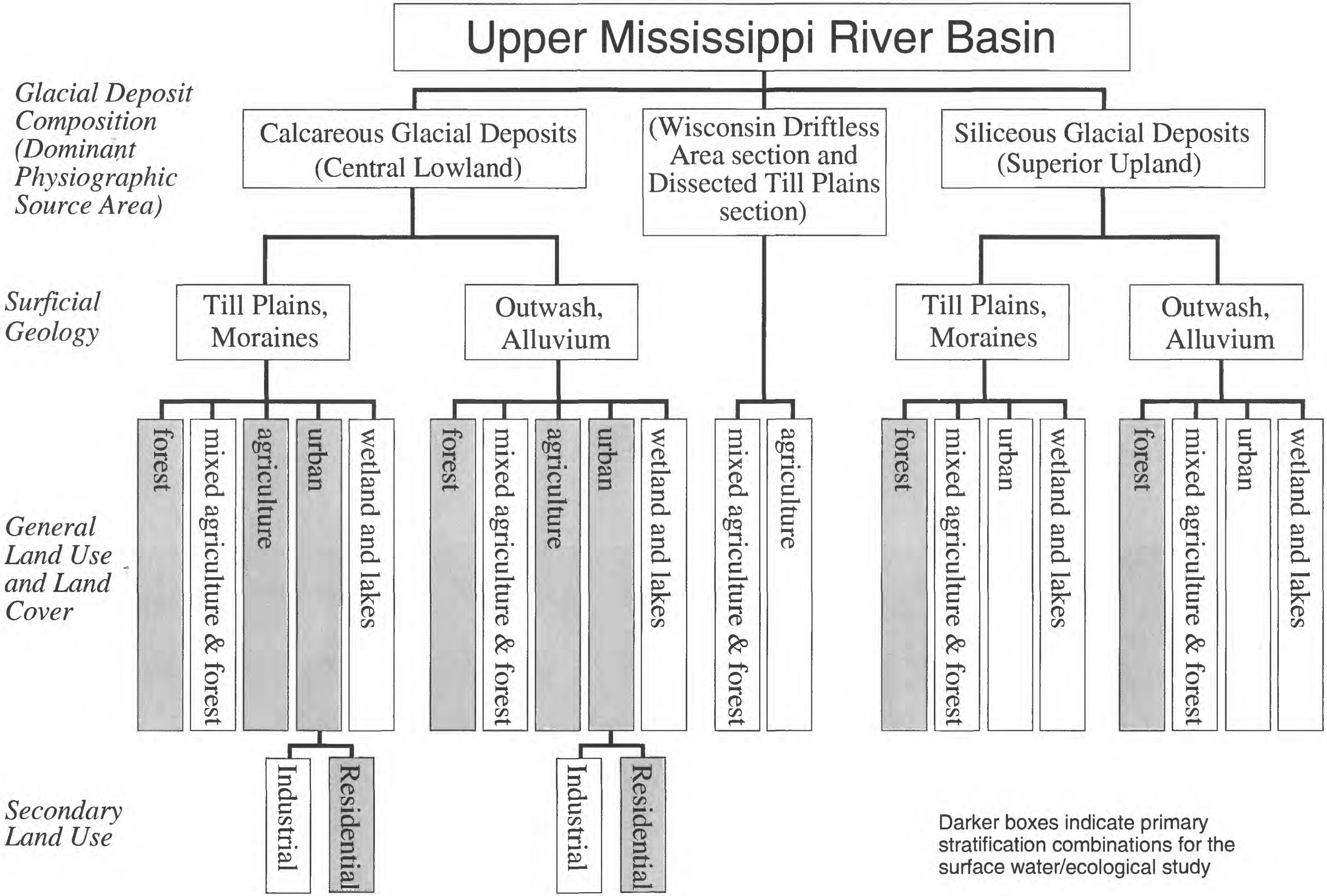


Figure 22.--Surface-water stratification for the Upper Mississippi River Basin study area.

Stratification for ground water component

Ground-water studies emphasize shallow ground water, the quality of which is likely influenced by overlying land use and land cover. Stratification for ground-water sampling is based on the spatial distribution of shallow surficial and buried sand and gravel and bedrock aquifers. As with the stratification of surface water, the first level of stratification was the glacial deposit composition, followed by the type of surficial geology (tills or outwash). Within the areas delineated by stratification, an additional level of stratification was added to differentiate among aquifers. For each aquifer, general land use and land cover were also used as a basis for the study design for the ground-water component (fig. 23).

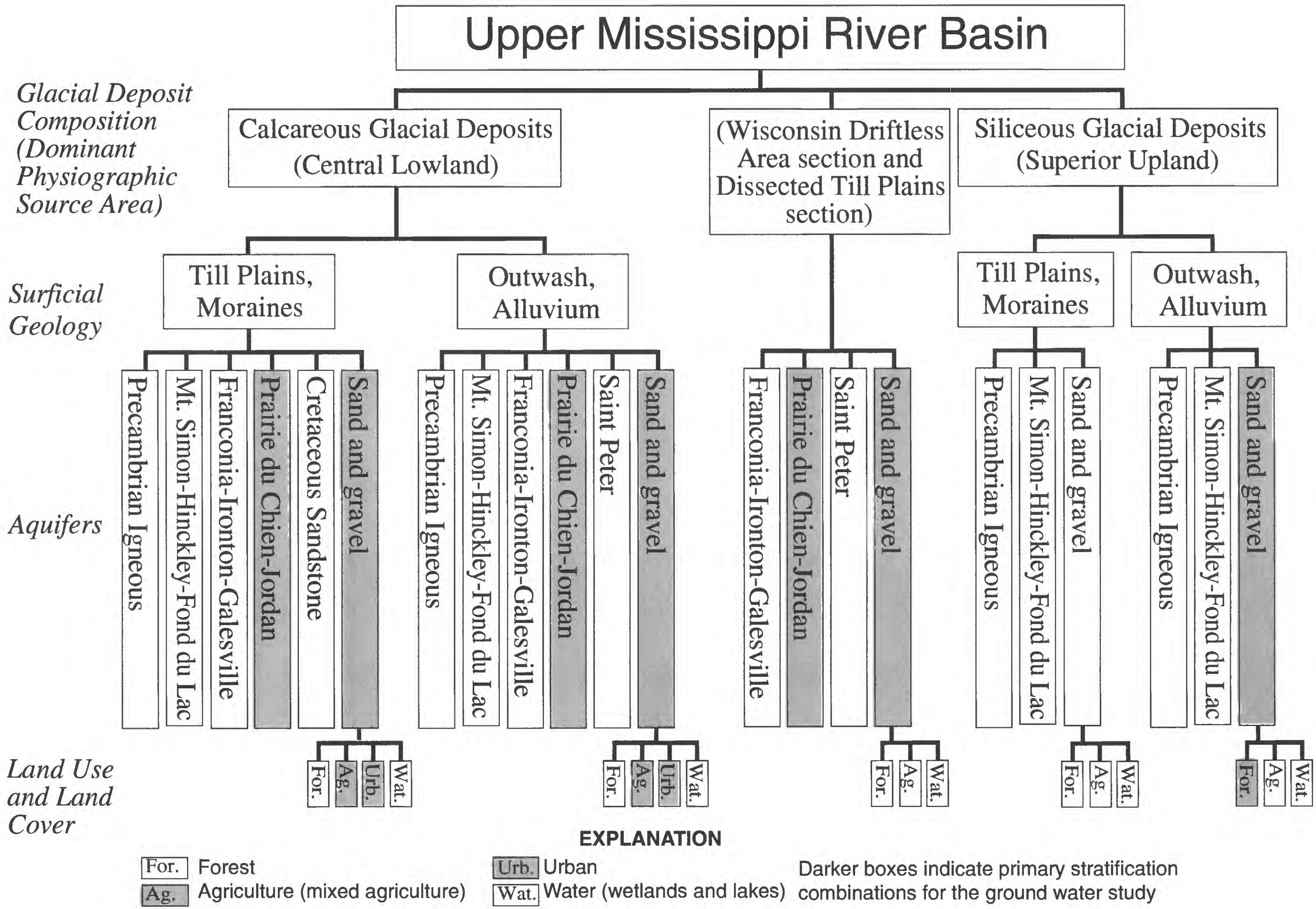


Figure 23.--Ground-water stratification for the Upper Mississippi River Basin study area.

Surface-Water Sampling Design

Water quality in streams is assessed through three types of studies: water column studies, bed sediment and tissue studies, and ecological studies (fig. 24, table 4). The objectives of surface-water sampling are to: (1) evaluate spatial and temporal distribution of physical, chemical, biological and ecological characteristics of streams, (2) compare water quality in streams and in different land-use and land cover areas, (3) define sources of contamination and, (4) establish a long-term monitoring plan. Water-column studies assess physical and chemical characteristics; bed sediment and tissue studies serve as initial characterization of trace elements and hydrophobic organic compounds; and ecological studies evaluate relations among physical, chemical, and biological characteristics. The sampling design of the three study components is similar.

Water-column studies

The objectives of the water-column studies are to provide an assessment of the spatial and temporal distribution of concentrations and loads of chemicals and nutrients at sites throughout the study area. Samples are collected at two types of fixed sites—basic fixed sites and intensive fixed sites (fig. 24, table 4). Basic fixed sites are sampled for general water quality and hydrology. Intensive fixed sites are sampled for seasonal and short-term temporal variability and for determining the presence and seasonal patterns of target constituents. These sites are further characterized as: (1) indicator sites located downstream from drainage basins that are relatively homogeneous with respect to natural and anthropogenic activities, and are generally small (less than several hundred mi^2) in areal extent, or (2) integrator sites, representing larger drainage basins in areas with multiple strata.

Synoptic surveys (fig. 24, table 4) are used to investigate the geographic distribution of selected water-quality characteristics during specific seasons and in relation to sources and transport. These surveys are designed to assess geographic distribution and potential chemical and nutrient sources in detail and frequently involve analysis of specific water-quality characteristics under seasonally extreme conditions. The surveys are generally of short duration, with high sampling density in space and in time, and are focused on one or a few specific water-quality issues. Synoptic surveys are designed to accomplish an assessment of geographic distribution and a mass-balance assessment of contaminant sources, sinks and transport during selected seasonal conditions.

Bed sediment and tissue study

The objective of the bed sediment and tissue (fig. 24, table 4) study is to describe trace elements and hydrophobic organic compounds. Fine-grained stream-bed sediment and biological tissues are collected for analyses of trace elements and hydrophobic organic compounds. Most bed sediment and tissue sites are collocated with basic-fixed and intensive-fixed sites. Additional sites are selected to increase spatial distribution. There are two phases of the bed sediment and tissue study: (1) the occurrence survey which is designed to identify significant contaminants; and (2) the distribution survey which focuses on important constituents and sites identified in the occurrence survey.

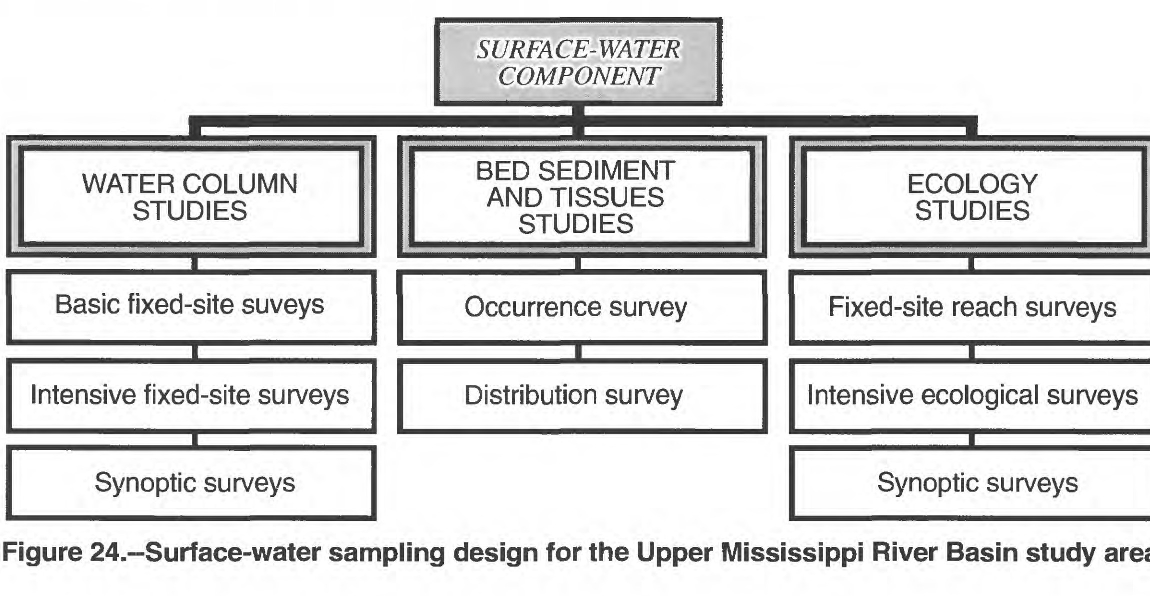


Figure 24.--Surface-water sampling design for the Upper Mississippi River Basin study area.

Ecological study

The objectives of the ecological studies are to characterize biological communities (fish, benthic macroinvertebrates, and algae) and habitat conditions; and to integrate physical, chemical, and biological data to evaluate water quality (fig. 24, table 4). The sampling unit for ecological studies is a stream reach that is representative of the surrounding area and located near water-column basic-fixed or intensive-fixed sites.

Three strategies are used to accomplish these objectives: (1) fixed-site reach surveys; (2) intensive-ecological surveys; and (3) synoptic surveys. Fixed-site reach surveys include collection of representative samples of fish, invertebrate and algal communities, and habitat characterization at one stream reach collocated with each basic-fixed or intensive-fixed water-column site. Intensive ecological surveys provide information on spatial and temporal variability of biological and habitat characteristics for a subset of the fixed sites. Three stream reaches are selected and sampled at intensive ecological assessment sites. Sampling procedures are identical to those used for fixed-site reach assessments. Spatial variability estimates are obtained by sampling three reaches at a fixed site. Temporal variability is estimated by sampling one stream reach annually for the three-year data-collection period. Ecological synoptic surveys concentrate on specific topics identified during the fixed-site reach surveys and the intensive ecological surveys.

Table 4.—Summary of data collection for surface-water presence and distribution assessment for water-column, bed sediment and tissue, and ecological studies in the Upper Mississippi River study area

Study	Objectives	Description and measured characteristics
Water-column studies	Fixed site surveys—describe concentrations and loads of chemicals, suspended sediment, and nutrients at sites throughout the study unit.	Sample near sites of continuous streamflow measurement for major ions, organic carbon, suspended sediment, pesticides, and nutrients.
	Synoptic surveys—describe short-term presence and distribution of contaminants over broad areas of the study area, and to evaluate the representative nature of the water chemistry sites.	Sample streams during high and low flow conditions for pesticides, nutrients, suspended sediments, organic carbon, volatile organic compounds, and streamflow.
Ecological studies	Fixed site and intensive ecological surveys—characterize biological communities (fish, benthic macroinvertebrates, and algae), and habitat characteristics; and to integrate chemical, physical, and biological data to assess water quality.	Sample fish, macroinvertebrates, algae, and characterize habitat.
Bed sediment and tissue studies—occurrence	Occurrence Surveys—determine the presence of selected contaminants in bed sediments, and fish tissue in the study unit.	Sample selected sites along the Mississippi, Minnesota, St. Croix River and selected tributaries for trace elements and hydrophobic organic compounds.
Bed sediment and tissue studies—distribution	Distribution surveys—determine the distribution of selected contaminants in bed sediments, and fish tissue at selected sites in the study area.	Same as above.

Ground-Water Sampling Design

Investigation of potential contamination of important water-supply aquifers, by pesticides, trace metals, nutrients, and VOC's is the primary objective of ground-water studies. Ground-water quality is being assessed for aquifer/land-use combinations using three sampling strategies including: (1) regional studies of selected major aquifers (study-unit surveys), (2) targeted-area studies in priority land-use areas (land-use surveys), and (3) localized studies of processes occurring along shallow ground-water flowpaths (flowpath studies) (table 5).

Study-unit surveys involve sampling existing wells completed in surficial sand and gravel aquifers in glacial outwash (fig. 25) and the Prairie du Chien-Jordan bedrock aquifer (fig. 26). The Prairie du Chien-Jordan bedrock aquifer is further differentiated into areas where the aquifer is overlain by other bedrock units and areas where it is the uppermost bedrock unit. They are intended to define the presence and distribution of a comprehensive array of constituents in significant aquifers. Wells sampled are selected using a random approach (Scott, 1990). Emphasis is placed on sampling existing low-capacity, short-screened wells. The majority of those wells will be either domestic or observation wells.

Land-use surveys are designed to determine the extent to which shallow ground-water quality is influenced by hydrogeologic setting and overlying land use. Land-use surveys are located in areas where ground water represents a source of current or future water supply, and where current or potential contamination from surface sources is likely (fig. 25). Land-use study areas are relatively limited in size (hundreds of mi^2). Wells sampled for these studies are selected at random using the grid-based method described by Scott (1990). Emphasis is placed on observation wells installed for each land use or land cover.

Flowpath studies characterize the spatial distribution of ground-water quality in particular land-use settings (fig. 25). These studies are used to develop an understanding of the physical, chemical and biological processes, and anthropogenic factors which control the evolution of ground-water quality along flowpaths. Flowpath studies consist of wells and nested wells along lines ranging from hundreds of feet to several miles in length, depending on the configuration of the subsurface flow system. Each transect extends from a ground-water divide to the discharge area for the flowpath.

Table 5.—Summary of data collection for ground-water studies in the Upper Mississippi River Basin study area

Study	Survey	Objectives	Description and measured characteristics
Glacial	Study-unit survey—surficial unconsolidated aquifers	Describe general water quality in surficial unconsolidated aquifers, which are the most susceptible to contamination.	Sample existing wells for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.
	Land-use survey—urban residential/commercial	Describe the quality of water in shallow surficial and deeper aquifers underlying urban land uses.	Sample existing wells, new wells, and rainfall for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.
	Land-use survey—agricultural	Describe the quality of water in shallow surficial aquifers underlying agricultural land uses.	Sample existing wells, new wells, for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.
	Land-use survey—woodlands	Describe the quality of water in shallow surficial aquifers beneath woodlands.	Sample existing wells, new wells for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.
	Flowpath study—urban	Describe the evolution of water quality along shallow ground-water flowpath beneath an urban area.	Sample multi-level wells/piezometer networks for major ions, nutrients, pesticides, volatile organic compounds, isotopes, chlorofluorocarbons, and radionuclides.
Bedrock	Study-unit survey—unconfined Prairie du Chien-Jordan	Describe the general water quality in the unconfined Prairie du Chien-Jordan aquifer, the most heavily-used bedrock aquifer in the study area.	Sample existing wells for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.
	Study-unit survey—confined Prairie du Chien-Jordan	Describe the general water quality in the confined Prairie du Chien-Jordan aquifer.	Sample existing wells for major ions, nutrients, pesticides, organic carbon, volatile organic compounds, and radionuclides.

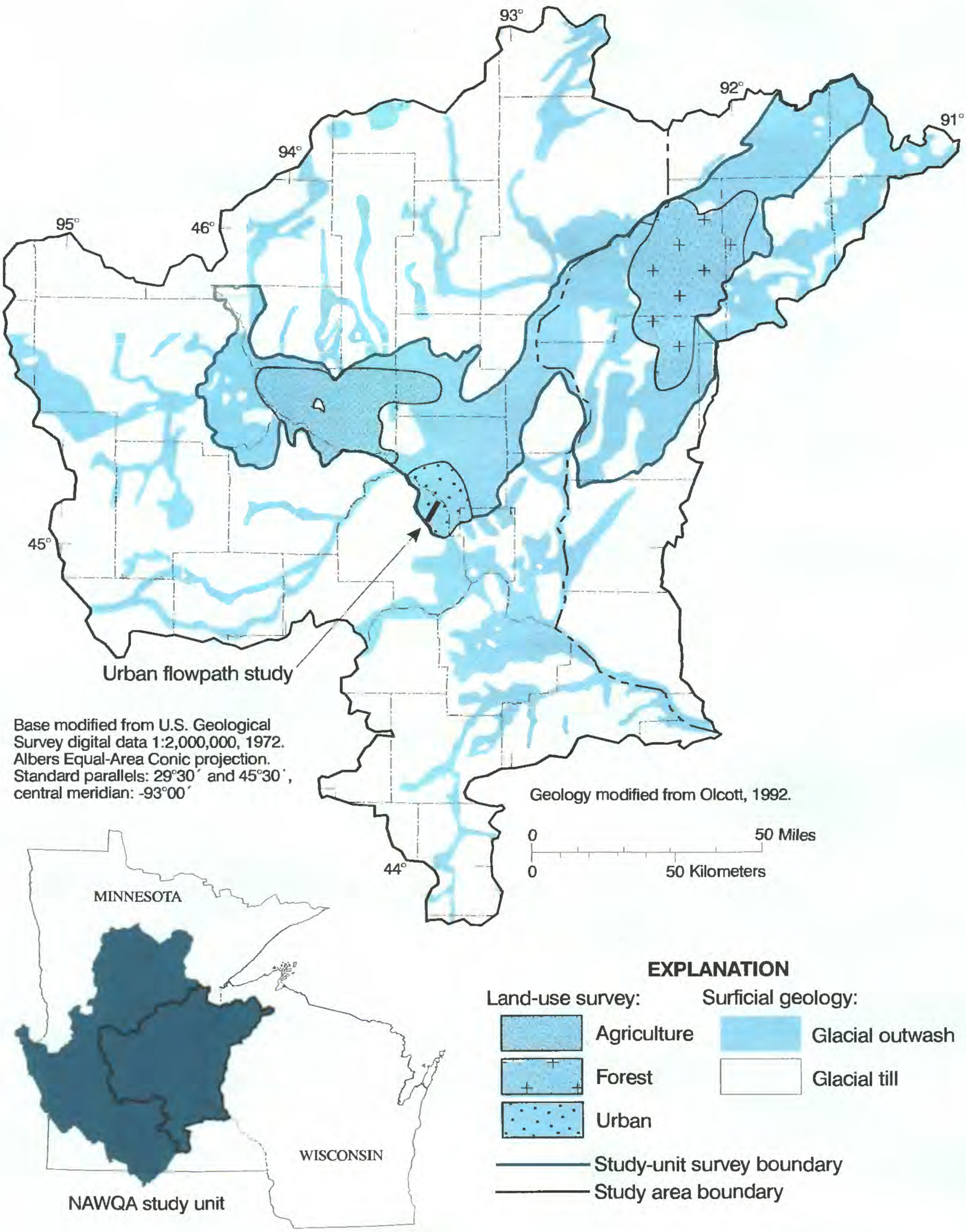


Figure 25.--Location of the ground-water study-unit surveys of the surficial hydrogeology, land use surveys, and flowpath study in the Upper Mississippi River Basin study area.

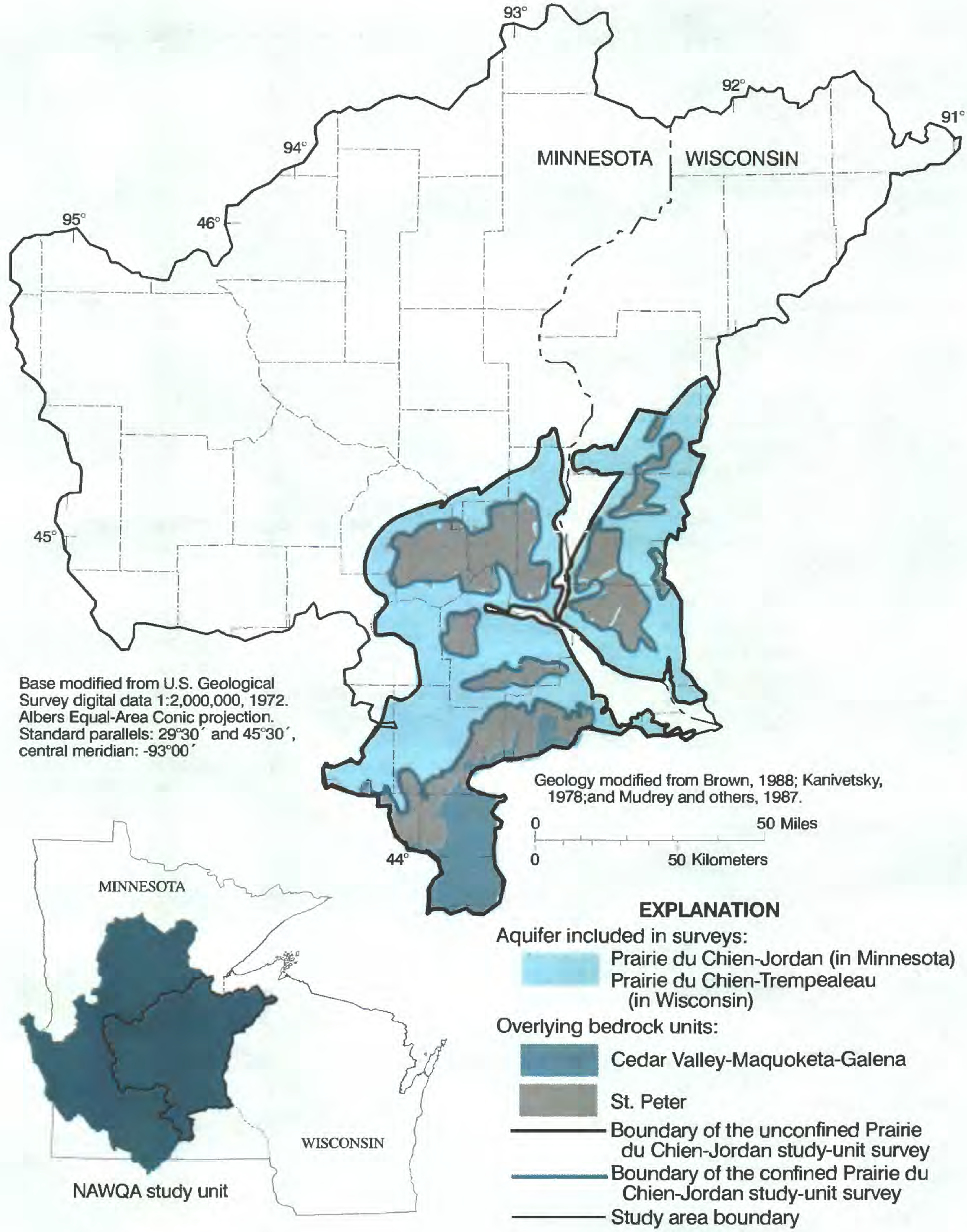


Figure 26.--Location of the ground-water study-unit surveys of the Prairie du Chien-Jordan aquifer in the Upper Mississippi River Basin study area.

Summary

The initial six-year phase of the Upper Mississippi River Basin NAWQA study, lasting from 1994 to 1999, focuses on data collection and analysis in a 19,500 mi^2 study area in Minnesota and Wisconsin that includes the Twin Cities metropolitan area. The study area is part of the 47,000 mi^2 Upper Mississippi River Basin NAWQA study unit. The study design focuses on factors that have an influence on or a potential influence on the water quality. The most significant contaminants include nutrients, pesticides, synthetic-organic compounds, and trace metals. Agricultural activities contribute significant nonpoint sources of contamination to surface and ground water. Urban land uses also are a source of surface and ground-water contamination.

The Upper Mississippi River Basin contains a diverse set of natural and anthropogenic characteristics that can control the areal distribution and flow of water and the distribution and concentration of constituents that affect water quality. A review of the environmental setting of the Upper Mississippi River Basin study unit is intended to put water quality in perspective with the geology, soils, climate, hydrology, aquatic ecology and historical uses of the land.

The Mississippi River generally flows southward from its source in northern Minnesota through areas of glacial moraines, lakes, lake plains and wetlands. The Upper Mississippi River Basin study unit encompasses about 47,000 mi^2 and includes all of the basin upstream from Lake Pepin. The climate of the study unit is subhumid continental. Average annual precipitation ranges from 22 inches in the western part of the study unit to 32 inches in the east. Annual runoff ranges from less than 2 inches in the west to 14 inches in the northeast. Two major tributaries to the Mississippi River contribute significant flow to the main stem—the Minnesota River and the St. Croix River.

The physiography of the study unit includes the Superior Upland and the Central Lowland Provinces. The Wisconsin Driftless Area and the Dissected Till Plains are unique physiographic sections of the Central Lowland Province. Hydrogeologic units in glacial deposits include surficial and buried sand and gravel aquifers and confining units. Bedrock aquifers and confining units are part of a thick sequence of sedimentary rocks that can be divided into four major aquifers separated by confining units.

The population of the study unit was about 3,640,000 as of 1990 and increased 16 percent between 1970 and 1990. Seventy-five percent of the population lives in the Twin Cities metropolitan area. Public water supplies served about 2,410,000 people in 1990. An average of 413 million gallons of water per day was used—59 percent from ground water and 41 percent from surface water. Land use and land cover in the study unit consists of forested, agricultural, and urban areas. About 63 percent of the land area is agricultural.

The quality of water in streams and ground water in the study unit is affected by both natural and anthropogenic factors. Alkalinity, hardness, dissolved-solids concentration, specific conductivity, and suspended sediment vary throughout the basin depending on natural and anthropogenic conditions. The quality of water is generally satisfactory for most domestic, public, industrial, and irrigation uses. Most water is of the calcium-magnesium-bicarbonate type.

Environmental stratification consists of dividing the study unit into subareas with homogeneous characteristics to assess natural and anthropogenic factors affecting water quality. The assessment of water quality in streams and in aquifers is based on the sampling design that compares water quality within homogeneous subareas defined by subbasins or aquifer boundaries. The study unit is stratified at four levels for the surface-water component: glacial deposit composition, surficial geology, general land use and land cover, and secondary land use. Ground-water studies emphasize shallow ground water where quality is most likely influenced by overlying land use and land cover. Stratification for ground-water sampling is superimposed on the distribution of shallow aquifers. For each aquifer and surface-water basin this stratification forms the basis for the proposed sampling design used in the Upper Mississippi River Basin National Water-Quality Assessment.

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