ENVIRONMENTAL SETTING AND IMPLICATIONS FOR WATER QUALITY IN THE WESTERN LAKE MICHIGAN DRAINAGES

Edited by Charles A. Peters

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With sections on

GEOLOGIC SETTING
By Faith A. Fitzpatrick

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IMPLICATIONS OF ENVIRONMENTAL SETTING FOR WATER QUALITY
By Charles A. Peters and David W. Hall

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

USGS
science for a changing world

Middleton, Wisconsin
1997

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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 policymakers 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 specific contamination problems; 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 U.S. 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

Robert M. Hirsch
Chief Hydrologist

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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
acre	0.004047	square kilometer
acre	0.4047	hectare
square foot (ft^2)	0.09294	square meter
gallon (gal)	3.785	liter
gallon	0.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	0.02832	cubic meter
foot per second (ft/s)	0.3048	meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second	28.32	liter per second
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meters per day
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
foot per mile (ft/mi)	0.18943	meter per kilometer
gallon per minute per foot [(gal/min)/ ft]	0.207	liter per second per meter [(L/s)/ m
gallon per day per foot [(gal/d)/ft]	12.4	liter per day per meter [(L/d)/m
gallon per day per square foot [(gal/d)/ft^2]	40.7	liter per day per square meter [(L/d)/m^2]
langley per day	1.0	calorie per centimeter squared

Temperature, in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) by use of the following equation: °F = 1.8 x °C + 32.

Abbreviated water-quality units: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

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.

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ENVIRONMENTAL SETTING AND IMPLICATIONS FOR WATER QUALITY IN THE WESTERN LAKE MICHIGAN DRAINAGES

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Abstract

In 1991, the U.S. Geological Survey began to implement its National Water-Quality Assessment (NAWQA) program. The Western Lake Michigan Drainages was one of 20 study units selected for investigation to begin in 1991. The study-unit investigation will include an assessment of surface- and ground-water quality. The quality of water in a study unit is intrinsically related to the natural and anthropogenic features of the study unit. The natural features include geology, weather and climate, vegetation, and hydrology. The anthropogenic features of the basin include population distribution, land use and land cover, agricultural practices, and water use. This report describes the natural and anthropogenic features that constitute the environmental setting of the Western Lake Michigan Drainages as well as the implications of those features on the water quality.

INTRODUCTION

In 1991, the U.S. Geological Survey (USGS) began to implement a National Water-Quality Assessment (NAWQA) program (Hirsch and others, 1988). The long-term goals of the NAWQA program are to describe the status and trends in the quality of a large, representative part of the Nation's surface- and ground-water resources and to provide a sound, scientific understanding of the primary natural and anthropogenic factors affecting the quality of these resources. To achieve these goals, the USGS is employing a multidiscipline approach that includes the collection of physical, chemical, ecological, and ancillary anthropogenic data. These data will provide multiple lines of evidence to assess water quality.

Study-unit investigations comprise the principal building blocks of the national assessment. The 59 study-unit boundaries are based on one or more of the following: surface-water drainage basins, the extent of ground-water aquifers, and political boundaries (fig. 1). The 59 study units represent 60-70 percent of the Nation's water use and population and will be implemented in groups (fig. 2). Three 10-year cycles of implementation are planned.

Prior to any data collection, the scientific staff of each study unit conducts at least two retrospective analyses: an environmental retrospective and a retrospective analysis of nutrients and sediments. The retrospective analyses help to develop an understanding of the hydrology and chemistry of the study unit and identify the general and specific water-quality issues. These analyses are the first steps in developing a conceptual water-resources model of a study unit.

This report describes the environmental conditions pertinent to the selection of sites for monitoring and synoptic sampling in the Western Lake Michigan Drainages (WMIC) study unit, and the interpretation of water-quality data collected as part of the NAWQA program. Many factors affect the surface- and ground-water quality of the WMIC. These include natural factors such as geology (unconsolidated deposits and bedrock), climate, and land vegetative cover, as well as anthropogenic factors such as land use, and point- and nonpoint-source pollution. These factors are all interrelated and affect the physical, chemical, and biological properties that control or reflect water-quality conditions in the study unit.

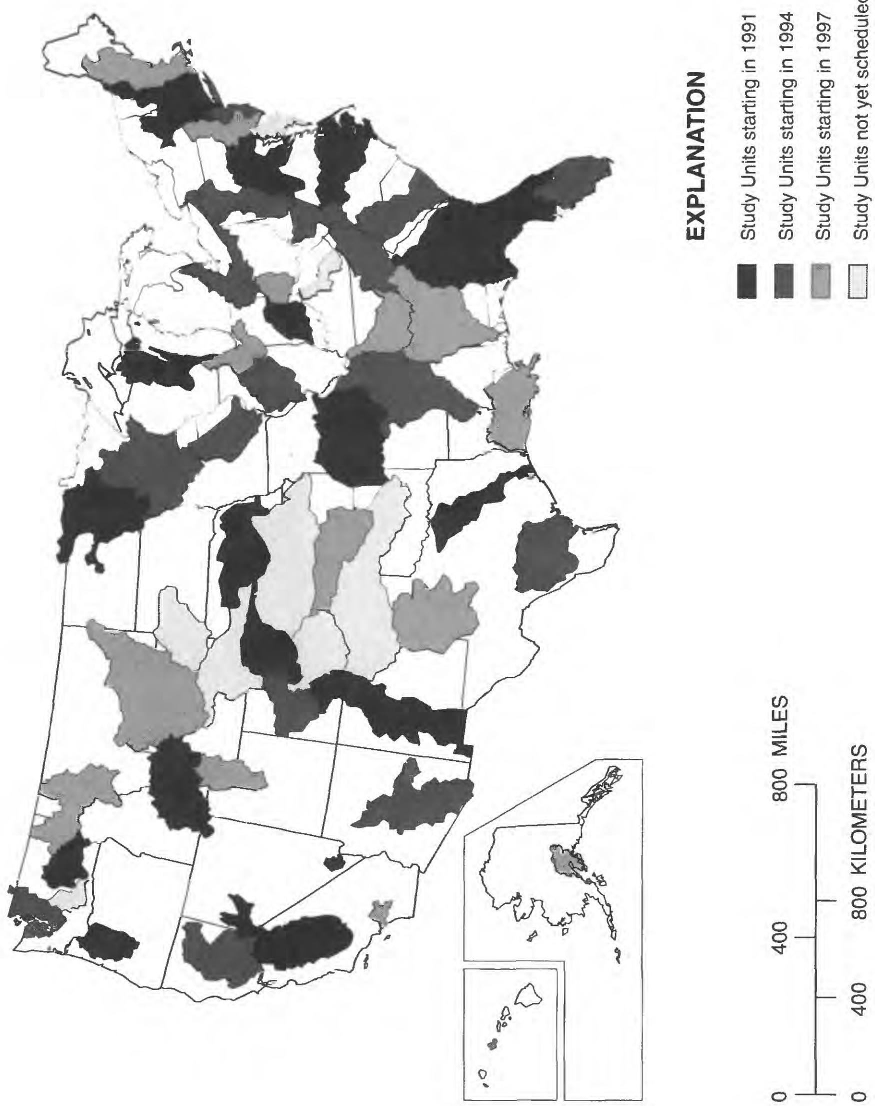


Figure 1. Location of study units in the National Water-Quality Assessment Program.

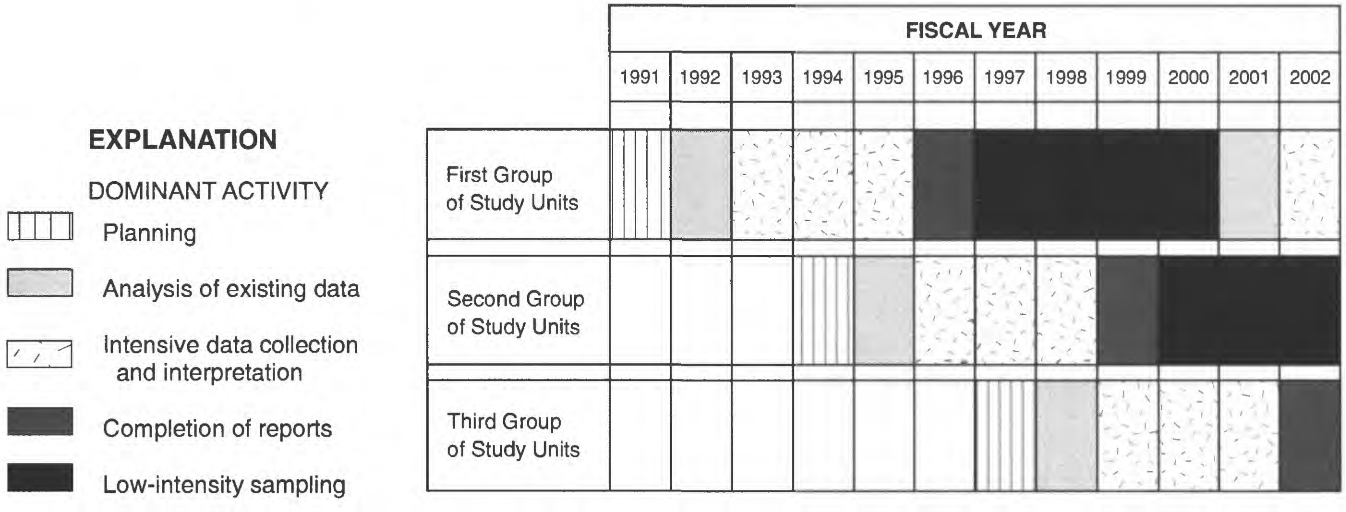


Figure 2. Schedule of first cycle of study-unit investigations, by dominant activity, for the National Water-Quality Assessment Program, fiscal years 1991-2002.

ENVIRONMENTAL SETTING

Physical Characteristics

The WMIC study unit drains a 19,900 mi^2 area of eastern Wisconsin and the Upper Peninsula of Michigan (fig. 3). Ten major rivers drain the basin including the Escanaba River and Ford River in the Upper Peninsula of Michigan, the Menominee River, which defines part of the state boundary for Wisconsin and Michigan, the Peshtigo and Oconto Rivers in northeastern Wisconsin, the Fox/Wolf River complex that drains into Green Bay, and the Manitowoc, Sheboygan, and Milwaukee Rivers that drain directly into Lake Michigan from the southeastern part of the study unit. Hydrologic subunits included in the WMIC study unit include 0403 and 0404 (fig. 3) and are discussed in Seaber and others (1984).

Geologic Setting

By Faith A. Fitzpatrick

The morphological and geochemical characteristics of streams as well as ground-water movement, storage, and chemistry are controlled by consolidated and unconsolidated rock lithologies and structure in the WMIC. Consolidated rocks in the basin include Precambrian crystalline rock, Cambrian sandstones, Ordovician dolomite, sandstone, and shale, Silurian dolomite, and Devonian dolomite (fig. 4A). General stratigraphy of the basin is described in table 1. All rock units dip eastward in the Lake Michigan bedrock basin, with the youngest rocks (Devonian) occurring at the bedrock surface in the southeastern part of the basin and the oldest rocks (Precambrian) occurring at the bedrock surface in the northwestern part of the basin. These units are overlain by Pleistocene glacial deposits, outwash, and glacio-lacustrine deposits; and Holocene alluvium, colluvium, lacustrine, and eolian deposits. Soils are developed in the glacial deposits and alluvium, or bedrock residuum where the unconsolidated deposits are thin or missing.

Landforms in the WMIC are controlled by underlying bedrock lithology and structure that have been modified by Pleistocene glacial processes. They consist of erosion-resistant bedrock uplands, glacial terminal and recessional end moraines, ground moraines, drumlin fields, outwash plains and valleys, dunes, and ancient lake plains. These landforms influence the patterns of drainages and hydraulic characteristics of surface- and ground-water flow. The depth to the bedrock surface is highly variable and ranges from 0 to greater than 100 ft below land surface.

Bedrock

Precambrian igneous and metamorphic rocks in the basin (fig. 4C) are Archean and Proterozoic in age (3 to 1.6 billion years old) and include granites, diorites, gabbros, some extrusive volcanics, gneisses, greenstone schists, iron formations, quartzites, and slates (Dutton, 1971; Granneman, 1984; Greenberg and Brown, 1983; Reed and Daniels, 1987). These discontinuous and highly deformed units are at the bedrock surface in the northwestern part of the basin (40 percent of the WMIC) and dip eastward to more than 2000 ft below sea level near Lake Michigan (Thornthwaite and Mather, 1957). Descriptions of the outcropping Precambrian rocks are plentiful, however, little is known about their composition where they underlie thick units of Paleozoic rocks.

Exposed Archean granites and gneisses are limited to domes surrounded by Proterozoic rocks in the north-central part (981 mi^2) of the WMIC (fig. 4C) (Granneman, 1984; Reed and Daniels, 1987). A thin band of Archean meta-sedimentary and meta-volcanic rocks also stretches across the center of Dickinson County. These rocks represent some of the oldest rocks found in the world and are thought to be part of the first stable continental crust. They form the basement for all younger rocks and are a southern extension of the Canadian Shield. The rocks have been metamorphosed and highly deformed by orogenic events that occurred during the Proterozoic Era. Streams that flow over Archean rocks include the Peshekee River, and the East, Middle and West Branches of the Escanaba River. Parts of the Michigamme River, Fence River, the upper reaches of the Ford River, and part of the Pine and Sturgeon Rivers in Dickinson County also flow over Archean rocks.

Proterozoic rocks underlie approximately 6,700 mi^2 of the basin and can be subdivided into four tectonic terrains that can be distinguished by their overall geochemistry and alteration characteristics (fig. 4C): northern Penokean terrain, Penokean volcanic belt, post-Penokean, and Wolf River batholith (Greenberg and Brown, 1983). The east-west trending Niagara

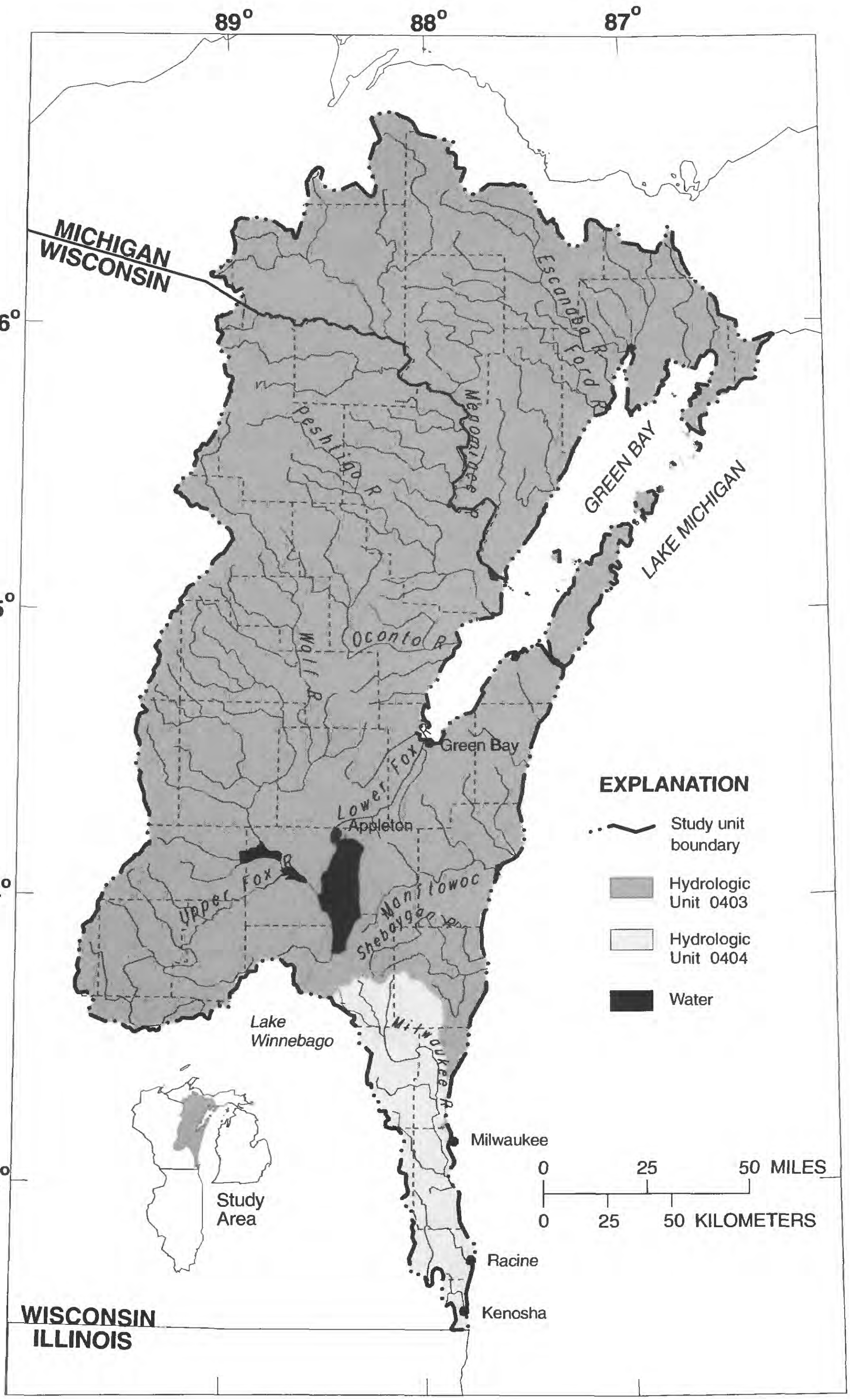


Figure 3. Location of the Western Lake Michigan Drainages study unit and hydrologic units.

fault separates the northern Penokean terrain from the southern Penokean volcanic belt. Rocks in these two terrains are the result of the Penokean orogeny which occurred about 1.8 billion years ago and correlate with the Marquette Range Supergroup (table 1). Abundant thick sedimentary units (mainly slates, graywacke, and iron formations) and subordinate tholeiitic volcanic rocks are present in the northern Penokean terrain, whereas abundant calc-alkalic volcanic rocks and subordinate sedimentary units are present in the Penokean volcanic belt south of the Niagara fault (Greenberg and Brown, 1983). Other differences between these two terrains include: (1) rocks in the northern Penokean terrain appear to be somewhat older than the southern terrain, (2) rocks in the northern terrain contain major iron formations that are not present in the southern terrain, and (3) domes cored by Archean rocks occur only in the northern terrain. Alteration in both terrains increases toward the Niagara fault, but is not limited to the faulted area.

Michigan streams that drain the northern Penokean terrain include the Paint River and its tributaries, and parts of the Fence River, Michigamme River, Ford River, Sturgeon River, and Pine Creek. Streams that drain the Penokean volcanic belt (in Wisconsin for the most part) include the Pine River, Popple River, Pemebonwon River, Pike River, Wausakee River, Peshtigo River, Rat River, Otter Creek, Middle Inlet, upper reaches of the Wolf River and Oconto River, most of the Tomorrow River, and some parts of the Little Wolf River. The Menominee and Brule Rivers are partially superimposed over the Niagara fault.

Post-Penokean rocks in the WMIC occur in small areas just north of the Wolf River batholith (fig. 4c). These rocks are composed mainly of granite or quartzite and discontinuously cover 116 mi^2.

The middle Proterozoic-aged Wolf River batholith (approximately 1.5 billion years old) is exposed at the bedrock surface over approximately 1,950 mi^2 in the west-central part of the WMIC (fig. 4C). It is composed of granitic and syenitic rocks, with some quartz monzonite in Shawano, Waupaca, and Portage counties. Streams that drain this area are the middle reaches of the Wolf River and its tributaries, upper branches of the Embarrass River, upper branches of the Little Wolf River, Second South Branch of the Oconto River, middle reaches of the North Branch Oconto River, and most of the drainage for Peshtigo Brook.

A large gap in time occurs in the rock record between the youngest Proterozoic rocks and the overlying Paleozoic rocks. This represents a time during which no deposition was occurring or a time of substantial and widespread erosion. Paleozoic rocks consist mainly of dolomite and sandstone interspersed with layers of limestone and shale that originated from deposition of sediments in a transgressing and regressing sea environment from 570 million to 345 million years ago.

Sandstone with subordinate dolomite and shale of Cambrian age stratigraphically overlies the lower Proterozoic rocks and occur at the bedrock surface in a band from the southwest corner of the basin to the north-central part of the basin (fig. 4A). The Cambrian rocks also are interspersed with Precambrian rocks in Michigan. In Michigan, the Munising Formation and the Trempeleau Formation define the Cambrian bedrock surface (Reed and Daniels, 1987; Twenter, 1981). South of the Michigan/Wisconsin border, the Cambrian rocks are undifferentiated and include the Trempeleau, Tunnel City, and Elk Mound groups (Krohelski, 1986; Mudrey and others, 1982; Young and Batten, 1980). The Ordovician Prairie Du Chien Group resembles the Trempeleau Group and it is difficult to distinguish the boundary between the two (Twenter, 1981). There is a discrepancy in the location of the Trempeleau/Prairie Du Chien boundary between the Wisconsin and Michigan state bedrock maps. Streams that flow over Cambrian rocks include all of the western tributaries to the Upper Fox River, the lower Wolf River, and the middle reaches of the streams that flow out of the Precambrian in an easterly direction toward Green Bay.

Ordovician rocks consist mainly of dolomite interspersed with sandstone, limestone, and minor shale. The rocks occur at the bedrock surface in a band running southwest to northeast through the center of the WMIC (fig. 4B). Stratigraphic names of the mappable units differ in Wisconsin and Michigan. In Wisconsin, these rocks are mapped as the Prairie Du Chien, Ancell, and Sinnipie groups (Krohelski, 1986; Gonthier, 1975; and Young and Batten, 1980); in Michigan, however, the units are mapped as Prairie Du Chien, Black River, Trenton, and Richmond groups. The Maquoketa shale occurs at the top of the Ordovician surface in Wisconsin. Streams that flow over Ordovician rocks include the Fond du Lac River, Lower Fox River, East River, Duck Creek, Suamico River, and Sturgeon River (Delta County); and the lower reaches of the Oconto, Peshtigo, Menominee, Little, Ford, Escanaba, Cedar, and Whitefish Rivers.

Silurian dolomite with subordinate shaley limestone and shale occur at the bedrock surface in a band running parallel to the Ordovician rocks (fig. 4A). Silurian rocks in Wisconsin are undifferentiated (Young and Batten, 1980); in Michigan, however, the Silurian rocks have been divided into 5 mappable units (from top to bottom): Engadine Group (dolomite), Manistique Group (dolomite), Burnt Bluff Group (dolomite), Cabot Head Shale, and Manitoulin Dolomite (Reed and Daniels, 1987). Streams that flow over Silurian rocks include all those that directly drain into Lake Michigan, including the Manitowoc River, Sheboygan River, and Milwaukee River.

A small area of Devonian-aged carbonate rocks occur directly north of the Milwaukee area along Lake Michigan to south of Sheboygan, Wisconsin. The unit is less than 5 miles wide and contains mainly dolomite, shaley limestone, and shale (Mudrey and others, 1982).

A second large gap in the geologic time record occurs between the youngest Paleozoic rocks and the oldest Quaternary unconsolidated deposits (table 1). During this time (about 345 million years to 1.8 million years ago), the rocks were tilted eastward as a bowl-shaped depression developed to the east due to differential subsidence and compaction in the Michigan basin. Variable resistance to erosion of the sedimentary rocks caused some areas to erode faster than others. Differential erosion rates produced lowlands and uplands that ran in bands parallel to the strike of the rock. One such feature is the Niagara Cuesta, which defines the contact between the more resistant Silurian dolomite and the less resistant Ordovician Maquoketa Shale (fig. 4A). The Precambrian rocks form an upland because they are relatively more resistant to erosion than the Paleozoic sedimentary rocks. Highly-developed drainage networks were formed in the bedrock surface during the time period between the Devonian and Quaternary.

Surficial Deposits and Soils

Surficial deposits in the basin consist mainly of unconsolidated glacial, fluvial, and eolian deposits composed of gravel, sand, silt, or clay. Quaternary-aged deposits are the result of erosional and depositional processes that occurred during Pleistocene glacial and interglacial periods, and the Holocene (the current interglacial). Glacial deposits and landforms on the surface are produced by processes that occurred during the last glacial period called the "Wisconsin." Glacial deposits are highly variable in texture, and usually occur in discontinuous units, making them difficult to map. Three characteristics of surficial deposits that are important for water-quality studies include source, texture, and thickness.

During the Wisconsin period, ice fronts advanced and retreated over the study unit several times. The resulting surficial glacial sediments were deposited between 25,000 and 9,500 years before present (Clayton and others, 1991; Hansel and others, 1985; Peterson, 1986). The three major lobes in the WMIC are: the Langlade, Green Bay, and Lake Michigan lobes (fig. 5). Ice movement for all lobes generally was from the northeast to the southwest. The western edge of the WMIC is defined by the terminal moraines marking the farthest extent of the Green Bay and Langlade lobes during the Cary advance (14,000 years ago). Later, during the Port Huron advance (about 12,500 years ago), ice advanced again into the study unit; however, it stopped in the vicinity of Lake Winnebago. The Two Rivers advance occurred at about 11,500 years ago, and extended to the Green Bay area. By 9,500 years ago, the ice front retreated north of Lake Superior.

The mineralogy of the glacial deposits reflects the source of the sediments. Glacial deposits in the Green Bay and Lake Michigan Lobes are typically more carbonate-rich than those derived from the Lake Superior basin. Glacial deposits derived from the Lake Superior area (Langlade, Keweenaw Bay, and Michigamme Lobes) are typically reddish-brown and very sandy or loamy with a low proportion of dolomite and other Paleozoic clasts (Mickelson and others, 1984; Farrand and Bell, 1984; Attig and others, 1988). Glacial deposits derived from Green Bay and the Lake Michigan basin are typically yellowish-brown or gray, sometimes sandy, and often silty and clayey. More detailed descriptions of the origin and composition of the glacial deposits and related sediments in the WMIC can be found in several publications including Attig (1985), Attig and others (1988), Black (1970), Black and others (1970), Clayton (1986), Farrand and Bell (1982), McCartney (1983), Mickelson and Clayton (1983), Mickelson and others (1984), Mickelson (1986), Need (1985), and Simpkins and others (1987).

Ancient levels of Lake Michigan varied from a maximum of 640 ft above sea level to less than 580 ft during the Pleistocene (Hansel and others, 1985).

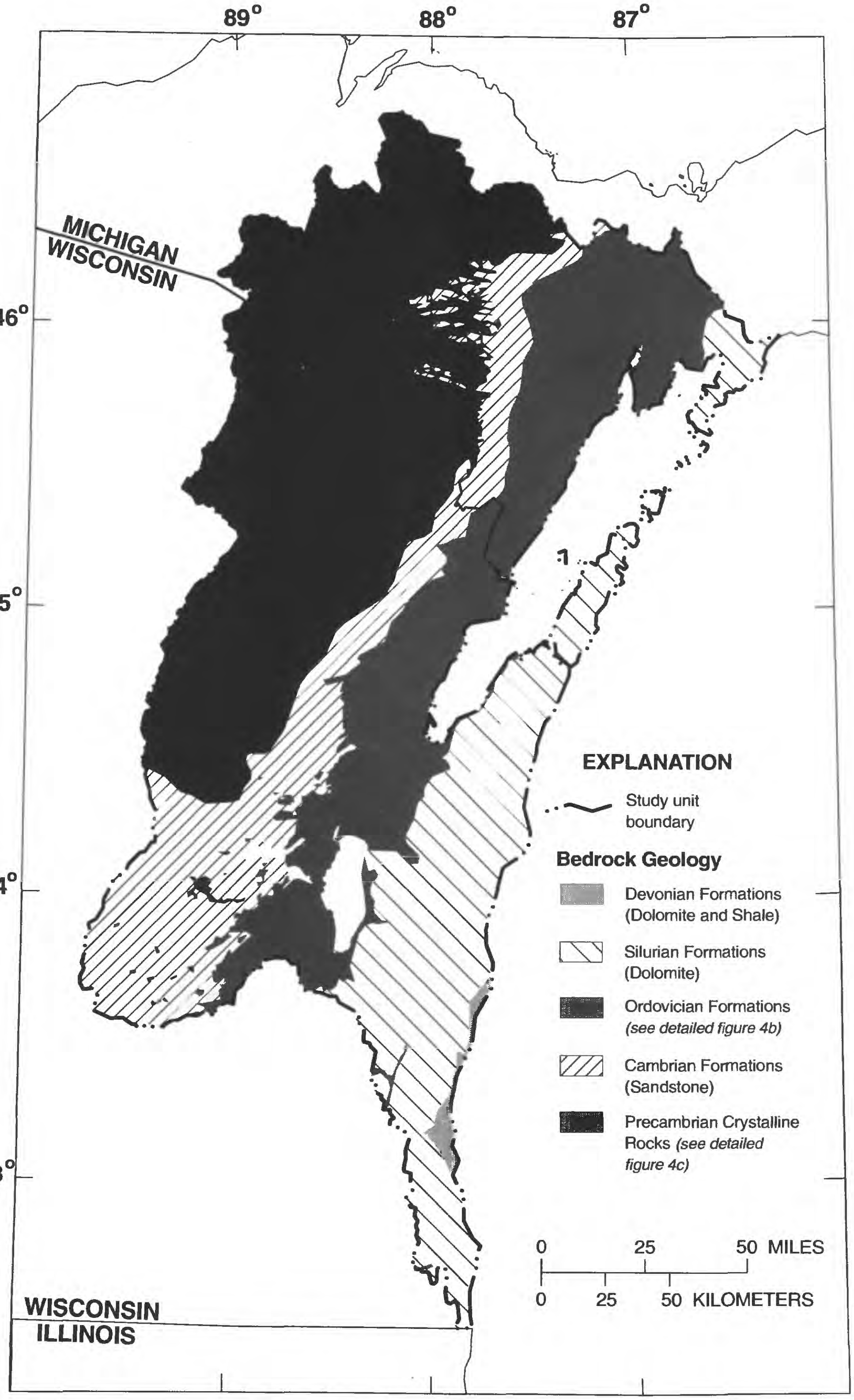


Figure 4a. Bedrock geology in the Western Lake Michigan Drainages study unit (modified from Krohelski, 1986; Young and Batten, 1980; Gonthier, 1975; and Mudrey and others, 1982).

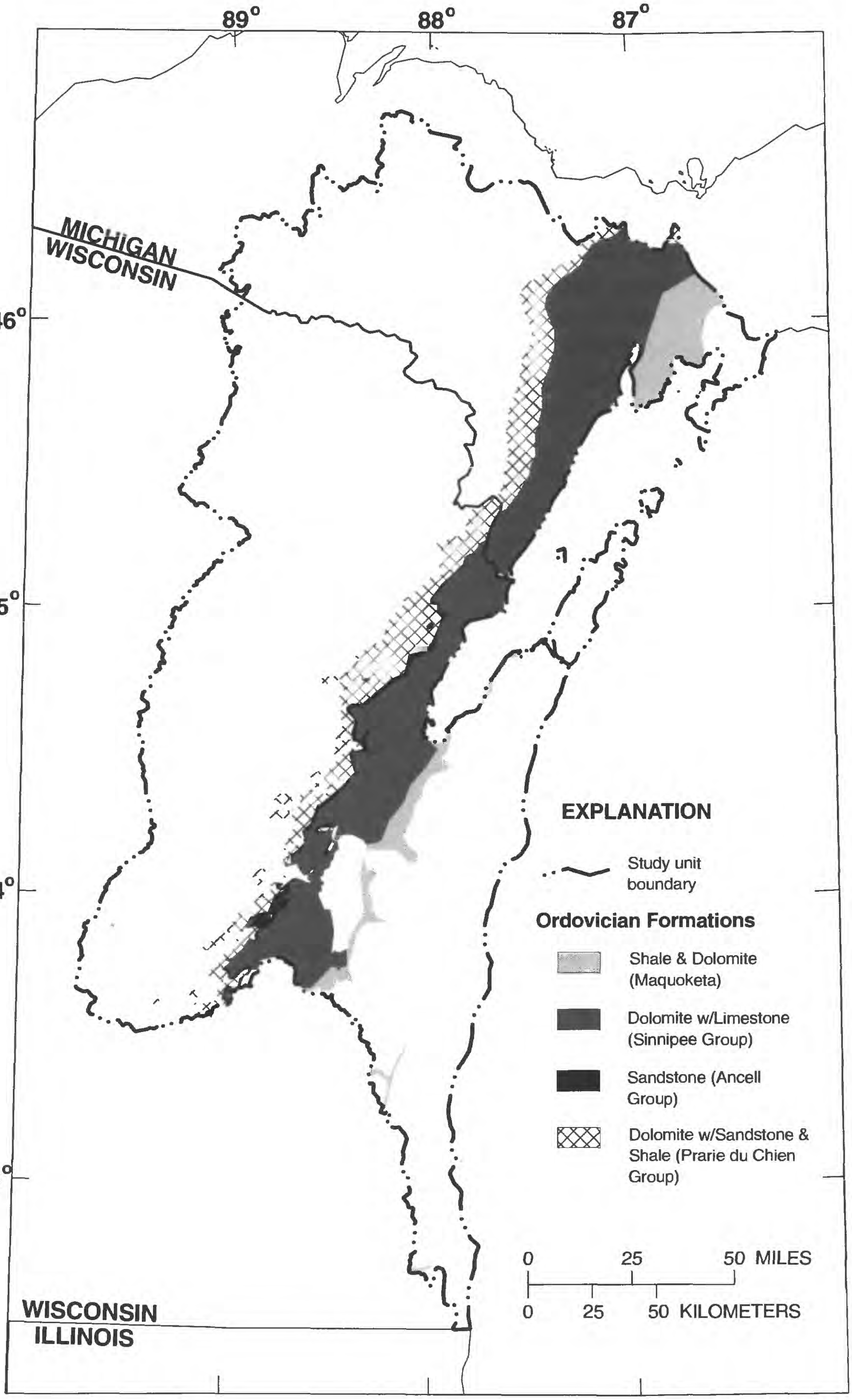


Figure 4b. Bedrock geology in the Western Lake Michigan Drainages study unit—Continued.

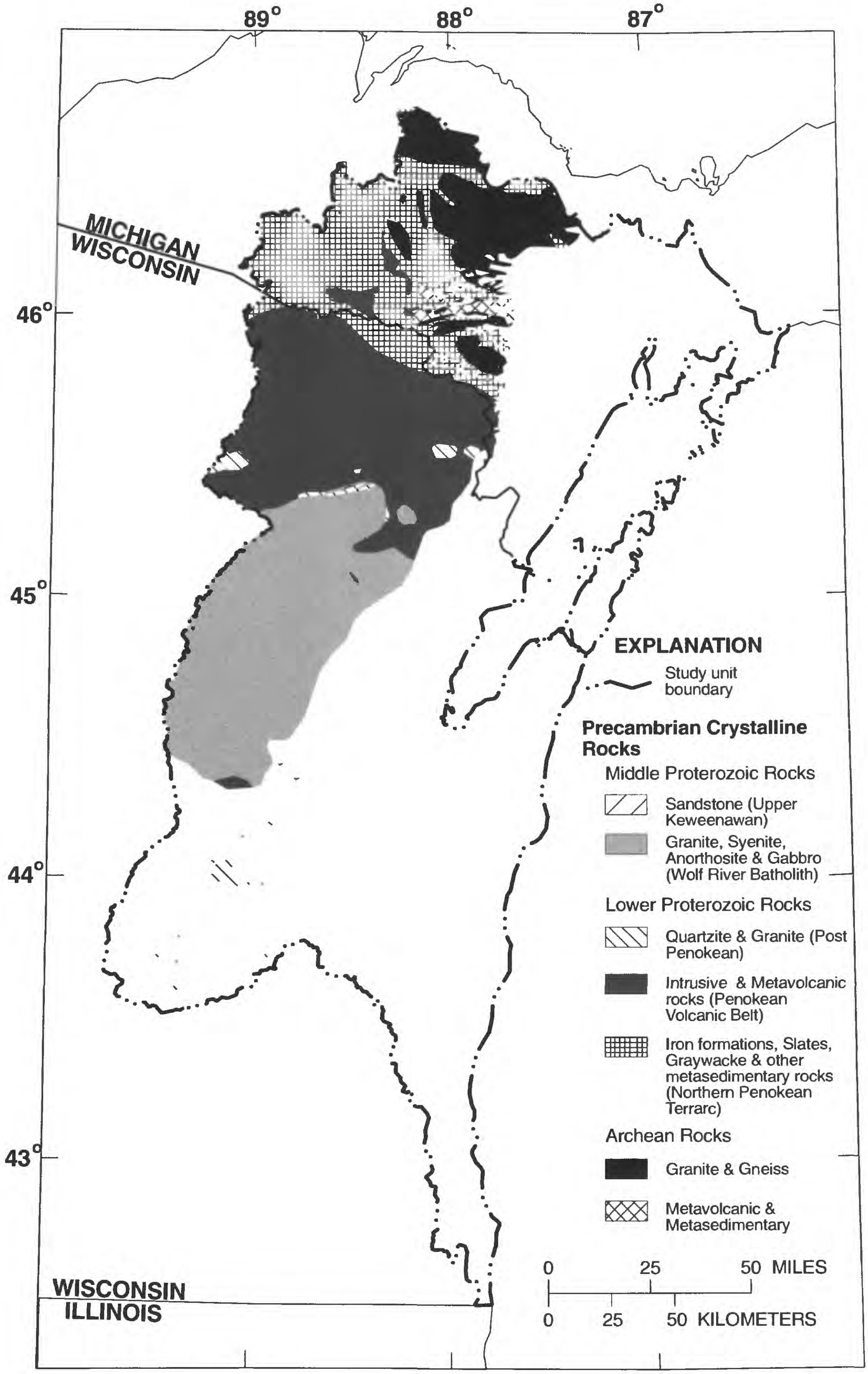


Figure 4c. Bedrock geology in the Western Lake Michigan Drainages study unit—Continued.

Table 1. Stratigraphy in the Western Lake Michigan Drainages study unit

[modified from Krohelski, 1986; Young and Batten, 1980; Gonthier, 1975; Mudrey and others, 1982; Dolo., Dolomite; Fm., Formation; Mem., Member; Qzte., Quartzite; Gr., Group]

Eon	Era	Period	Wisconsin		Michigan	
			Geologic unit	Lithology	Geologic unit	Lithology
Phanerozoic	Cenozoic	Quaternary	Holocene			
			Pleistocene	Unconsolidated glacial deposits, outwash, and lacustrine deposits.	--not present in study unit in Michigan--	
	Paleozoic	Devonian	Undifferentiated	Dolomite, brown to gray, and gray shale. Crevices and solution channels abundant but discontinuous.		
		Silurian	Undifferentiated	Dolomite with varying amounts of fossil fragments, gypsum crystals, pyrite, and limestone. Crevices and solution channels abundant but discontinuous, includes Cayugan, Niagran, and Alexandrian Series.	Niagran Series Engadine Gr. Manistique Gr. Burnt Bluff Gr. Alexandrian Series Cataract Gr.	Dolomite Shale and dolo., includes Cabot head Shale and Manitoulin Dolo.
		Ordovician	Maquoketa Fm. Brainerd Mem. Fort Atkinson Mem. Scales Mem.	Predominately dolomitic shale. The Fort Atkinson Member is fossiliferous dolomite. Includes the Neda Formation.	Cincinnatian Series Richmond Gr.	Shale with subordinate dolomite and limestone
			Sinnipee Gr. Galena Fm. Decorah Fm. Platteville Fm.	Galena and Platteville Formation are dolomite. The Decorah Formation is shale.	Mohawkian Series Trenton Gr. Black River Gr.	Limestone and dolomite
			Ancell Gr. Glenwood Fm. St. Peter Fm. Tonti Mem. Readstown Mem.	The Glenwood Formation is a silty sandstone. The Tonti Member is a fine- to medium-grained sandstone and the Readstown Member is a sandy shale.		
			Prairie du Chien Gr. Shakopee Fm. Willow River Mem. New Richmond Mem. Oneota Fm.	The Prairie du Chien Group is generally dolomite with varying amounts of oolitic chert. The group can be subdivided only where the New Richmond Member, a sandstone, shaly sandstone, or dolomitic sandstone, is present.	Prairie du Chien Gr.	Dolomite

Table 1. Stratigraphy in the Western Lake Michigan Drainages study unit—Continued

Eon	Era	Period	Wisconsin		Michigan	
			Geologic unit	Lithology	Geologic unit	Lithology
Phanerozoic (cont.)	Paleozoic (cont.)	Cambrian	Trempealeau Gr. Jordan Fm. St. Lawrence Fm.	The Jordan Formation is fine- to medium-grained sandstone. The St. Lawrence Formation is a silty glauconitic dolomite.	St. Croixan Series Lake Superior Gr. Trempealeau Fm. Munising Fm.	Dolomite and sandstone
			Tunnel City Gr. Mazomanie Fm. Lone Rock Fm.	The Mazomanie Formation is a fine- to medium-grained sandstone. The Lone Rock Formation is a silty sandstone to a sandy dolomite.		
			Elk Mound Gr.	The members of the Elk Mound group are usually not differentiated.		
			Eau Claire Fm. Mount Simon Fm.	Where distinguishable the units generally present are a very fine- to fine-grained sandstone and a medium- to coarse-grained sandstone.		
Precambrian	Proterozoic	Middle	Wolf River Batholith	Granites, syenites, quartz monzonites with anorthosite and gabbro inclusions.		
		Lower	Rib Mountain Qzte. Mosinee Hill Qzte. McCaslin Qzte.	Quartzite, and associated slate, dolomite, ferruginous slate, conglomerate and chert. Post-tectonic granite.		
			Intrusive Rocks	Intermediate to granitic intrusive rocks, generally discrete, weakly to moderately deformed bodies. Tonalitic to granodioritic rocks, massive to foliated and commonly intruded by granitic rocks. Banded, layered, and migmatitic gneiss with subordinate amphibolite and biotite schist. Metamorphosed ultramafic to mafic intrusive rocks.	Intrusive Rocks Quinnesec Fm.	Mafic rocks and granite

Table 1. Stratigraphy in the Western Lake Michigan Drainages study unit—Continued

Eon	Era	Period	Wisconsin: Geologic unit	Wisconsin: Lithology	Michigan: Geologic unit	Michigan: Lithology
Precambrian (cont.)	Proterozoic (cont.)	Lower (cont.)	Metavolcanic and metasedimentary rocks Tyler Fm. Palms Qzte. Bad River Dolo. Ironwood Fm. Riverton Iron Fm.	Meta-argillite, meta-siltstone, quartzite, meta-graywacke, meta-conglomerate, meta-iron formation, and marble, with some minor interbedded metavolcanic rocks. Magnetic iron formation. Dominantly mafic metavolcanic rocks with subordinate felsic metavolcanic rocks; greenschist, and amphibolite metamorphic facies. Mafic, intermediate, and felsic metavolcanic rocks with subordinate metasedimentary rocks; dominantly greenschist metamorphic facies.	Paint River Gr. Riverton Iron Fm. Dunn Creek Fm.	Iron formations and slate
					Baraga Gr. Badwater Greenstone. Michigamme Fm. Bijiki Iron Fm. Goodrich Qzte. Amasa Fm. Hemlock Fm.	Greenstone, slate, iron formations, and quartzite
					Menominee Gr. Negaunee Iron Fm. Vulcan Iron Fm. Ironwood Iron Fm. Siamo Slate Ajibik Qzte. Palms Fm.	Metavolcanic rocks, iron formations, slate, quartzite
					Chocolay Gr. Randville Dolo.	Conglomerate, quartzite, and dolomite
	Archean		--not present in study unit in Wisconsin--			Ultramafic rocks Granitic and gneissic Volcanic and sedimentary

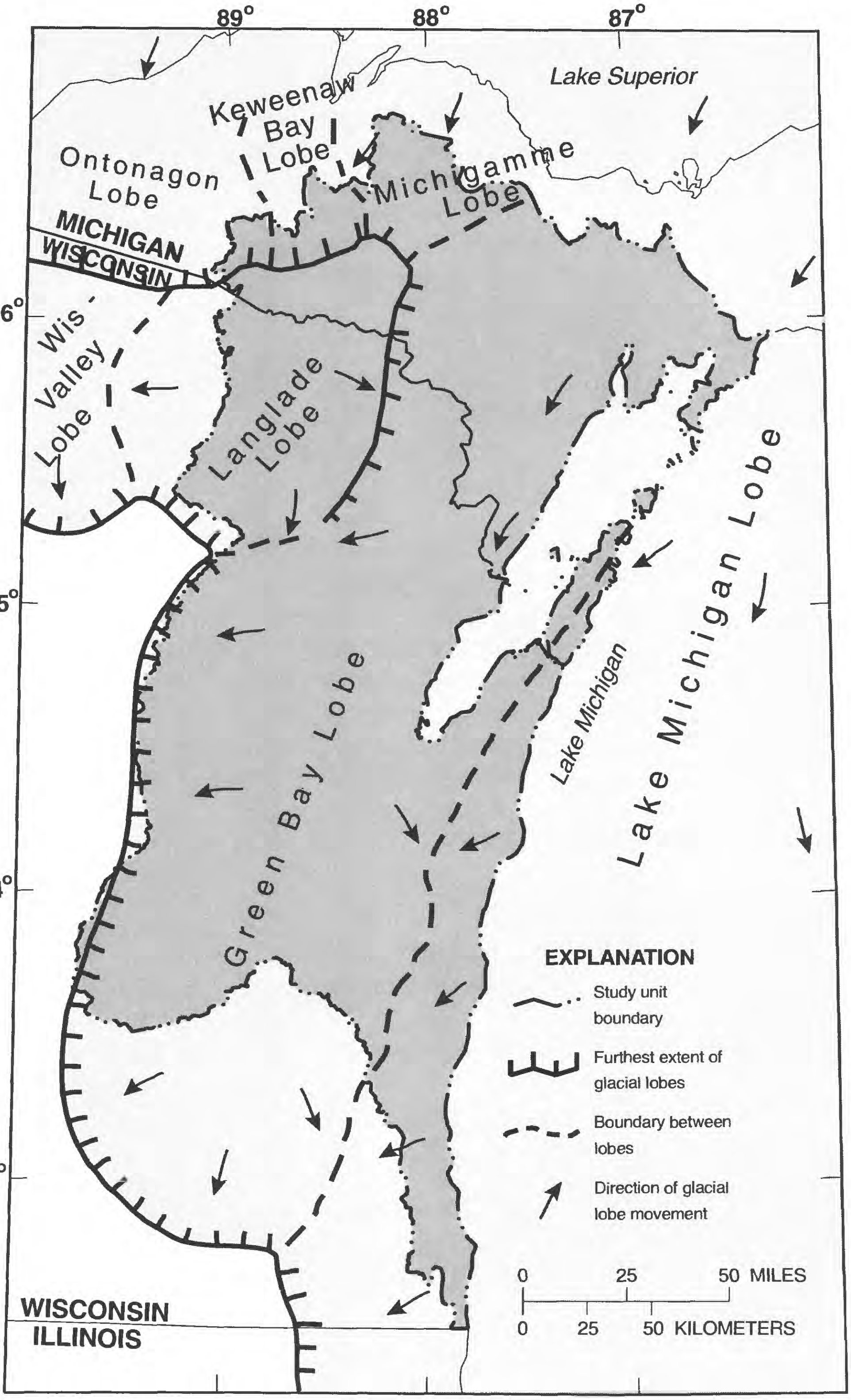


Figure 5. Major glacial ice advances and texture of surficial deposits in the Western Lake Michigan Drainages study unit (modified from Clayton and others (1991) and Peterson, 1986).

Large volumes of meltwater were released from the glaciers both gradually and catastrophically. Often, drainage of meltwater was blocked by advancing or retreating ice fronts and sediment dams, which resulted in formation of large, extensive glacial lakes. These lakes are reflected in the present landscape by broad, flat plains composed of fine-grained sediment. Meltwater also carved valleys into the glacial drift that in many cases are occupied by modern streams. These valleys are typically oversized for the stream's present-day hydrologic regime.

The textural characteristics (fig. 6) of the surficial deposits influence the quality of stream reaches by affecting overland and stream bank erosion rates, particle size of suspended and streambed sediment, vegetation, aquatic biota, and land-use practices. Sand-and-gravel and sand deposits occur mainly in outwash plains and in glaciofluvial meltwater channels, and are most extensive in the western part of the basin. Loamy deposits consist mainly of glacial drift in ground and end moraines and occur in the northern and central parts of the basin. Clayey deposits occur in the central and eastern parts of the basin and are mainly glaciolacustrine in origin. Isolated peat deposits cover a small part of the Michigan portion of the basin.

The thickness of surficial deposits in the WMIC is highly variable and ranges from being absent to nearly 400 ft thick. In general, deposits are thickest in end moraines and toward the southeast. Surficial deposits are very thin in the northern part of the basin, where igneous/metamorphic rocks form an erosion-resistant upland.

Types of soils in the WMIC are dependent on their position in the landscape, texture and chemistry of the parent material (either bedrock, glacial or recent sediments), stage of development, and vegetation. In the southern part of the WMIC, forest, prairie, and wetland soils are common. These include alfisols, entisols, inceptisols, mollisols, spodosols, and histosols (Wisconsin Geological and Natural History Survey, 1968). Spodosols are common in the northwest part of the basin, where parent materials are sandy and conifers are common (Wisconsin Geological and Natural History Survey, 1968; Michigan State University and U.S. Department of Agriculture, 1981). Bog soils are scattered throughout the basin in marshy and wetland areas.

Physiography

Two physiographic provinces have been mapped by Fenneman (1938) and Martin (1965) in the WMIC. They are: (1) the Laurentian Upland Division, Superior Upland Province, and (2) the Interior Plains Division, Central Lowland Province, Eastern Lake Section (fig. 7). The provinces and sections are based on common topography, rock types and structure, and geologic and geomorphic history. Altitudes in the study unit ranges from about 1500 ft in the northwestern areas to near sea level in areas along the shore of Lake Michigan.

The Superior Upland Province is restricted to Precambrian rocks by definition (Fenneman, 1938). Thus, the boundaries for this province approximate the boundary between Precambrian and Cambrian rocks. However, the boundary does not match the boundary between Precambrian and Paleozoic rocks on current bedrock geology maps. This most likely is due to differences in scales between the maps. Topography of this province is variable, and controlled mainly by bedrock lithology and structure. Lowlands are present where the bedrock is more erodible, and ridges where the bed-rock is less erodible. Glacial drift that overlies the bedrock is variable in thickness, and is absent in some areas.

The Central Lowland Province is distinguished from the Superior Upland Province by its topography, which is controlled mainly by glacial depositional processes instead of bedrock structure, and its bedrock geology, which is composed of several Paleozoic bedrock basins and escarpments. Characteristics of the Eastern Lakes Section include relatively young glacial deposits with pitted outwash and drumlins and extensive glacio-lacustrine deposits. Bedrock structure is controlled by the Niagara Escarpment.

Vegetation

By Faith A. Fitzpatrick

The WMIC study unit currently contains remnants of all native plant communities that were recognized in Wisconsin before European settlement. The major plant groups include mixed coniferous-deciduous forest, deciduous forest, upland prairie and brush, boreal forest, and wetland vegetation (Finley, 1976). Within each group, several communities are based on dominance of certain plant species (table 2). Although most of these communities were mapped as discontinuous units, the boundaries represent approximate dis

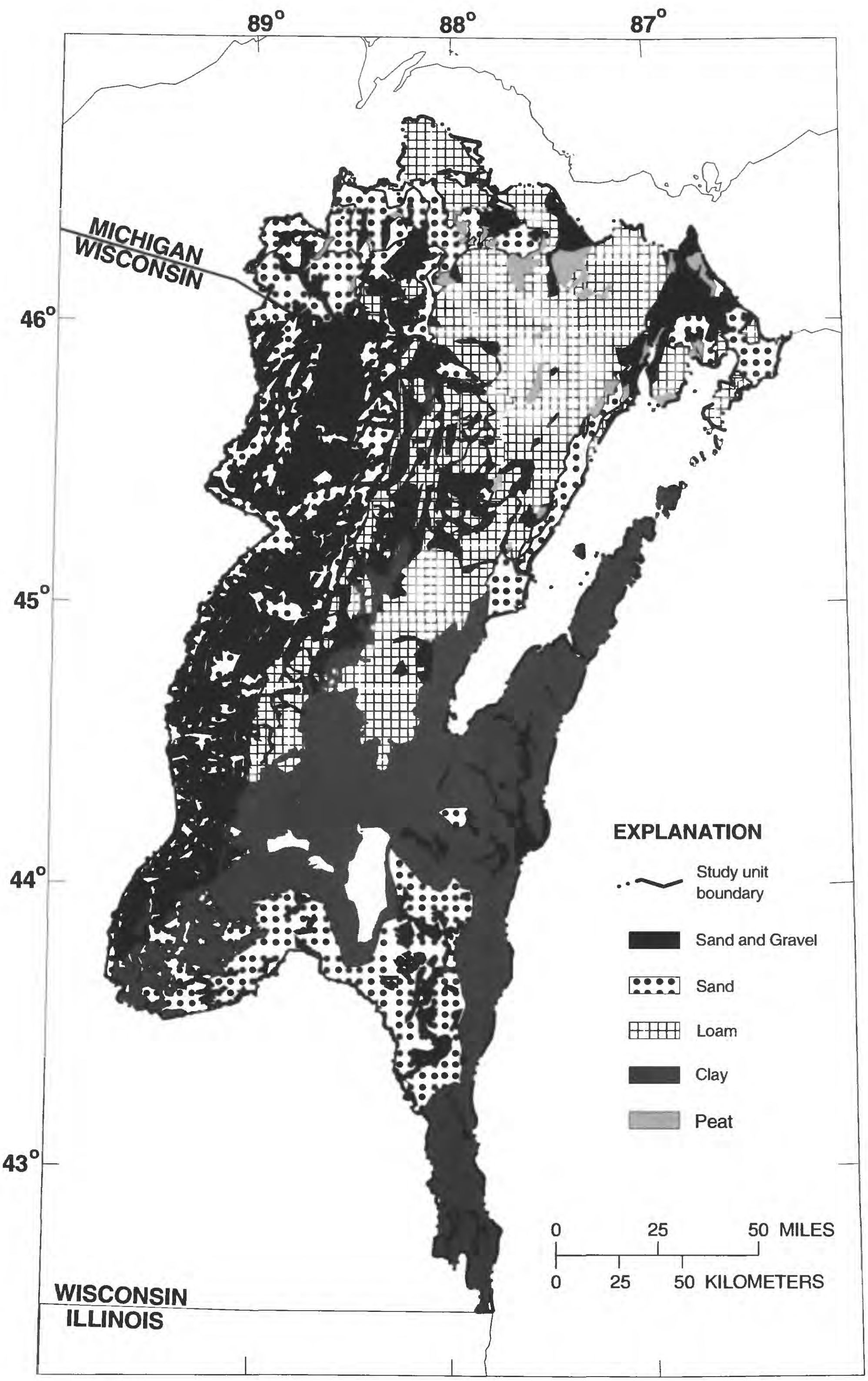


Figure 6. Texture of surficial deposits in the Western Lake Michigan Drainages study unit.

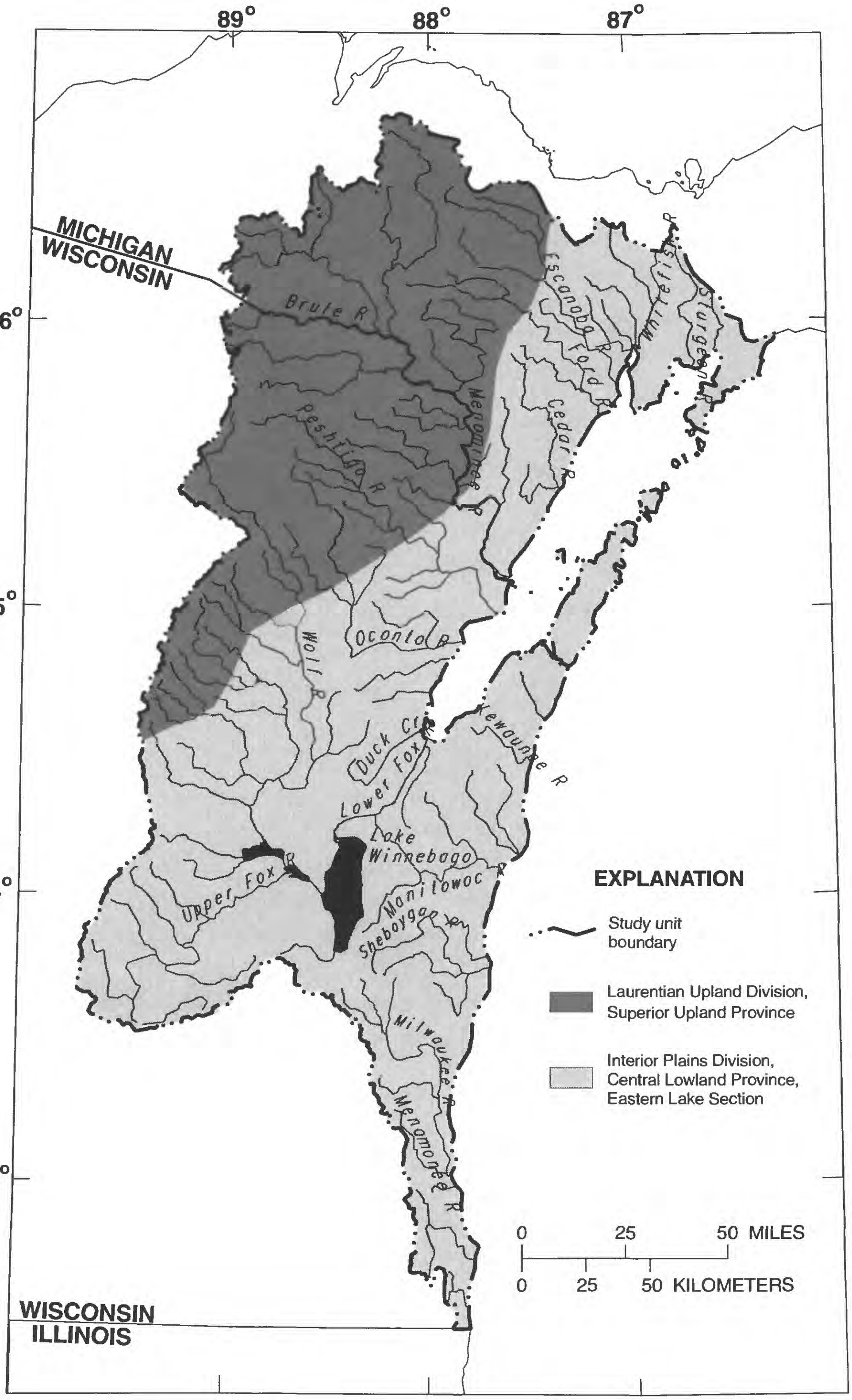


Figure 7. Physiographic provinces in the Western Lake Michigan Drainages study unit (modified from Fenneman, 1938; and Martin, 1965).

Table 2. Original vegetation communities in the Western Lake Michigan Drainages study unit
[modified from Finley, 1976]

Group	Community
Mixed coniferous-deciduous	Beech-hemlock-sugar maple-yellow birch-pine forest
	Hemlock-sugar maple-yellow birch-pine forest
	Sugar maple-yellow birch-pine forest
	White pine-red pine forest
	Jack pine-Hill's oak forests and barrens
	Aspen-white birch forest
Deciduous forest	Beech-sugar maple-basswood-oak forest
	Sugar maple-basswood-oak forest
	Oak forest
	Oak openings and barrens
Upland prairie and brush	Upland prairie
	Brush
Wetland vegetation	Swamp conifers
	Lowland hardwoods
	Marsh and sedge meadow, wet prairie, lowland shrubs
Boreal forest	Boreal forest

tributions because plant species naturally occur across a continuum.

Empirically, there is a zone that corresponds to the southern-most limit of the conifer-deciduous forest, and the northern most limit of the upland prairie. This 'Tension Zone' (Curtis, 1959) extends across Wisconsin and continues through the center of the study unit from the northwest (Outagamie County) to southeast (Milwaukee County). A combination of factors such as average snowfall, summer temperatures, and evaporation are thought to contribute to the placement of this zone. The amount of effective precipitation is considered the most important factor.

Since European settlement, all the plant communities have been modified to various degrees by human activity. For example, prairie vegetation is extremely rare throughout Wisconsin due to removal by frequent fire and conversion to agricultural land. Only small pockets remain along railroads, in historical cemeteries, and nature preserves. Other major human activities that have strongly influenced these plant communities include logging and urban development.

Ecoregions

By Barbara C. Scudder *and* David A. Saad

The ecoregions defined for the area in and around the WMIC were the result of an effort to use existing spatial frameworks to classify streams for more effective water-quality management (Omernik and Gallant, 1988). The spatial framework used to define these ecoregions was in the form of four component maps: (1) potential natural vegetation (Kuchler, 1970), (2) land-surface form (Hammond, 1970), (3) soils (Ohio Department of Natural Resources, Division of Land and Soil, 1973; U.S. Department of Agriculture, 1957), and (4) land use (Anderson, 1970).

Important factors such as climate and length of growing season are integrated into the component maps. Ecoregions delineated from these component maps subdivided into areas that are 'generally typical' (shaded) and 'most typical' (cross-hatched) of that ecoregion (fig. 8). The WMIC is composed of four ecoregions: Northern Lakes and Forests, North Central Hardwood Forests, Southeastern Wisconsin Till Plains, and Central Corn Belt Plains. Parts of the report 'Ecoregions of the Upper Midwest States' (Omernik and Gallant, 1988), from which the following information was gathered, is currently being revised and updated.

Northern Lakes and Forests

Northern Lakes and Forests is the largest ecoregion, covering about 9,700 mi^2 (49 percent) of the WMIC in the northern half of the study unit. This ecoregion supports mixed northern hardwood forest vegetation, in addition to extensive areas of coniferous forest. Soils in this ecoregion are formed primarily from sandy and loamy glacial drift materials. Till plains, morainal hills, broad lacustrine basins, and sandy outwash plains are typical land-surface forms and numerous lakes dot the landscape. Extensive wetlands cover flat and/or low-lying areas. Local relief is minimal on the plains, but ranges between 200 and 500 ft in the hilly areas. Most of this ecoregion is ungrazed forest and woodland, some of which is used for timber production and recreation. Farming is limited due in part to relatively nutrient-poor soils, and a short growing season. The areas that are cultivated provide mainly forage and feed grains for livestock. Mining activities also take place in some parts of this ecoregion. Most streams in the ecoregion are perennial, commonly originating in lakes or wetlands. Stream density is relatively low, with less than one mile of streams per square mile. Many streams originating within this ecoregion drain watersheds of more than 1,000 mi^2.

North Central Hardwood Forests

Most central and west-central parts of the study unit are classified as the North Central Hardwood Forests ecoregion. This ecoregion is transitional between the Northern Lakes and Forests ecoregion and the agricultural ecoregions to the south, and covers about 25 percent (4,900 mi^2) of the study unit. The soils of this ecoregion are characterized by many different particle sizes. These soils have been primarily derived from glacial materials. The land surface consists of nearly level to rolling glacial till plains, lacustrine basins, outwash plains, and rolling to hilly moraines and beach ridges. Lakes dominate the landscape in many parts of this ecoregion. Local relief is minimal in the plains, and ranges between 100 and 200 ft in morainal areas. The land use in this ecoregion is mixed, although much of it is cultivated to provide feed for dairy cattle or is permanent pasture. The areas that remain forested are used for woodlots, pulp, and timber production. Stream density and flow are highly variable throughout this ecoregion. Density ranges from virtually zero (that is, no streams), such as in kettle/wetland terrain, to more than two miles of perennial streams per square mile. Stream flow is intermittent in some portions of the ecoregion and perennial in others.

Southeastern Wisconsin Till Plain

The Southeastern Wisconsin Till Plain ecoregion covers about 5,200 mi^2 (25.9 percent) in the south central and southeastern portions of the study unit. The vegetation types represent a transition between the hardwood forests of the North Central Hardwood Forests ecoregion to the north, and oak savannas of the Driftless Area to the west, and the tall-grass prairies of the Central Corn Belt Plains to the south. The soils of this ecoregion were formed in a humid temperate climate under hardwood forest vegetation. The land surface is characterized by outwash plains, lacustrine basins, and level to rolling till plains mantled with silt in some locations. Drumlins and morainal belts are distinct features and add as much as 250 ft of relief in some areas. Lakes and bogs are common in many parts of this ecoregion. Altitude ranges from about 600 ft along the shore of Lake Michigan to greater than 1,000 ft on some hills. Dairy and livestock farming is the predominant land use in this ecoregion and most cropland is dedicated to the cultivation of forage and feed grains. The rest of the cropland consists of pasture and farm woodlots. The larger watersheds typically cover 400 to 1,000 mi^2. The density of perennial streams averages about one-half mile per square mile.

Central Corn Belt Plains

About 140 mi^2 in the southeastern tip of the study unit (less than one percent of the study unit) is included in the Central Corn Belt Plains ecoregion. This area around Racine and Kenosha, Wisconsin is described as 'generally typical' of the ecoregion. Most of the soils in this ecoregion have developed under tall-grass prairie. Much of the area is covered by a glacial till plain mantled with loess. In general, this plain has low relief, but some morainal hills have local relief of nearly 200 ft.

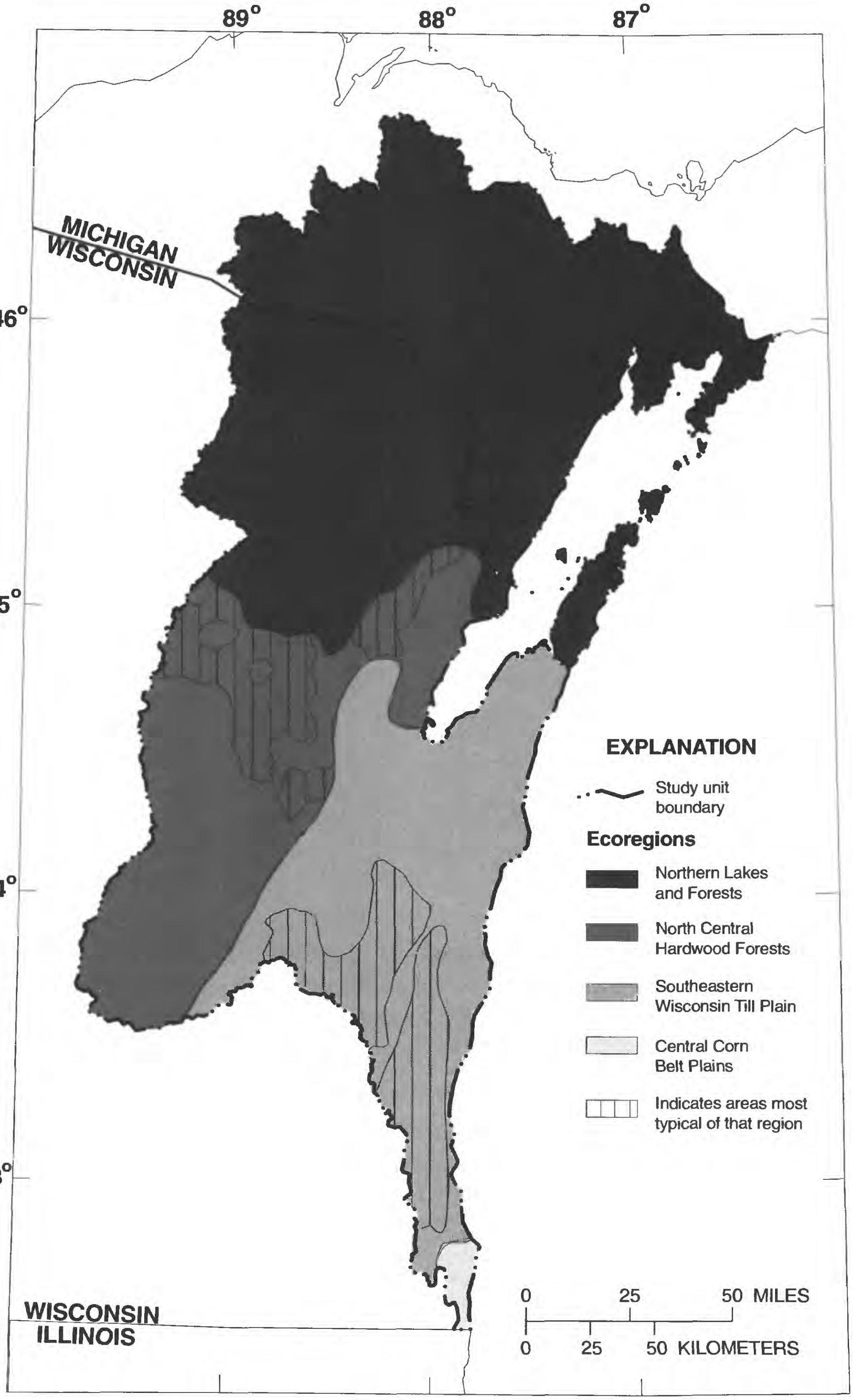


Figure 8. Ecoregions of the Western Lake Michigan Drainages study unit.

Stream valleys are generally shallow with small streams having narrow valley floors and large streams having broad valley floors. A few natural lakes occur near Lake Michigan in this ecoregion. Land in this ecoregion is used primarily for cropland to grow feed for livestock. Some land is used for raising livestock. About 5 percent remains wooded, primarily on wet floodplains, steeply sloping valley sides, and morainal ridges.

Land Use and Land Cover

By David A. Saad

Land-use/land-cover information for the WMIC was obtained from high-altitude color-infrared aerial photography taken between 1971 and 1981. Land-use/land-cover classes based on Anderson and others (1976) classification system were manually interpreted from the aerial photographs. Maps, 1:250,000 scale, were produced from the interpreted data and digitized into a geographic information system (GIS). Ten of these digitized maps (Escanaba, Green Bay, Iron Mountain, Iron River, Madison, Manitowoc, Marquette, Milwaukee, Racine, and Rockford), covering the entire study unit, were joined together with a GIS and analyzed for land-use/land-cover distribution.

The area covered by the principal level I and level II land use/land cover categories is shown in table 3. The distribution of level I land-use/land-cover categories is shown on figure 9. Forested land is the largest level I category, accounting for approximately 41 percent of the WMIC, and is located mainly in the northern portion of the study unit. This cover type is composed of three level II classifications, deciduous forest, evergreen forest, and mixed forest. Deciduous and mixed forests are found mainly in the northern and northwestern parts, whereas evergreen forests are located mainly in the northern and northeastern parts. Agricultural land is the second largest level I classification area and accounts for approximately 37 percent of the study unit. Most agricultural areas are located in the southern portion of the study unit. More than 99 percent of this land is classified as cropland and pasture. Small areas that are classified as orchards, groves, vineyards, are located in the northern part of Door County, Wis.

Wetlands account for approximately 16 percent of the level I classification in the study unit. Wetlands are divided into the level II classifications of forested wetlands (wetlands dominated by woody vegetation) and non-forested wetlands (wetlands dominated by wetland herbaceous vegetation or are non-vegetated). About 89 percent of the wetlands are classified as forested and are dispersed over much of the northern portion of the study unit. Large contiguous areas of forested wetlands are located in the northeastern part of the study unit and around the perimeter of the northwestern end of Green Bay. Non-forested wetlands are located mainly along portions of the Upper Fox River and the lower end of the Wolf River. Small dense areas of non-forested wetlands are also located along the middle reaches of the Escanaba River in Michigan's Upper Peninsula.

Approximately 3 percent of the study unit has the level I classification of 'water'. This includes lakes, streams, and reservoirs. Some of the most prominent water features include Lake Winnebago, Lake Poygan, and Lake Butte des Mortes in the south central portion of the study unit. The northwestern part of the study unit is dominated by a high density of small lakes.

Large areas of urban or built-up land are located near the major cities in the southeastern portion of the study unit and account for about 3 percent of the level I land-use areas. Some of these major cities include Appleton, Fond du Lac, Green Bay, Kenosha, Manitowoc, Marinette, Milwaukee, Oshkosh, Racine, and Sheboygan, all located in Wisconsin. Smaller areas of urban or built-up lands are located in the northern portion of the study unit near Marinette, Wis. and Escanaba and Menominee, Mich. Most of the population in the study unit (2,435,120 in 1990) lives in and around these urban areas. Table 4 shows the population for some of the major cities in the WMIC study unit. Less than 1 percent of the study unit is classified as barren land. Most of the barren land has the level II classification of strip mines, quarries, and gravel pits.

Natural Areas

By Barbara C. Scudder

Although numerous National Wildlife Refuges have been established in Wisconsin and Michigan by the U.S. Fish and Wildlife Service (USFWS) to conserve species and natural communities, only one is located in the WMIC. The Fox River National Wildlife Refuge was established in 1978 and encompasses 836 acres. It is located east of the town of Endeavor, Wis., in Marquette County (U.S. Fish and Wildlife Service, 1988; Patricia Meyers, U.S. Fish and Wildlife Service, Horicon, Wis., written commun., 1993).

Table 3. Sizes of level I and level II land-use/land-cover catergories for the Western Lake Michigan Drainages study unit

[mi.^{2}, square miles]

Land-use/land-cover catergory		Area (mi.^{2})	Percent of level II in level I (mi.^{2})	Percent of WMIC
Level I	**Level II**			
Urban	Residential	340	53	1.7
	Commercial	120	18	0.59
	Industrial	42	6.5	.21
	Transportation/communication	49	7.5	.24
	Industrial/commercial	2	0.37	<0.1
	Mixed urban	18	3	<0.1
	Other	76	12	.38
totals		650	100	3.3
Agriculture	Cropland and pasture	7,400	100	37
	Orchards, groves, etc.	14	.20	<0.1
	Confined feeding lots	.76	<0.1	<0.1
	Other	.99	<0.1	<0.1
totals		7,420	100	37
Forest	Deciduous	2,700	34	14
	Evergreen	1,800	22	9.0
	Mixed forest	3,500	43	18
totals		8,000	100	41
Water	Streams and canals	16	2.4	<0.1
	Lakes	460	72	2.3
	Reservoirs	69	11	.35
	Bays and estuaries	97.5	15	.49
totals		640	100	3.1
Wetland	Forested	2,700	89	14
	Non-forested	340	11	1.7
totals		3,040	100	16
Barren land	Beaches	.22	.33	<0.1
	Sandy areas, other than beaches	.11	.16	<0.1
	Strip mines, quarries, and gravel pits	39	58	.20
	Transition areas	28	41	.14
totals		67	100	.34
Study area totals		19,900	100	100

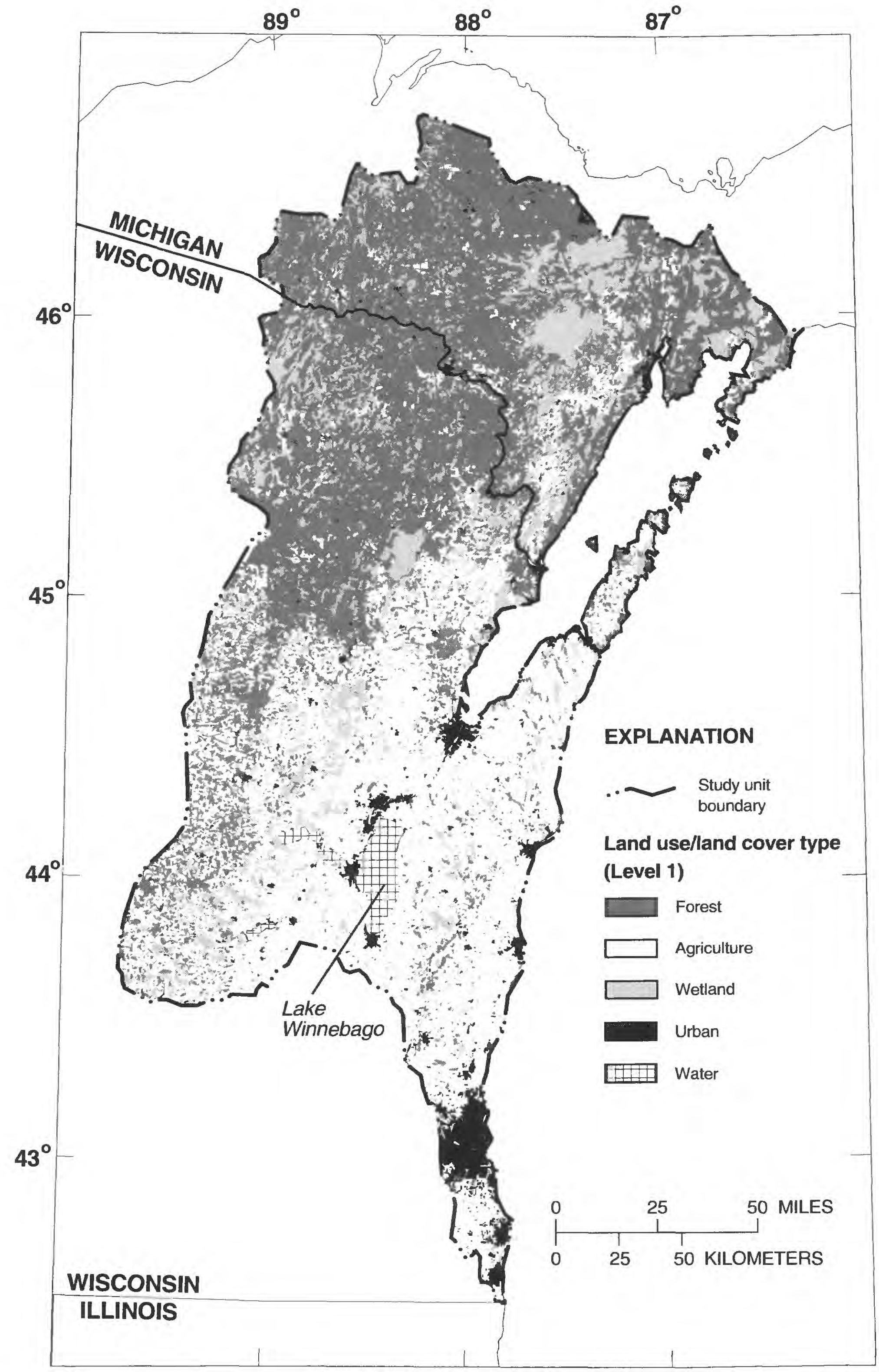


Figure 9. Land use/land cover in the Western Lake Michigan Drainages study unit.

Table 4. 10-year populations for some of the major cities in the Western Lake Michigan Drainages study unit

[Data from Bureau of Census, 1991; Andriot, 1983.]

City	Year									
	1990	1980	1970	1960	1950	1940	1930	1920	1910	1900
Appleton, Wis.	65,695	59,032	56,377	48,411	34,010	28,436	25,267	19,561	16,733	15,085
Escanaba, Mich.	13,659	14,355	15,368	15,391	15,171	14,830	14,524	13,103	13,194	9,549
Fond du Lac, Wis.	37,757	35,863	35,515	32,719	29,936	27,209	26,449	23,427	18,797	15,110
Green Bay, Wis.	96,466	87,899	87,809	62,888	52,735	46,235	37,415	31,017	25,236	18,684
Kenosha, Wis.	80,352	77,685	78,805	67,889	54,368	48,765	50,262	40,472	21,371	11,606
Manitowoc, Wis.	32,520	32,547	33,430	32,275	27,598	24,404	22,963	17,563	13,027	11,786
Marinette, Wis.	11,843	11,965	12,696	13,329	14,178	14,183	13,734	13,610	14,610	16,195
Menominee, Wis.	9,398	10,099	10,748	11,289	11,151	10,230	10,320	8,907	10,507	12,818
Milwaukee, Wis.	628,088	636,212	717,372	741,234	637,392	587,472	578,249	457,147	373,857	285,315
Oshkosh, Wis.	55,006	49,620	53,082	45,100	41,084	39,089	40,108	33,162	33,062	28,284
Racine, Wis.	84,298	85,725	95,162	89,144	71,193	67,195	67,542	58,593	38,002	29,102
Sheboygan, Wis.	49,676	48,085	48,484	45,747	42,365	40,638	39,251	30,955	26,398	22,962

[1]Data from Bureau of Census, 1991; Andriot, 1983.

The first state natural areas program in the U.S. was begun in Wisconsin in 1951. These areas were established in order to preserve remnants of natural plant and animal communities, many of which are the last refuges of rare and endangered plants and animals. Cooperative management agreements and purchase of private lands through the Match-Grant Program are used to preserve the state natural areas, which have state legal protection. Of the current 270 natural areas in Wisconsin, 78 are located in the WMIC (table 5). Michigan has one state natural area in the WMIC, Laughing Whitefish Falls on the Whitefish River (Dennis Albert, Michigan Department of Natural Resources, oral commun., 1993).

At six sites in the study unit, the Wisconsin chapter of The Nature Conservancy is working to protect natural habitat or is assisting others to do so (Nancy Braker, The Nature Conservancy, Madison, Wis., written commun., 1991). These sites are: Chiwaukee Prairie near Kenosha; Rush Lake/Gromme Preserve near Oshkosh; Point Sauble near Green Bay; and in Door County, the Ridges Sanctuary, Mink River, and Shivering Sands. The Nature Conservancy has no preserves in Michigan that are in the WMIC study unit (Dave Ewert, The Nature Conservancy, East Lansing, Mich., oral commun., 1991).

Climate and Weather

By Dale M. Robertson

The WMIC study unit has a temperate, continental climate associated with a large annual range in air temperature and little monthly variation in precipitation. The study unit is in the mid-latitude belt, which is marked by large seasonal changes in the solar-zenith angle and day length, which together produce a significant north-south temperature gradient (Wisconsin Agricultural Statistics Service, 1987). The north-south gradient and the seasonal range in temperature are modified, however, by the neighboring Laurentian Great Lakes. The continentality index (CI) (Conrad and Pollak, 1962) across the study unit ranges from approximately 50 to 55 (inland) to approximately 40 to 48 near the shores of Lake Michigan and Lake Superior. A CI value near 100 represents a very continental climate, whereas a value near zero represents a coastal climate. The variation across the WMIC demonstrates the moderating effect of the Great Lakes on the local climate.

Climate

Three primary factors control the climate of the study unit: latitude and solar input, weather systems (air masses and storms), and the Great Lakes. The sun's position determines the duration and effectiveness of solar heating by controlling the day length and the angle of incidence of its rays. Extreme seasonal variability and a strong north-south gradient in air temperatures are common characteristics for areas at latitudes similar to that of the WMIC study unit (between 42.5°N and 46.5°N).

The area experiences a variety of weather conditions that may change daily. The dry, sunny weather associated with high-pressure systems is usually interrupted every four to eight days by the passage of low-pressure-storm systems that bring overcast skies, precipitation, and the influence of a different air mass (Phillips and McCulloch, 1972). Four air masses primarily influence the study unit: the Continental Polar (cP), the Maritime Tropical Gulf (mT), the Maritime Polar Pacific (mP), and the Continental Tropical (cT) (fig. 10). During the winter, the mP and cP air masses most strongly influence the area. These two air masses are present approximately 70 percent and 15-20 percent of the time, respectively. The mP air masses are often strongly modified by the time they reach the area and, therefore, usually bring moderate temperatures and dry conditions (Palm and deSouza, 1983). The cP air masses change very little during their southward movement and usually bring bitterly cold and dry weather to the area. The mT and cT air masses only rarely influence the area in the winter, but when present often bring warmer weather and sometimes heavy, wet snow or freezing rain. In the summer, mP air masses are still very influential, but less common than in winter (present 25 to 35 percent of the time) and usually bring cool, clear weather. The mT air masses are much more dominant in the summer than in the winter (present 25 to 35 percent of the time) and usually bring warm, humid conditions and often afternoon thunderstorms (Phillips and McCulloch, 1972). During the summer, the area may also be occasionally influenced by strongly modified mP air masses of Atlantic origin which usually bring seasonably cool and dry weather, cT air masses which usually bring hot dry air, and cP air masses which usually bring unseasonably cool and dry air.

Table 5. Wisconsin State Natural Areas located in the Western Lake Michigan Drainages study unit

Area number	State Natural Area	County
2	Cedarburg Bog	Ozaukee
8	Cedar Grove Hawk Research Station	Sheboygan
11	Haskell Noyes Memorial Woods	Fond du Lac
12	Peninsula Park Beech Forest	Door
13	Peninsula Park White Cedar Forest	Door
17	The Ridges Sanctuary	Door
24	Wilderness Ridge	Manitowoc
35	Ripon Prairie	Fond du Lac
37	Seagull Bar	Marinette
39	Charles Pond	Oconto
42	Summerton Bog	Marquette
43	Poppy's Rock	Waupaca
46	VanderBloemen Bog	Manitowoc
47	Sister Islands	Door
48	Cherney Maribel Caves	Manitowoc
50	Two Creeks Buried Forest	Manitowoc
54	Chiwaukee Prairie	Kenosha
55	Marinette County Beech Forest	Marinette
56	Sander's Park Hardwoods	Racine
57	Toft Point	Door
59	Spruce Lake Bog	Fond du Lac
61	Cedarburg Beech Woods	Ozaukee
67	Fairy Chasm	Ozaukee
70	Lawrence Creek	Marquette
71	Kohler Park Dunes	Sheboygan
78	Flora spring Pond	Langlade
87	Point Beach Ridges	Manitowoc
90	Newport Conifer-Hardwoods	Door
92	Miscauno Cedar Swamp	Marinette

Table 5. Wisconsin State Natural Areas located in the Western Lake Michigan Drainages study unit—Continued

Area number	State Natural Area	County
93	Milwaukee River and Swamp	Fond du Lac
94	Spring Lake	Fond du Lac
95	Renak-Polak Maple-Beech Woods	Racine
96	(Muir's) Ennis Lake-Muir Park	Marquette
100	Fountain Creek Wet Prairie	Green Lake
101	Tellock's Hill Woods	Waupaca
104	Dunbar Barrens	Marinette
110	Jackson Harbor Ridges	Door
117	Scott Lake-Shelp Lake Natural Area	Forest
118	Giant White Pine Grove	Forest
119	Bose Lake Hemlock-Hardwoods	Forest
123	Comstock Bog-Meadow	Marquette
125	Mud Lake	Door
129	Jung Hemlock-Beech Forest	Shawano
135	Kewaskum Maple-Oak Woods	Washington
141	Mud Lake Bog	Waupaca
155	Oshkosh-Larsen Trail Prairies	Winnebago
158	Keller Whitcomb Creek Woods	Waupaca
159	Mukwa Bottomland Forest	Waupaca
163	Oxbow Rapids, Upper Wolf River	Langlade
169	Kurtz Woods	Ozaukee
172	Puchyan Prairie	Green Lake
175	Whitefish Dunes	Door
176	High Cliff Escarpment	Calumet
178	Bass Lake Fen	Waushara
179	Myklebust Lake	Waupaca
181	New Hope Pines	Portage
190	Oakfield Ledge	Fond du Lac
194	Pope Lake	Waupaca
197	Riveredge Creek and Ephemeral Pond	Ozaukee

Table 5. Wisconsin State Natural Areas located in the Western Lake Michigan Drainages study unit—Continued

Area number	State Natural Area	County
204	Marshall's Point	Door
207	Berlin Fen	Green Lake
208	Sapa Spruce Bog	Ozaukee
214	Hortonville Bog	Outagamie
218	Mink River Estuary	Door
223	Observatory Hill	Marquette
224	Mud Lake - Radley Creek Savannah	Waupaca
225	Koro Prairie	Winnebago
227	Pickerel Lake	Portage
233	Moonlight Bay Bedrock Beach	Door
234	Bloch Oxbow	Marinette
252	Woodland Dunes	Manitowoc
253	Milwaukee River Floodplain Forest	Washington
254	Kettle Hole Woods	Sheboygan
255	Crooked Lake Wetlands	Fond du Lac and Sheboygan
256	Milwaukee River Tamarack Lowlands and Dundee Kame	Fond du Lac
257	Butler Lake Flynn Springs	Sheboygan
258	Johnson Hill Kame	Sheboygan
259	Kettle Moraine Red Oaks	Sheboygan

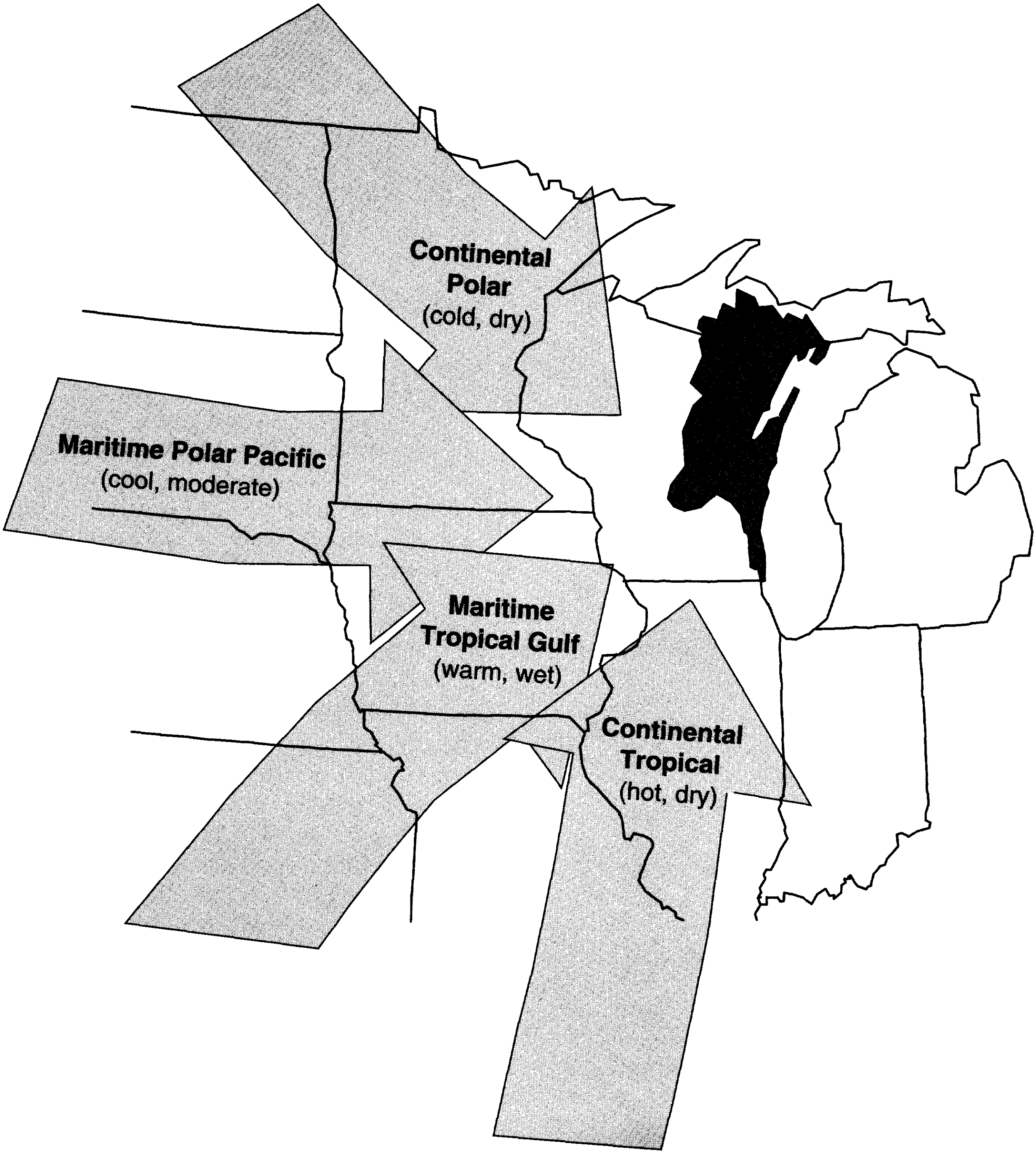


Figure 10. Principal air masses that affect the climate of the Western Lake Michigan Drainages study unit.

Spring and fall are transition periods with often complex weather patterns that lead to rapidly changing conditions. These periods have more frequent frontal systems moving through the area, which often bring wide-spread showers. The influence of the different air masses is transitional between that for summer and winter.

The third factor influencing the climate of the study unit is the effect of the Great Lakes, primarily Lakes Michigan and Superior. Water warms and cools more slowly than land due to its higher specific heat capacity. This differential results in the air over the lakes being cooler than that over land in the spring and early summer, and significantly warmer in the fall and early winter. The result is a moderating effect on coastal areas along the lakes. This "lake effect" results in alterations in north-south climatic gradients along the western shore of Lake Michigan on the study unit's eastern boundary. This differential also results in a moderation of daily temperature extremes.

Air masses entering the region are often affected by the differential in air temperature caused by the Great Lakes. During March through August, the cooler air near the lakes has a stabilizing influence on the air column in the area. Thus, low pressure systems entering the region are weakened and the amount of precipitation is often reduced (Palm and deSouza, 1983). During September to March, the warmer air near the water surface increases the instability of the air column. In this case, low pressure systems entering the area increase in intensity and the chance of precipitation increases.

Weather

Extensive daily weather records are available for many sites throughout the study unit (fig. 11). These sites are operated by several different organizations and are designed to collect different types of information. The largest network consists of cooperative weather observers who record daily air temperatures and total precipitation (rainfall and snowfall); a few of these sites collect only precipitation data and a few collect total-hourly precipitation (only rainfall).

Extensive meteorological information is collected at six sites within or just outside of the study unit. These sites are associated with airports or university-operated experimental farms and collect hourly (or more frequent) information for air temperature, precipitation, wind speed, wind direction, relative humidity, and, at some of these sites, solar radiation. Only two of these sites (Green Bay and Milwaukee) are within the study unit (fig. 11).

The density of these data collection sites and the length of their records are variable. Ten of the 57 sites in the study unit are located in Michigan. Twenty-seven sites within the study unit have daily air temperature and precipitation data that extend over 50 years, with only four of these sites located in upper Michigan. Several of the sites have long term air temperature and precipitation information, but only Green Bay and two sites just outside the study unit (Madison, Wis. and Minocqua, Wis.) have been examined in detail for long-term trends.

Air Temperature

Average annual, seasonal, and daily air temperatures vary widely across the study unit. Average annual temperatures range from approximately 48°F in the southern tip of the study unit to approximately 39°F in the northern regions (fig. 12). The Great Lakes influence the north-south gradient in air temperature, yet have little effect on the average annual air temperatures. This results in warmer temperatures near the lakes in the winter and cooler air temperatures near the lakes in the summer. Since these effects almost cancel when considered on an annual basis, monthly-average air temperatures are discussed for January, April, July, and October. All of the monthly statistics for the study unit were obtained from Wendland and others (1985), which used data from sites across the midwest for the period from 1951 to 1980.

January is usually the coldest month of the year throughout the study unit, with an average air temperature of 15°F, but a range from 20°F in the south to 10°F in the north. During this time, most of the surfaces of Lakes Michigan and Superior usually remain ice-free and are therefore significantly warmer than the nearby land. The isotherms deflect northward on the eastern side of the study unit reflecting the strong lake effects during the winter, especially very near Lake Michigan. A similar effect occurs in the northern regions where the winds blowing across Lake Superior moderate winter temperatures. During the latter part of the winter, a significant part of the lakes may freeze, decreasing the effect on the nearby air temperatures. The average maximum and minimum air temperatures during January are approximately 23°F and 6°F, respectively.

April is a month of transition from cold winter to warm summer air temperatures. During this time, the lakes are significantly colder than nearby land resulting

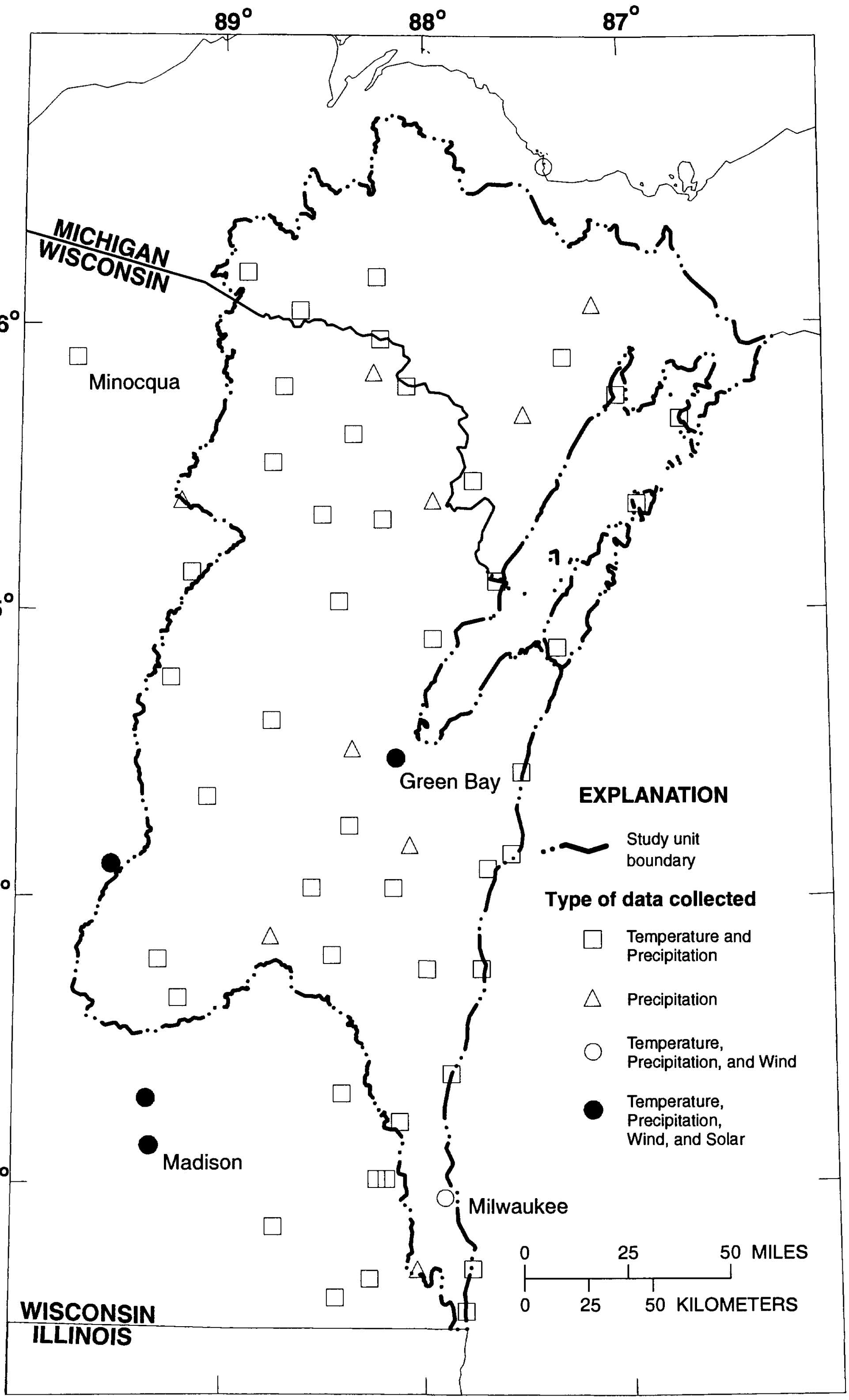


Figure 11. Weather sites in and near the Western Lake Michigan Drainages study unit.

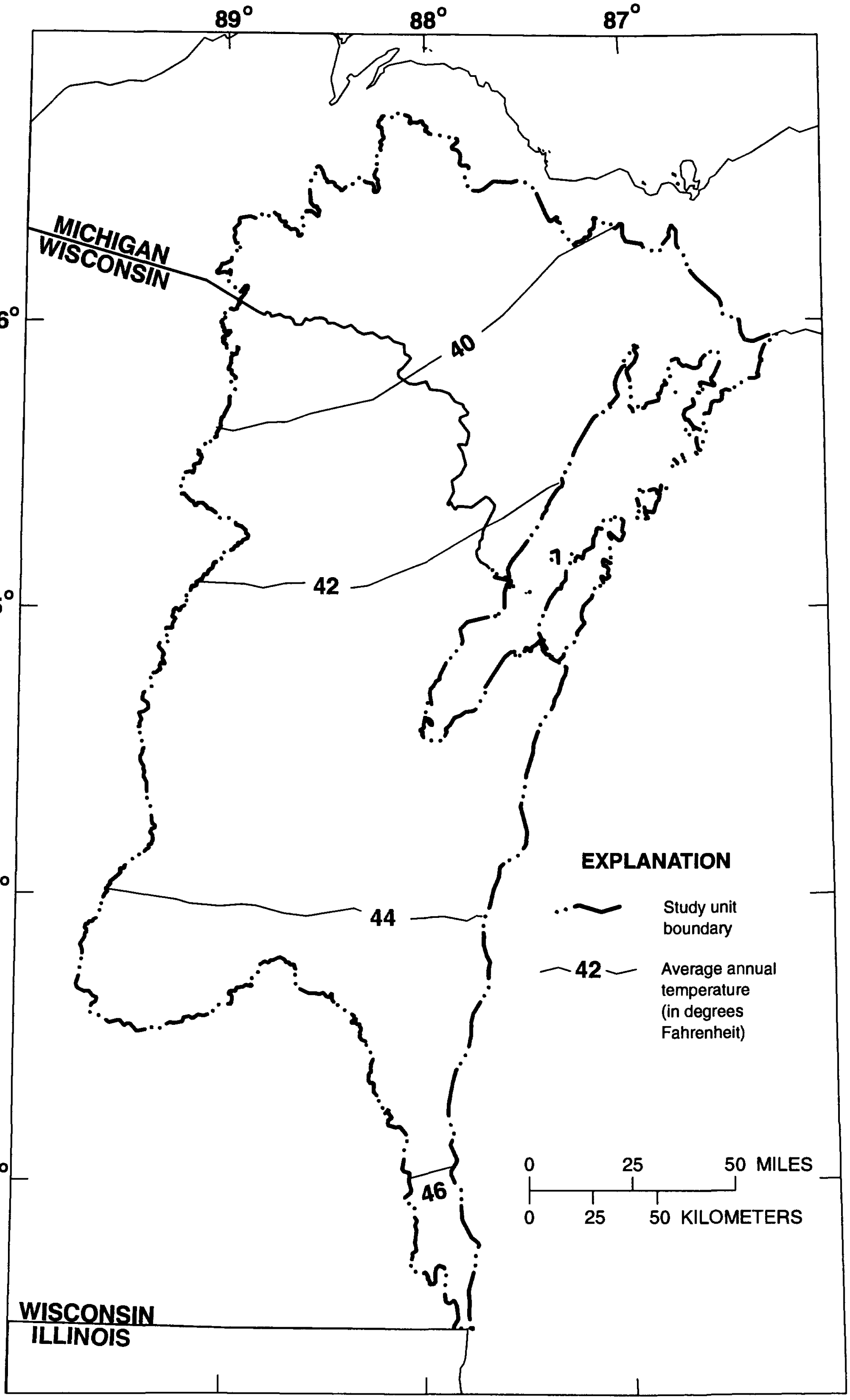


Figure 12. Isotherms of average annual temperatures in the Western Lake Michigan Drainages study unit (based on data from Wendland and others, 1985).

in cooler areas near the lakes. The average temperature across the study unit in April is approximately 43°F, but ranges from about 46°F in the south to about 42°F in the north. The average maximum and minimum air temperature during April are approximately 52°F and 32°F, respectively. The "lake" effect is most influential on maximum daily air temperatures, while minimum daily air temperatures are only weakly affected.

July is usually the warmest month of the year with an average air temperature of approximately 68°F and a range of from 71°F in the south to 65°F in the north. During July, the Great Lakes remain cooler than nearby land and, therefore, affect local air temperatures. The lake effect is much more localized at this time of year compared to other seasons and primarily affects maximum air temperatures measured on land immediately adjacent to the Great Lakes. Much of this effect is caused by lake breezes on otherwise calm days. The average maximum and minimum air temperatures in the study unit during July are approximately 79°F and 57°F, respectively.

October is a month of transition back to colder, winter conditions. The average air temperature during October is approximately 48°F, but ranges from 52°F in the south to 45°F in the north. Average-monthly air temperatures demonstrate relatively little influence from the lake effect. However, average maximum and minimum air temperatures for the month demonstrate strong influences from the lake effect with maximum air temperatures being depressed near the lake and minimum air temperatures being highly elevated. As much as a 7°F east-west gradient across the study unit occurs in average minimum air temperatures. Average minimum air temperatures are relatively constant all along Lake Michigan and average approximately 41°F.

The median length of the growing season (or the period from the last spring frost or the last daily minimum air temperatures below 32°F until the first fall killing frost) ranges from less than 100 days in the north to about 180 days in the southern tip of the study unit (Wisconsin Agricultural Statistics Service, 1987). The median date of the last spring frost ranges from after June 6th in the northern regions to around April 26th in the southern regions. The median date of the first killing frost in the fall ranges from before September 13th in the northern regions to about October 24th in the southern regions (Wisconsin Agricultural Statistics Service, 1987).

Precipitation

Total annual precipitation (fig. 13) ranges from approximately 28 to 34 in. across the study unit (Wendland and others, 1985). The most precipitation occurs in the extreme northern regions of the study unit and is primarily due to lake-effect precipitation. Precipitation has a seasonal component with most of the precipitation (60 percent) occurring in the summer months between May and September when 3 to 4 in. fall per month. Less precipitation occurs in the winter over most of the study unit, especially during January and February when only about 1.0 to 1.5 in. falls per month.

Total winter snowfall has a strong north-south gradient with much more snowfall occurring in the northern-most regions (fig. 14) (Wendland and others, 1992), based on the average from 1961 to 1990. Total snowfall ranges from approximately 140 in. in far northern regions to about 40 in. in the southern regions. The increased snowfall in the northern part of the study unit is caused in part by lake-effect snow immediately south of Lake Superior. Also, the generally colder temperatures in the north result in more precipitation in the form of snow rather than rain.

Directly associated with the increased snowfall in the north is a longer duration of snow cover. The date of the 50-percent probability of the first snow cover of one inch or more ranges from about November 20 in the north to after January 1 in the south. The dates of the 50-percent probability of the last snow cover of one inch or more ranges from about April 10 in the far northwest part of the study unit to about March 1 in the southern tip (Phillips and McCulloch, 1972).

Wind

Hourly wind data are collected at Green Bay, Milwaukee, and several sites located just outside of the study unit. The wind information presented here is from data collected at Green Bay from 1951 through 1960 for April, July, October, and January (Phillips and McCulloch, 1972). Wind speed and direction both demonstrate seasonal changes. Winds are strongest in the early spring (April), with average speeds from all directions being over 10 miles per hour (mph) and a range from 11 to 14 mph. During spring the prevailing winds are from the southwest and northeast. During summer (July), wind speeds are less variable with average speeds for all directions being approximately 8 to 10 mph. The prevailing wind direction during summer is from the south or south-southwest. In fall (October), winds become stronger, with average speeds from

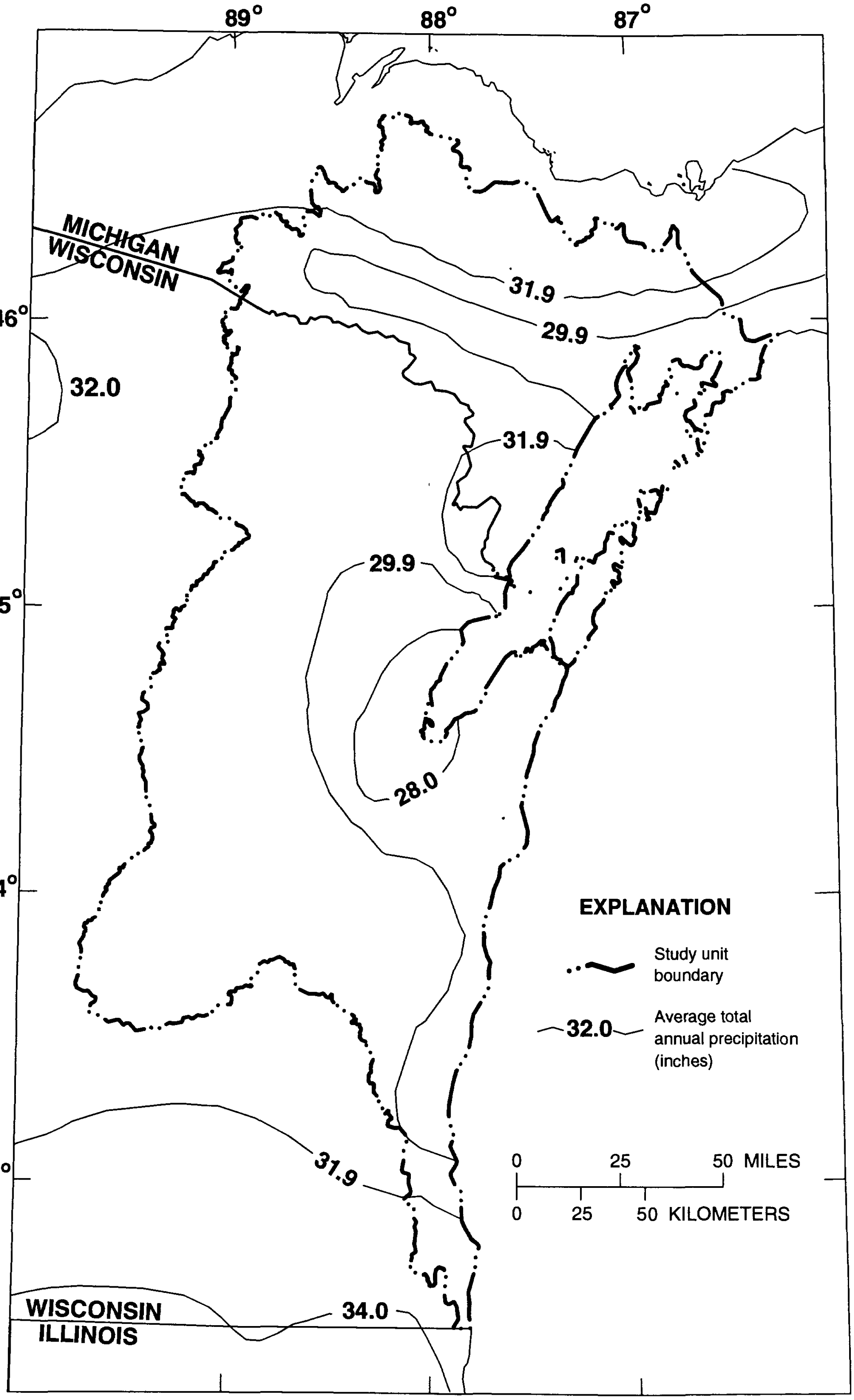


Figure 13. Annual precipitation in the Western Lake Michigan Drainages study unit (based on data from Wendland and others, 1985).

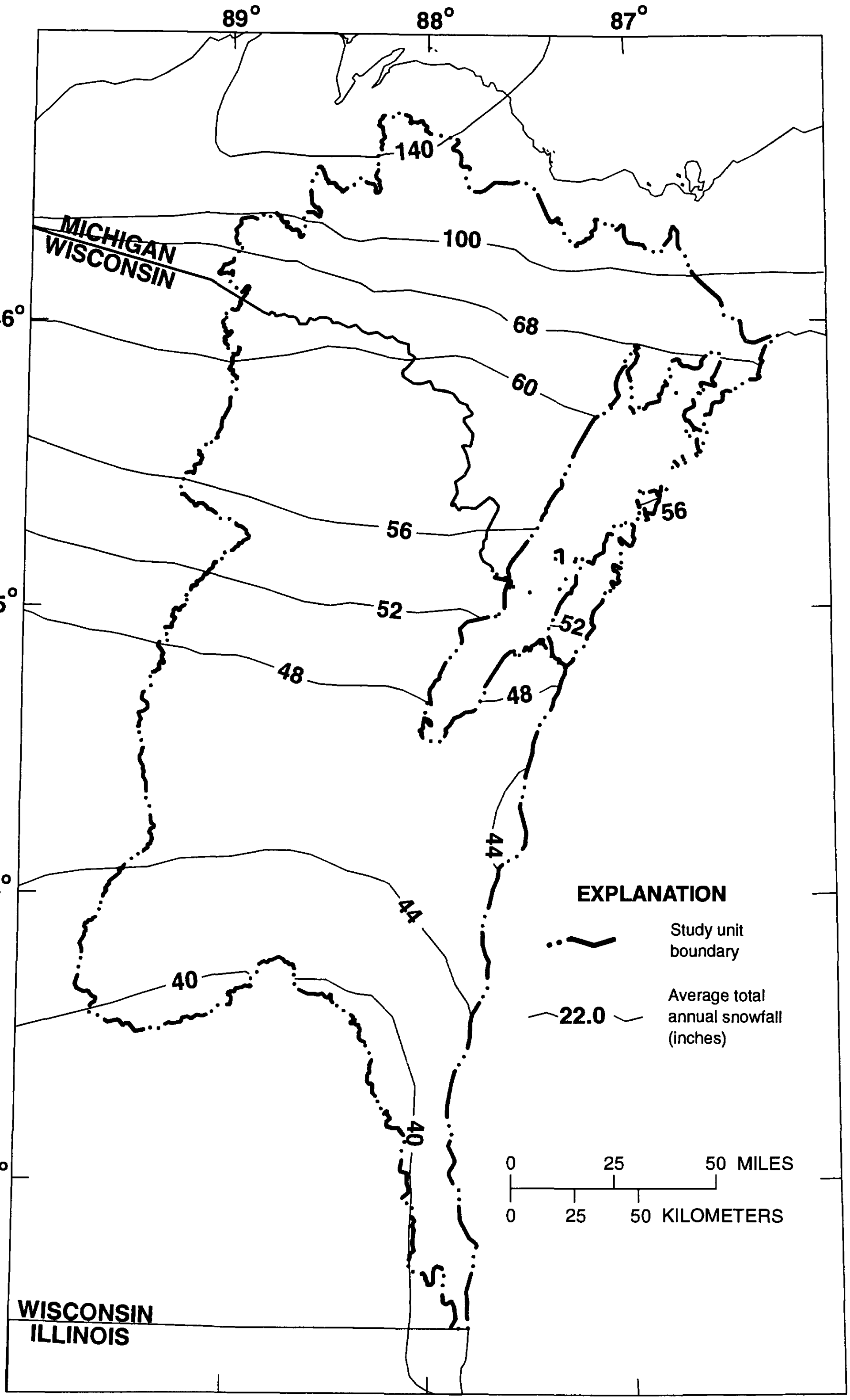


Figure 14. Average annual snowfall in the Western Lake Michigan Drainages study unit (based on data from Wendland and others, 1985).

different directions exceeding 9 mph and range from 9 to 12 mph. The prevailing wind direction remains from the south-southwest, but northerly winds are somewhat common. In the winter (January), average wind speeds are more variable, ranging from 7 to 14 mph. The prevailing winds during the winter are from the west or northwest.

Solar Radiation

Solar radiation (total global) measurements are made at only one site (Green Bay) within the study unit but also at several additional sites immediately adjacent to the study unit. Global solar radiation is the total solar radiation received at the land surface. The average daily radiation throughout the study unit is approximately 330 langleys per day (Phillips and McCulloch, 1972). Solar radiation has a strongly sinusoidal annual cycle with a minimum of approximately 120 langleys per day in December and a maximum of approximately 500 to 550 in June and July (Phillips and McCulloch, 1972). Daily variability is extreme and primarily dependent on cloud cover and secondarily on atmospheric contamination near larger cities.

Humidity

The evaporation rate at any given temperature is inversely proportional to the humidity or vapor pressure. Vapor pressure has a strong seasonal cycle with a weak north-south gradient. In the far northern regions, the average monthly vapor pressure ranges from 2.5 millibars (mb) in January to about 16 mb in July (Phillips and McCulloch, 1972). In the south, in contrast, average monthly vapor pressures range from 3 mb in January to about 18 mb in July. Vapor pressures are relatively constant throughout the day. However, as air temperatures become cooler at night, the relative humidity (which is inversely related to air temperature) increases and condensation often occurs. In the winter, condensation is in the form of frost.

Evapotranspiration

More than half of the precipitation that falls on the study unit is lost through evaporation and transpiration. Average annual evapotranspiration estimates have been made for the period from 1931 to 1960 for the Wisconsin portion of the study unit using a water-budget technique (Oakes and Hamilton, 1973; Olcott, 1968; Skinner and Borman, 1973) (fig. 15). The water-budget technique is based on the sum of evaporation and transpiration which is equal to the sum of precipitation and change in storage, less runoff and groundwater storage. Estimates shown in figure 15 were made using average values for individual components of the water budget for individual river basins for the 30-year period with the assumption that the change in storage over this period was negligible. Evapotranspiration varies across the study unit from less than 18 in. per year (in./yr) in the north to over 24 in. in the southern regions. Less evapotranspiration occurs in the northern regions due to cooler air temperatures and a shorter growing season. This difference results in more runoff (discussed below) in the northern areas of the study unit than in the southern areas. Robertson (1987) estimated average annual evaporation plus evapotranspiration to be approximately 22 in./yr in the northwestern regions of the study unit using the Thornthwaite method (Thornthwaite and Mather, 1957).

Direct measurement of evaporation is extremely difficult; therefore, estimates for water surfaces are often made using pan measurements. Evaporation from water surfaces estimated from pan measurements and a pan correction coefficient, often referred to as potential evaporation, is slightly higher than that estimated for land and water surfaces using water budget techniques. In the southern regions of the study unit potential evaporation was estimated to be about 2 in. greater than actual evaporation, whereas in the northern regions potential and actual evaporation are estimated to be very similar (Phillips and McCulloch, 1972). No direct measurements of pan evaporation are regularly made within the study unit; however, measurements are made just outside the study unit at Rainbow Flowage, Wis., Marshfield, Wis., and Seney, Mich. (Nurnberger, 1982). Estimates of long-term evaporation and free-water surface evaporation for the contiguous 48 United States, including the study unit, are presented in Farnsworth and others (1982).

Evaporation and transpiration have a strong seasonal component with much more of both occurring in the summer months. Pan measurements at Marshfield, Wis., just west of the central region of the study unit, suggest monthly potential evaporation ranges from about 7.5 in. per month (in./mo) in July to less than 2 in. per month in the winter. Estimated monthly and annual potential evaporation in the north-central region of the study unit using several theoretical relationships. Annual estimates were quite variable ranging from 21 to 33 in./yr and monthly estimates ranging from about 4 to 7 in. per month in July to essentially no net

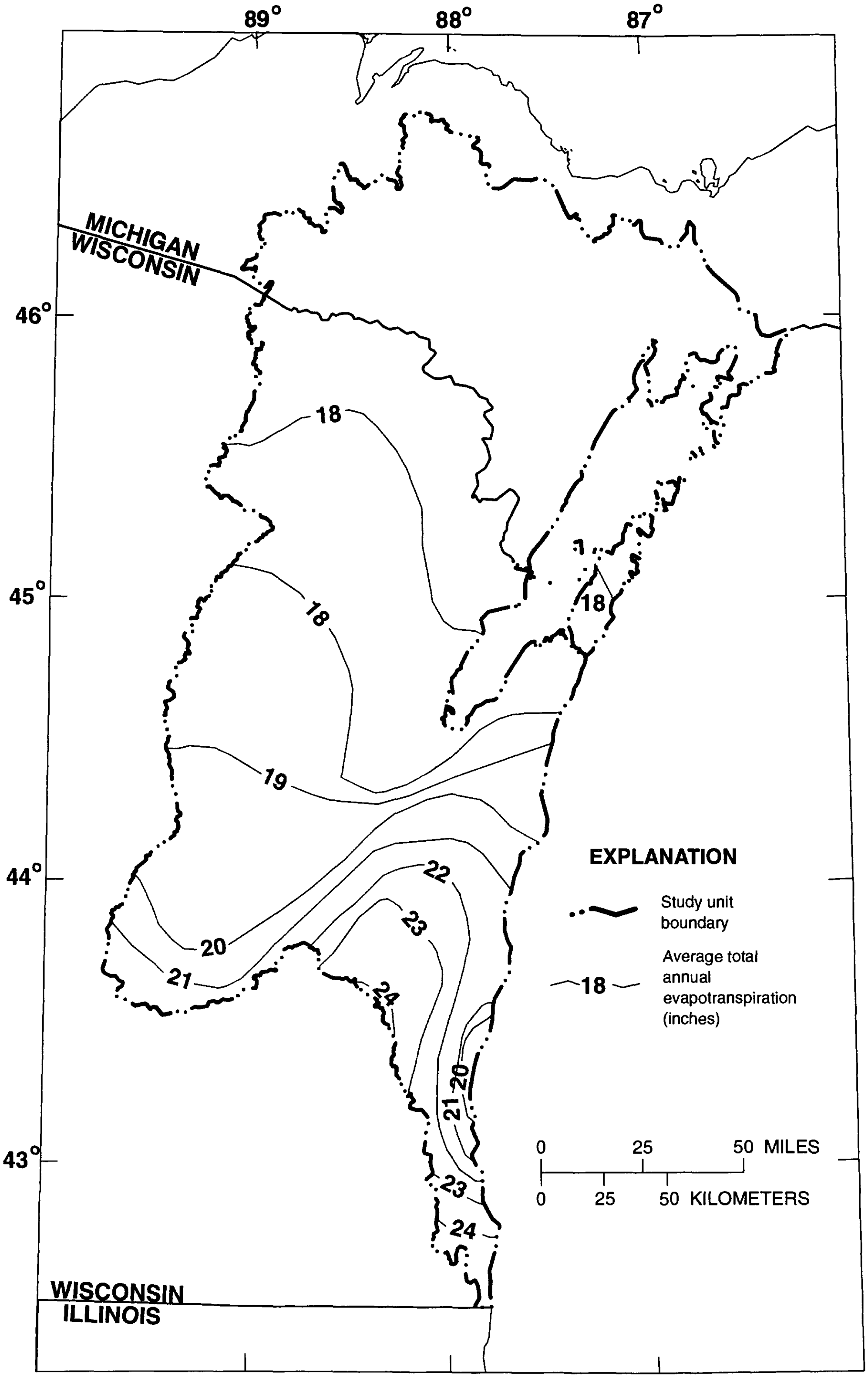


Figure 15. Average total annual evapotranspiration in the Western Lake Michigan Drainages study unit (based on data from Oakes and Hamilton, 1973; Olcott, 1968; and Skinner and Borman, 1973).

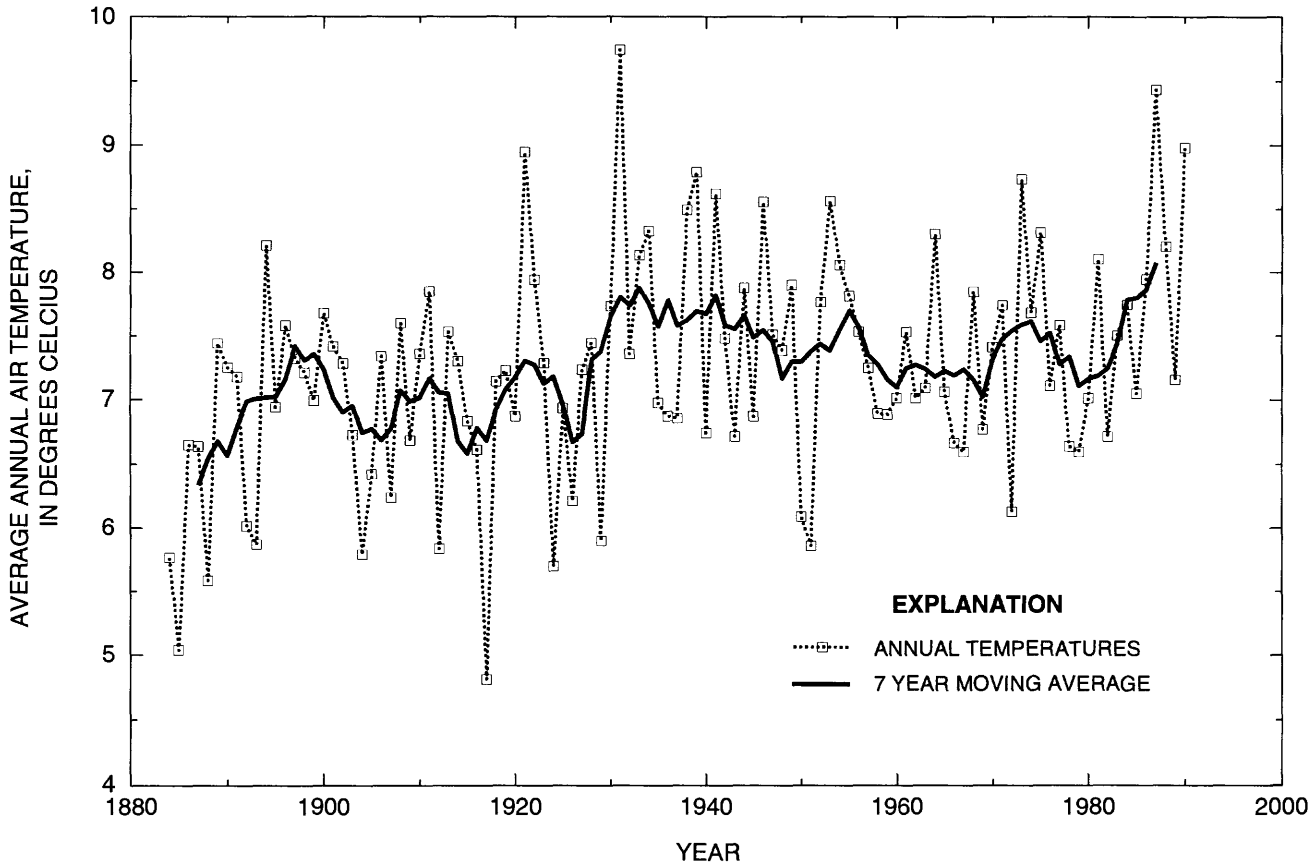


Figure 16. Average annual air temperatures at Madison, Wis, 1890–1992.

potential evaporation in November. Robertson (1987) also estimated evaporation plus transpiration in the northwestern region of the study unit to range from 5 in./mo in July to zero in the winter months using the Thornthwaite method (Thornthwaite and Mather, 1957).

Climatic Changes and Unusual Periods

In addition to the normal annual variability that occurs in weather conditions, several extended periods of unusual weather conditions and apparent climatic changes that have occurred over the past 100 to 140 years. Only air temperature and precipitation data are sufficient in length and quality to detect and quantify these changes and are therefore discussed below.

Air Temperature

Average global air temperatures have increased over the past 110 years, the period of reliable weather records, by approximately 1.5°F (Hensen and Lebedeff, 1987). A similar change has occurred at Madison, Wis. near the southern boundary of the WMIC study unit (fig. 16) (Robertson and others, 1992). Since 1890, air temperature records indicate two changes have occurred in average-annual air temperature. The largest change was a period of warming from about 1890 to 1930. Another period of relatively rapid warming appears to have occurred from 1980 to 1992, during which average annual air temperatures appeared to be slightly higher than the 1930-40 period, which has been identified throughout the U.S. as a significantly warmer period.

Changes in seasonal air temperature were examined by Robertson (1989) and Robertson and others (1992) for Madison, Wis. Winter air temperatures (extended back to 1851 using lake ice records) have increased approximately 4°F since 1851. This overall change appears to have been caused by two rather abrupt changes: an increase of approximately 3°F about 1890 to 1930 and an additional increase of approximately 1.5°F about 1980 to 1992. Average summer air temperatures have been relatively stationary since 1880 except for a period of unusually high air temperatures in the 1930's. The higher annual temperatures in the 1930's were marked by higher summer air temperatures, whereas the higher recent air temperatures were marked by higher winter air temperatures.

Precipitation

To describe long-term changes and unusual periods of precipitation, data collected at several sites were examined: one site in Michigan (Escanaba) and four sites in Wisconsin (Brule Island, Oconto, Oshkosh, and Racine). The period of record for each site has a variable starting date (1890 to 1922), but each continues to 1990. Deviations from the overall average total-annual precipitation are variable and unusually wet or dry years seldom extend throughout the entire study unit (fig. 17). However, by smoothing the time series using a three-year moving average (plotted in year two), several unusual periods become apparent in each record (fig. 18). No long-term trend is apparent in any of the records except for Racine which, by chance, started in a dry period and ended in a wet period.

Several periods with higher than normal precipitation have occurred since 1890 (fig. 15). All of the sites except Escanaba had higher than normal precipitation in the 1970's and 1980's, except for a short period in the late 1970's. The earlier wet periods were more variable, with the northern sites having wet periods occurring in the 1930's and 1950's. The mid-region (Oconto and Oshkosh) also had a wet period in the 1900's and 1910's (Oconto).

Extended dry periods were also variable across the study unit. All of the regions except the extreme south (Racine) experienced the short drought in the late 1980's. The central region of the study unit experienced unusually dry conditions from 1930 to 1960. However, in the north and the south, this extended period was interrupted by several wetter than normal years centered around 1940. The southern part of the study unit experienced very dry conditions from about 1900 to 1950. This drought did not appear to have much influence on the central regions (Oconto), and the records in the north are too short to determine if any effect occurred.

Atmospheric Deposition

Atmospheric deposition has been monitored within and adjacent to the study unit since 1978. Currently, several federal and state agencies are involved in monitoring atmospheric deposition.

In 1978, the National Atmospheric Deposition Program (NADP) was established to monitor trends and characterize geographical patterns in precipitation chemistry throughout the United States. In 1982, NADP merged with the National Trends Network (NTN) of the National Acid Precipitation Assessment Program (NAPAP) into what is now known as the NADP/NTN. The program has grown from 22 sites in 1978 to 205 sites in 1990. In 1992, this program had eight sites within 50 miles of the study unit, with one being located on the Popple River (National Atmospheric Deposition Program, 1991).

The NADP/NTN program collects atmospheric wet and dryfall samples every six to eight days. Each set of samples is analyzed for pH, specific conductance, (soluble reactive) phosphate, and major ions (ammonium, calcium, chloride, magnesium, nitrate, and sulfate). Seasonal loading, precipitation-weighted mean concentrations, and national isopleth plots are published annually to summarize these measurements. The WMIC study unit is located near a steep gradient in pH concentrations (fig. 19).

The Great Lakes Atmospheric Deposition (GLAD) program also maintains three sites in the study unit (Milwaukee, Manitowoc, and Green Bay) and has additional sites in northwestern Wisconsin, the Upper Peninsula of Michigan, and near Chicago, Ill. The GLAD program, which began in 1981, collects weekly wet-deposition samples. The samples are analyzed for pH, specific conductance, acidity, alkalinity, and selected metals, ions, and nutrients.In addition, from 1987 to 1990, biweekly wetfall samples and 24-hour dryfall (air) samples (collected one out of every six days) were collected at Green Bay and Peninsula State Park, Wis., and at Big Bay Du Noc and Eagle Harbor, Mich., and analyzed for polychlorinated biphenyls (PCBs) and dieldrin as part of the Green Bay Mass Balance Study (E. Klappenbach, U.S. Environmental Protection Agency, Region 5, oral commun., 1992). Data collected in 1982 and 1983 are described and compared

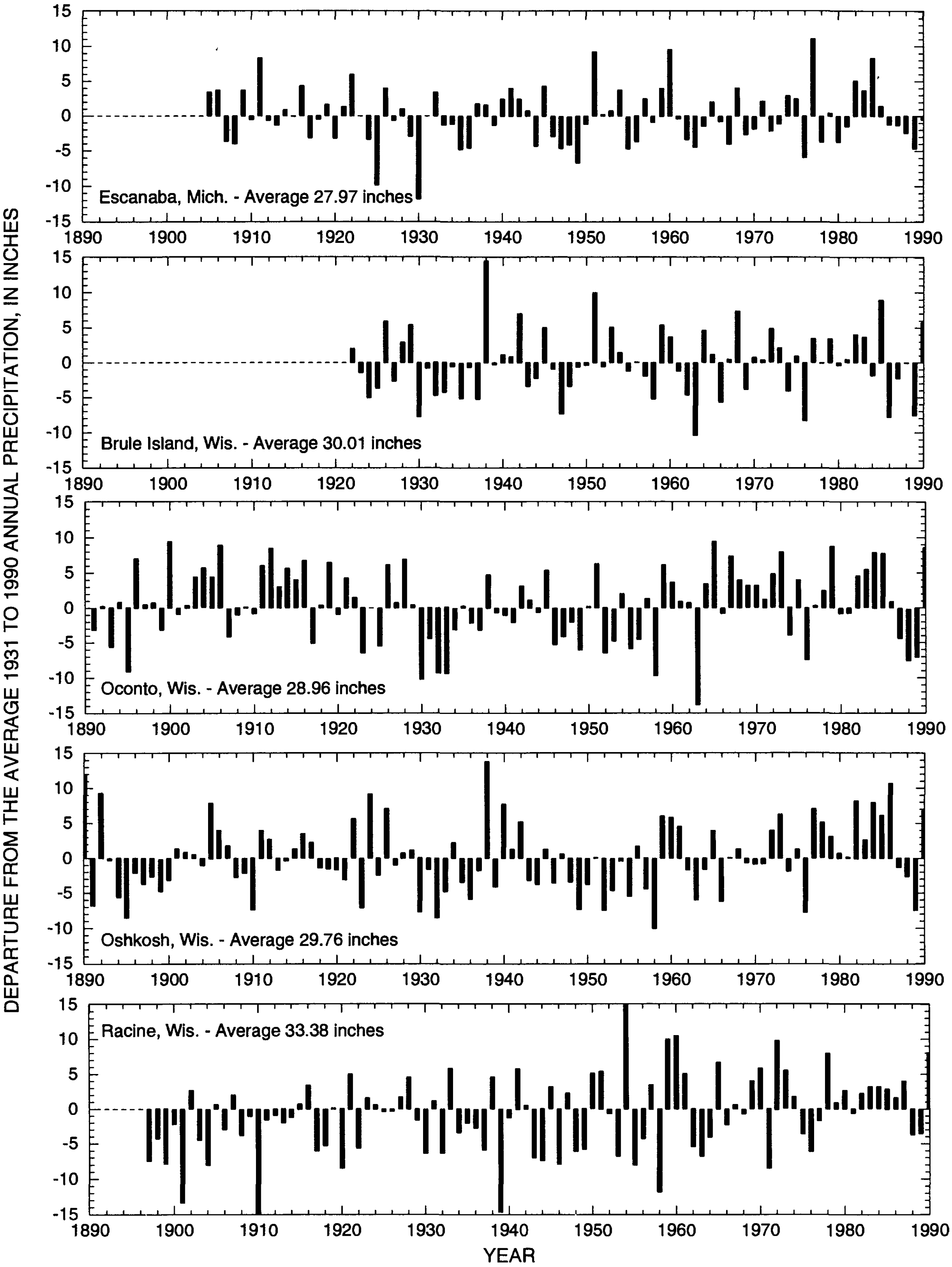


Figure 17. Deviations and smoothed deviations from average annual precipitation at five sites in the Western Lake Michigan Drainages study unit, 1890–1990.

with NADP data by Gatz and others (1988). The data were also combined with that from NADP sites to provide better spatial distributions for atmospheric deposition in 1982-83 (Gatz and others, 1988). Mercury deposition in wetfall has been monitored by the Wisconsin Department of Natural Resources (WDNR) at three sites in Wisconsin, including one in the central region of the study unit (Wisconsin Department of Natural Resources, 1991).

Dry deposition is also monitored on a national level by the National Dry Deposition Program (NDDN). This program, which began in 1987, has one site near the west-central part of the study unit at Perkinstown, Wis. (Wisconsin Department of Natural Resources, 1991). Approximately weekly samples are collected by air filtering devices and analyzed for sulfate, nitrate, nitric acid, sulfur dioxide, ammonia, calcium, sodium, magnesium, and potassium. Although the concentrations in these samples are contained in a computerized data base, they have not been converted into loads due to difficulties in quantifying the mass of the fallout.

Wisconsin has three additional sites in a Dry Deposition Network (WDDN), one located at the Popple River reference site (Wisconsin Department of Natural Resources, 1991). The sites in the WDDN program are sampled following the same protocols as those in the NDDN program.

The impacts of precipitation chemistry on surface and ground water in the WMIC study unit are due to acid precipitation and toxic pollutant inputs. Each of these impacts are considered separately.

Acid Precipitation

Precipitation with a pH of less than 5.0 is generally considered to be acidic due to human activities. This pH value represents a 4-fold higher acid content than 'normal' rain water with a nominal pH of 5.6, predicted from carbon dioxide equilibria. Precipitation in the WMIC study unit is clearly acidic, with an average pH of about 4.7 (fig. 19), representing a roughly 8-fold higher acid content than nominally unaffected precipitation.

Acid precipitation results largely from oxidation of sulfur and nitrogen oxides in the atmosphere to produce sulfuric (H_2SO_4) and nitric (HNO_3) acid, respectively. The largest single source of acidity in precipitation in the study unit is coal combustion in large power plants which produces the majority of sulfur dioxide (SO_2) (Wisconsin Department of Natural Resources, 1990). Oxides of nitrogen also contribute to acidity and are primarily formed by the oxidation of atmospheric nitrogen in automobile engines.

Lakes and streams that are characterized by low acid neutralizing capacity (<50 μeq L^{-1}) and low alkalinity (<200 μeq L^{-1}) are considered to be susceptible to damage from acid precipitation (Wisconsin Department of Natural Resources, 1990). Both acid neutralizing capacity and alkalinity are controlled largely by the chemical character of the soils, surficial deposits, and bedrock of the watershed. The most susceptible lakes and streams occur in the northern third of the study unit which is underlain by igneous and metamorphic rocks characterized by little buffering capacity. The lakes and streams in the southern two-thirds of the study area are underlain by calcareous sedimentary strata characterized by relatively high buffering capacity. Thus, none of the lakes in this area are considered susceptible to damage by acid precipitation.

Potential ecological effects of acidic precipitation on surface waters include: a forced change in aquatic species to acid-tolerant taxa, mobilization of toxic substances such as heavy metals from sediments, and mercury accumulation in large sport fish (walleye and northern pike). The latter effect is notable in that mercury levels in excess of standards drive several of the fish consumption advisories in the study unit (Wisconsin Department of Natural Resources, 1990). Interestingly, high levels of mercury have been found in several remote lakes, implicating atmospheric deposition as a major source of mercury to these systems.

Toxic Pollutants in Atmospheric Deposition

Atmospheric deposition (along with contaminated sediments) is presently considered to be the major source of several critical pollutants in Lake Michigan and its watershed (Eisenreich and Strachan, 1992; Strachan and Eisenreich, 1988). These pollutants include PCBs, pesticides (DDT, dieldrin, toxaphene, and mirex), PAH's, dioxins, furans, hexachlorobenzene, mercury, and alkylated lead; the critical pollutants identified by the International Joint Commission (Eisenreich and Strachan, 1992; Strachan and Eisenreich, 1988). These trace toxic substances exist in the atmosphere as vapors, adsorbed onto particles, and associated with water droplets or ice crystals. Processes that enhance the transfer of these pollutants from the atmosphere to surface water (and possibly ground water) include wet and dry deposition, direct

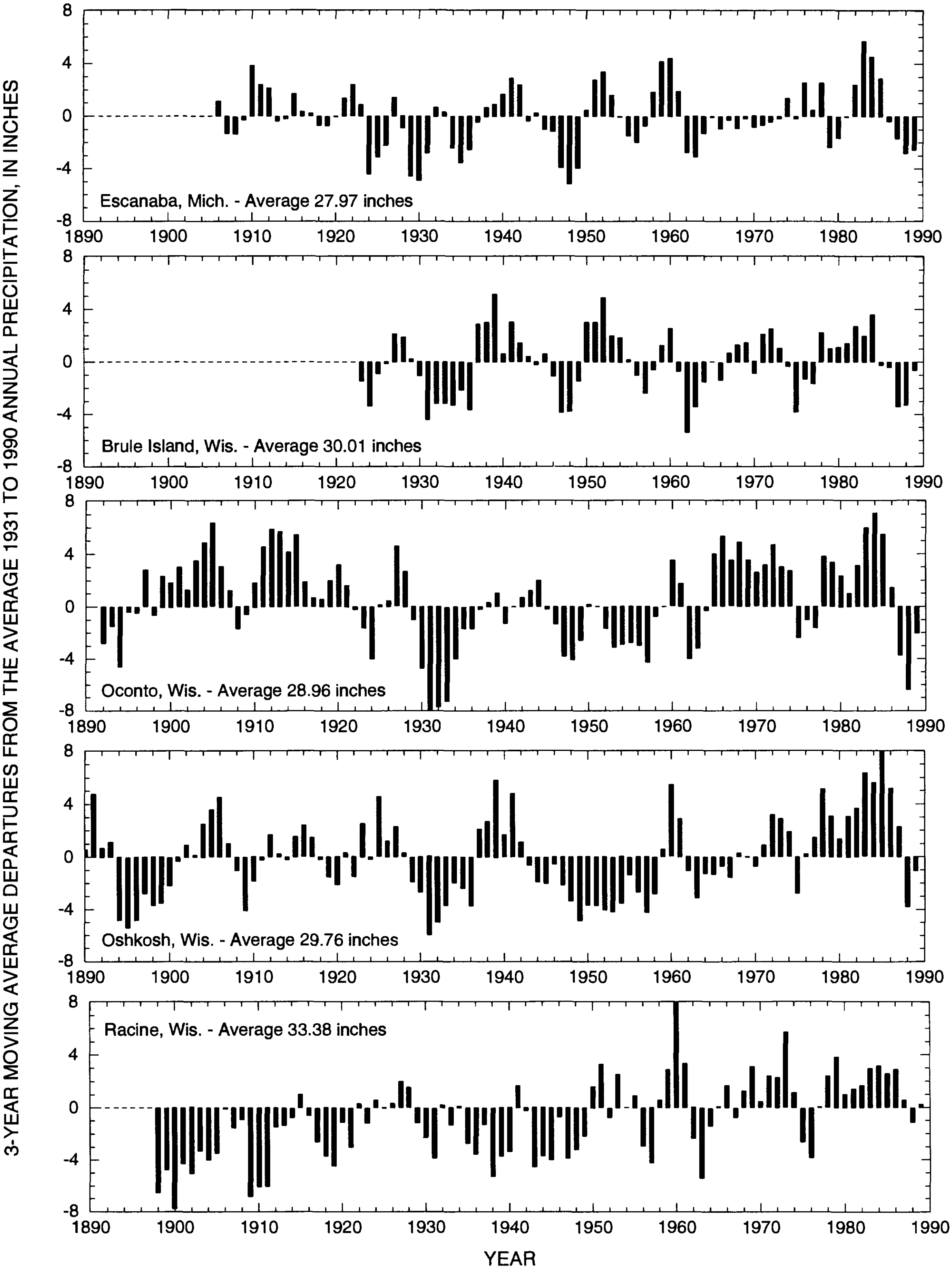


Figure 18. Three year smoothed deviations from average annual precipitation at five sites in the Western Lake Michigan Drainages study unit, 1890–1990.

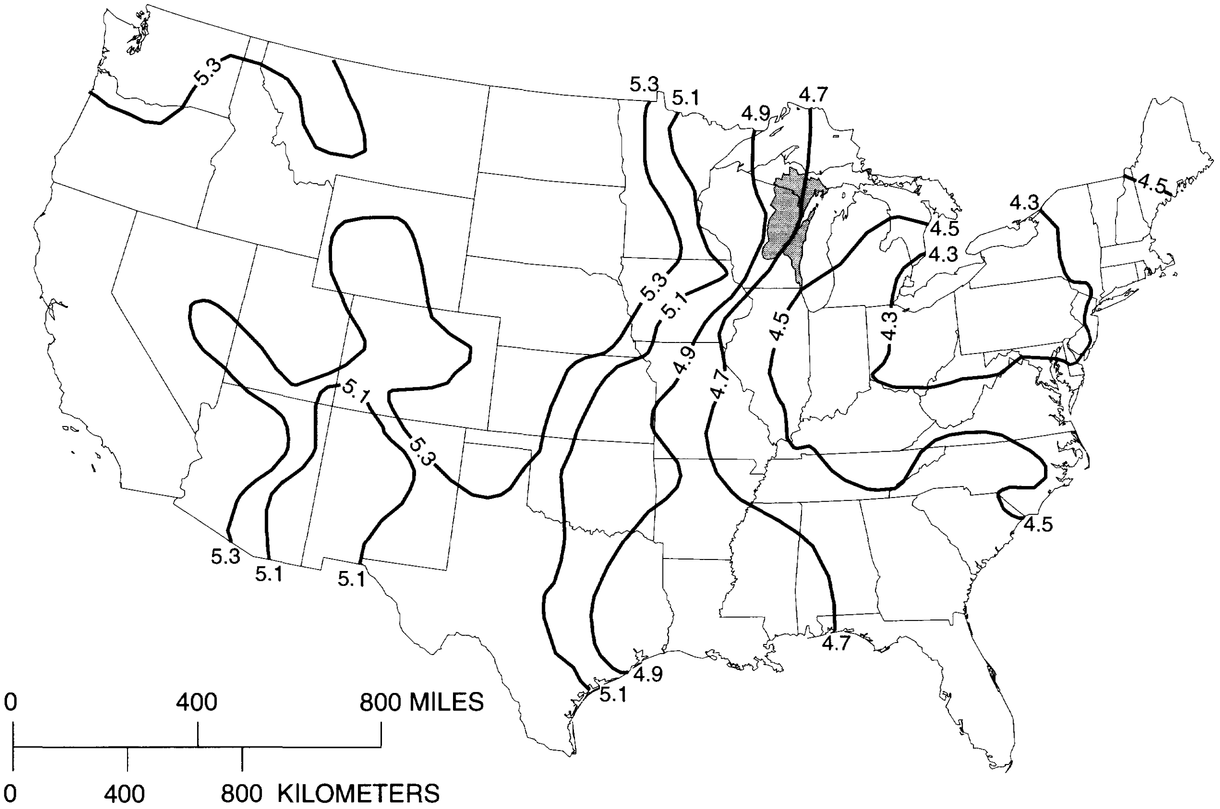


Figure 19. Annual precipitation-weighted mean hydrogen ion concentrations (pH) for the U.S. in 1990.

gas exchange, and scavenging of gases and particles by water and ice in clouds.

Absolute loading of PCBs from the atmosphere to Lake Michigan appears to have peaked around 1970 and the net transfer now appears to be from Lake Michigan to the atmosphere, reversing a long-term trend. Other sources of some of these contaminants include municipal and industrial incineration, engines, furnaces, and landfills. There are very few reliable analyses for any other persistent organics in the study unit.

Hydrologic Characteristics

By Faith A. Fitzpatrick, Dale M. Robertson, Daniel J. Sullivan, *and* David A. Saad

Surface Water

Surface water is influenced by a variety of natural and human factors, the effects of which are often difficult to distinguish and separate (Dunne and Leopold, 1978). Type, intensity, duration, and frequency of precipitation are the main driving forces that affect streamflow in the study unit. Other natural factors include drainage area, basin topography, storage (presence of lakes and wetlands), vegetative cover, snowcover, and soil permeability (Krug and others, 1992). Human effects on streamflow are both direct and indirect. Building of dams, diversions, withdrawals, and discharges directly affect both long-term records and seasonality in streamflow. The indirect effects of other factors, such as conversion of natural vegetation to agriculture or urban land, are harder to distinguish from natural variations, because these effects are superimposed on natural variations.

Drainage Basins

The Fox/Wolf River system drains the largest basin (6,330 mi^2) in the WMIC study unit. The headwaters of the Wolf River define the western boundary of the WMIC. The Wolf River is known for its scenic beauty, fishing, and white-water paddling. It flows south and joins the Upper Fox River in the southwestern part of the basin. Downstream of this confluence, the Upper Fox River flows through the city of Oshkosh, Wis. and enters Lake Winnebago, where the direction of the stream changes to northeast. This section of the Fox River below Lake Winnebago is known as the Lower Fox River. It flows through Appleton, Wis. and drains into Green Bay at the city of Green Bay, Wis.

The Menominee River drains the second largest basin (4,070 mi^2) in the WMIC. Its headwaters, mainly the Paint, Brule, Pine, and Popple Rivers, drain the northwestern part of the study unit. The river and its tributaries flow mainly from the northwest to the southeast and also drain into Green Bay at the twin cities of Menominee, Mich. and Marinette, Wis. The third largest river system in the WMIC is the Peshtigo River basin. It drains 1,100 mi^2 adjacent to and south of the Menominee River system. The general aspect of the drainage also is northwest to southeast. It enters Green Bay near Peshtigo, Wis.

These three river systems combined drain 58 percent of the WMIC. The remaining 42 percent of the study unit is drained by streams that flow directly into Lake Michigan and range in drainage area from about 1000 mi^2 to less than 10 mi^2. The six larger remaining river systems include the Escanaba River (870 mi^2) and Ford River (450 mi^2) in Michigan; and the Oconto River (982 mi^2), Manitowoc River (526 mi^2), Sheboygan River (418 mi^2), and Milwaukee River (696 mi^2) in Wisconsin. Combined, these six rivers drain another 20 percent of the WMIC study unit.

Streamflow Conditions

Streamflow data at six USGS gaging stations with long-term flow records (fig. 20) were examined (Blumer and others, 1991; Holmstrom and others, 1991). These streams represent flow conditions in large to medium streams, in mid-basin and at river mouths, and in forested, urban, and agricultural settings (table 6). Mean monthly and annual streamflow data were retrieved from the USGS National Water Data Storage and Retrieval System (WATSTORE) (Hutchinson, 1975). The period of record available for each site ranged from 92 years (Fox River at Berlin, Wis.) to 73 years (Fox River at Rapide Croche Dam near Wrightstown, Wis.).

Streamflows at most gaging stations have been affected by humans in one way or another (Blumer and others, 1991; Holmstrom and others, 1991), and gaging stations in the WMIC are no exception. Streamflow at the Menominee River, the Wolf River near Shawano, and the Fox River at Rapide Croche Dam near Wrightstown are regulated by power plants or dams upstream (U.S. Geological Survey, 1986). There are about 206 dams of various sizes and purposes in the Western Lake Michigan Drainages (fig. 21).

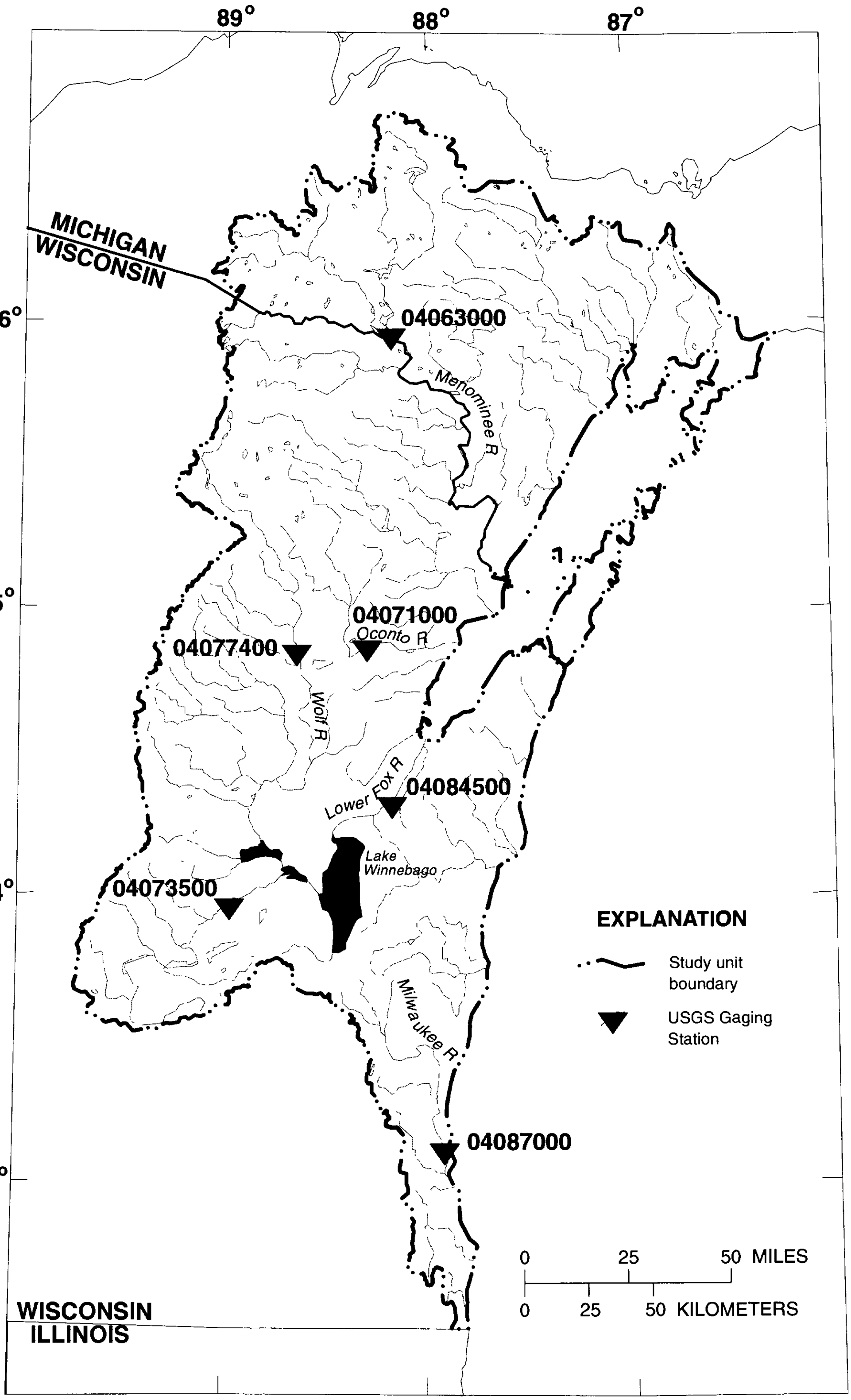


Figure 20. Location of U.S. Geological Survey gaging stations in the Western Lake Michigan Drainages study unit with long-term streamflow records.

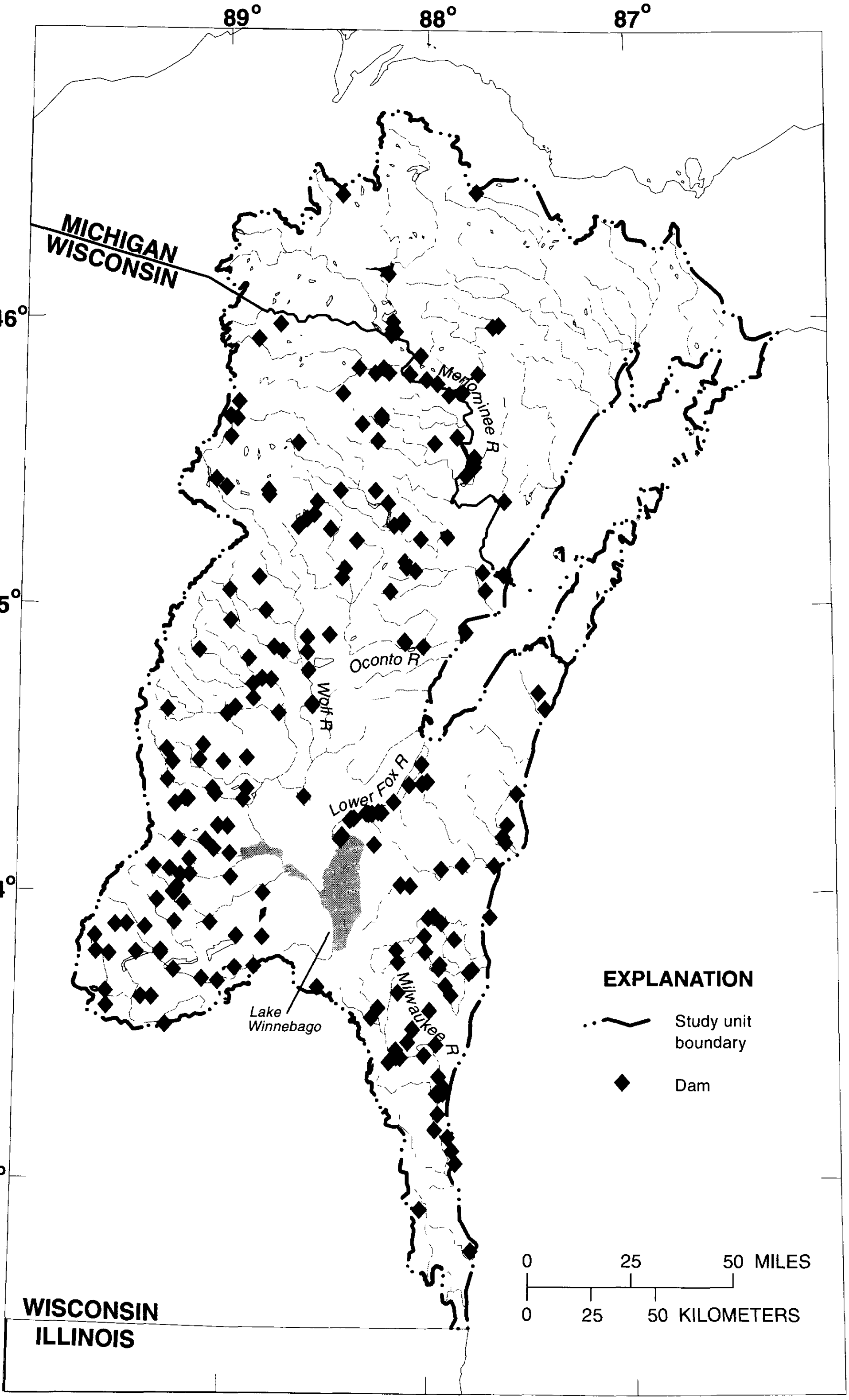


Figure 21. Location of dams in the Western Lake Michigan Drainages study unit.

Table 6. Description of selected U.S. Geological Survey gaging stations in the Western Lake Michigan Drainages study unit

Station number	Station name	Location		Drainage area mi^2	Years of record	Average annual discharge	Land cover
04063000	Menominee River near Florence, Wis.	45°57'04"	88°11'13"	1760	77	1,838	Forest
04071000	Oconto River near Gillett, Wis.	44°51'53"	88°18'00"	705	77	578	Forest
04073500	Fox River at Berlin, Wis.	43°57'14"	88°57'08"	1340	92	1,122	Agriculture
04077400	Wolf River near Shawano, Wis.	44°50'09"	88°37'30"	816	79	758	Forest/ Agriculture
04084500	Fox River near Rapide Croche Dam at Wrightstown, Wis.	44°19'03"	88°11'50"	6010	73	4,252	Agriculture/ Urban
04087000	Milwaukee River at Milwaukee, Wis.	43°06'00"	87°54'32"	696	77	426	Urban/ Agriculture

Low-flow and flood magnitude and frequency characteristics have been published for gaging stations in the WMIC by Holmstrom (1980), Krug and others (1992), and Young (1963). These reports also contain methods for estimating flow characteristics at ungaged sites. Most of the flow at all sites occurs in the spring from snowmelt (fig.22). The month with the largest average flow is March at the southern sites and April at the northern sites where spring thaw occurs later in the year. Lowest flows generally occur in winter (January and February) at both the Oconto (unregulated flow) and Wolf (some dam-regulated flow) Rivers. The Menominee River (regulated), the Fox River at Berlin (regulated), and the Milwaukee River (regulated) have winter flows which are similar to summer flows. The Fox River at Wrightstown is the only site that has much lower flow in summer than in winter, due to the dam upstream of this site. During the summer dry season, flow is restricted to keep the level of water in Lake Winnebago higher and more stable (commonly referred to as "recreational pool" level) than in winter. During winter, water is released from the dam to maintain a lower pool level in Lake Winnebago.

Maximum variability in streamflow is greatest during the spring at all sites. Changes over the time series for each month have varied a great deal at all sites; however, some sites have similar trends in deviations of flow from average for a given month. Seasonal variations in flow from the Wolf River and the Oconto River are similar and may reflect local climatic variations over the last 80 years.

Widespread droughts and floods often occur at irregular intervals in the WMIC study unit. From 1910 to 1988, seven major droughts and 12 floods have occurred in Wisconsin (U.S. Geological Survey, 1991) (table 7). Droughts have lasted from two to five years whereas floods are usually single events or a series of events that occur over a shorter period of time (days to weeks).

In order to compare flow records with statewide occurrences of floods and droughts, time series of the deviations from average annual streamflow for each year were constructed for selected sites over the entire period of record (fig. 23). Deviations from average annual flow indicate relatively dry and wet years. The drought of the early 1930's (1929-1934) affected the entire study unit (fig. 23). Streamflow was below average for approximately 8 years, from 1930 to 1937. In 1931, annual flow in the Menominee River near Florence was a record low; however, during the rest of the drought, streamflow was only somewhat lower than average. The worst drought on record for the Menominee River occurred from about 1918 to 1926. These spatial patterns in annual streamflow reflect the spatial distribution of spring precipitation for these years (Karl and Knight, 1985). For example, in the spring of 1930,

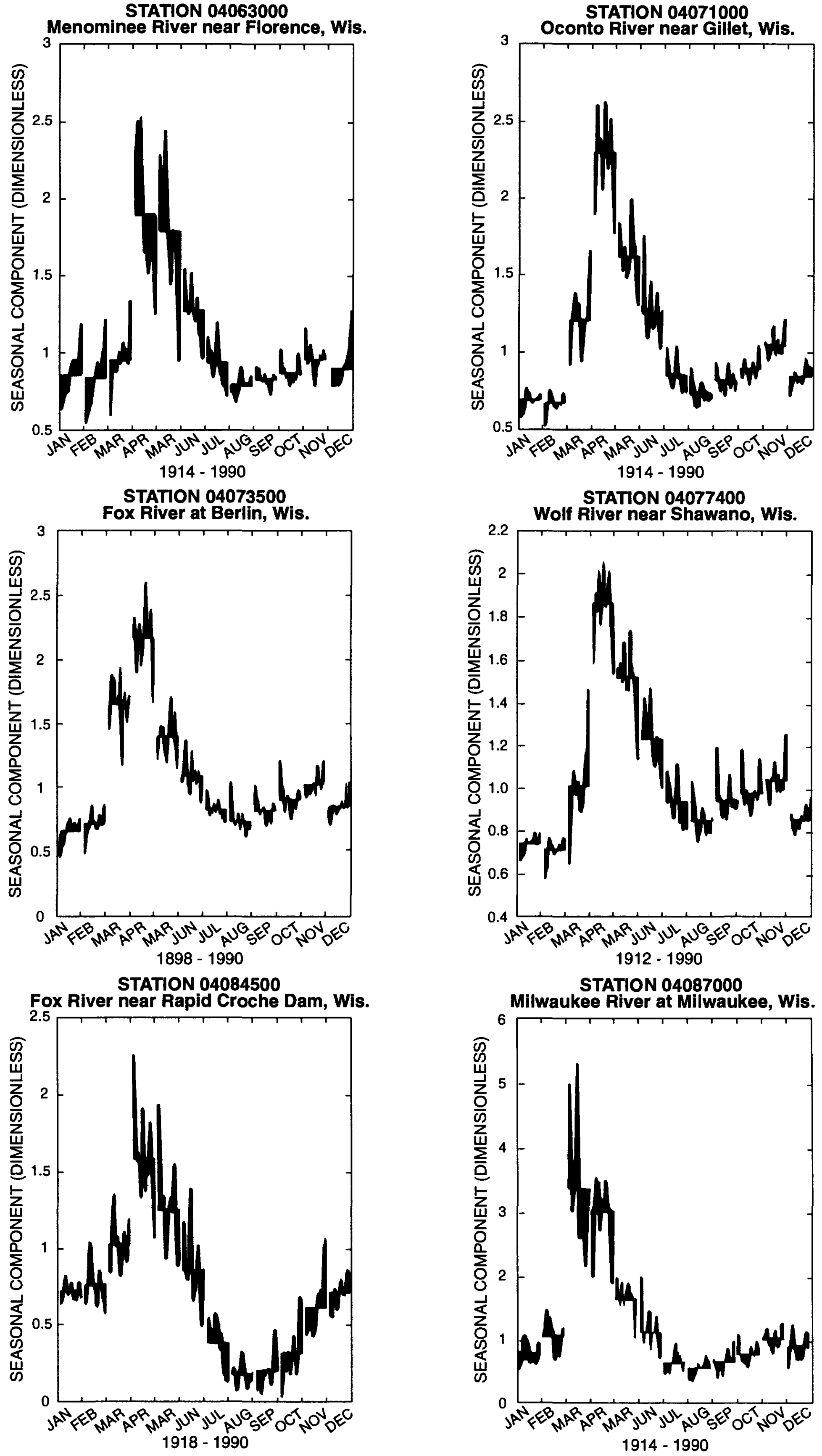


Figure 22. Monthly variations in long-term streamflow data for selected sites in the Western Lake Michigan Drainages study unit.

Table 7. Chronology of major and other memorable floods and droughts in Wisconsin, 1910 through 1988

[modified from U.S. Geological Survey, 1991]

Event	Date	Area affected	Recurrence interval (years)	Remarks
Drought	1910-11	Statewide	Unknown	Drought preceded installation of gaging stations to record the events.
Flood	July 24, 1912	Upper Wisconsin River	>100	Thunderstorms; largest 24-hour rainfall in Wisconsin. Largest flood recorded at Merrill.
Flood	Mar.-Apr., 1922	Statewide	15 to >100	Snowmelt.
Drought	1929-34	Statewide	<25 to >75	Extended until 1942 in parts of Wisconsin. Recurrence interval may have exceeded 100 years.
Flood	Sept., 1938	Black and Wisconsin Rivers and nearby basins.	10 to >100	Intense thunderstorms. Levee failure at Portage. Deaths, 5; much crop damage.
Flood	Aug. 31-Sept. 1, 1941	North-central Wisconsin	>100	Near-record rainfall over large areas. Record flood at many sites. Deaths, 1.
Flood	June 1943	Statewide	10 to >100	Widespread, intense thunderstorms. Floods on various streams resulted from separate storms.
Drought	1948-50	Northern Wisconsin	10 to >70	Some locations more severe than drought of 1929-34, but of shorter duration.
Drought	1955-59	Statewide	30 to 70	Few locations more severe than drought of 1929-34, but of shorter duration.
Flood	Mar. 25-Apr. 10, 1959	Southern Wisconsin	10 to >100	Snowmelt combined with moderate rainfall.
Floods	Mar.-May, 1960	Statewide	50 to 100	Floods in separate areas. Rapid snowmelt combined with thunderstorms.
Drought	1962-65	Statewide	10 to 50	Most severe in south-central Wisconsin.
Flood	Apr. 1965	Mississippi River	>100	Combined snowmelt and rainfall. Largest recorded flows in history. Damage, $15 million.
Flood	Mar.-Apr., 1967	Central and west-central Wisconsin	15 to >100	Rapid snowmelt followed by intense thunderstorms. Damage, $4 million.
Flood	Mar.-Apr., 1973	Central and southern Wisconsin	20 to >100	Snowmelt floods followed by thunder-storm floods. Damage, $24 million.
Drought	1976-77	Central Wisconsin	10 to 80	Some large rivers had smaller flows than during 1929-34. Damage, $600 million.
Flood	July 1-5, 1978	South-central and southwest Wisconsin	>100	Series of intense thunderstorms. Deaths 2; damage, $51 million.
Flood	Aug. 6, 1986	Milwaukee area	>100	Intense thunderstorms (5.2 in. of rain in 2 hours) Deaths, 2; damage, $30 million.
Drought	1987-88	North and central Wisconsin	10 to 100	Record daily and monthly minimum discharges on 2 major rivers.

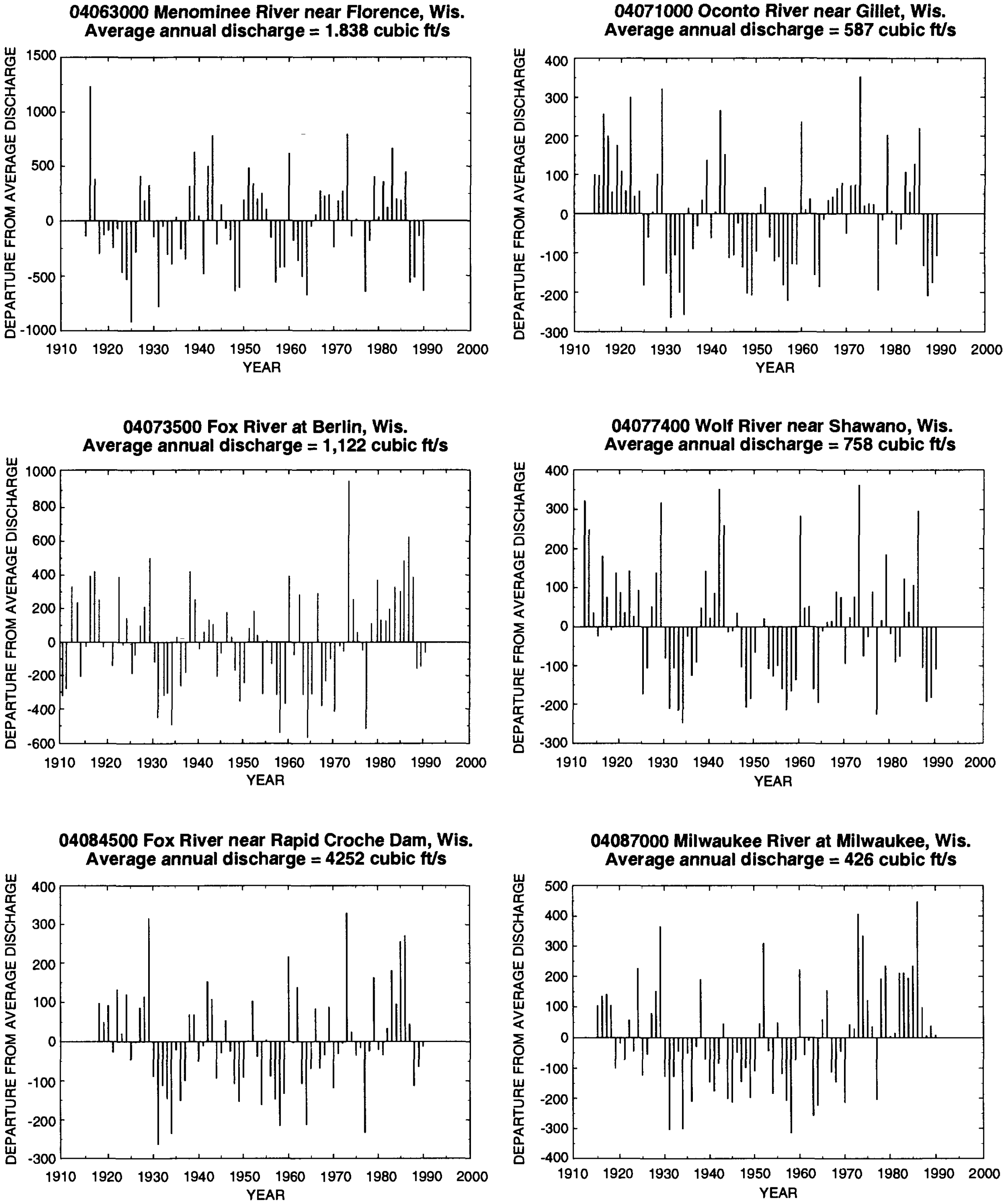


Figure 23. Deviations from average annual flow for selected sites in the Western Lake Michigan Drainages study unit.

1932, and 1933, climatic conditions were very dry to extremely dry (less than 5 in. of precipitation in 3 months) in the southern part of the WMIC, while in the northern part, conditions were moderately dry to normal (Karl and Knight, 1985). In 1931, the entire study unit was very dry to extremely dry.

The drought of the late 1940's affected streamflow at all sites; however, streamflow decreased most at northern sites (fig. 23). Starting in 1946, spring climatic patterns were dryer in the northern part of the WMIC and conditions continued to be unusually dry until 1950 (Karl and Knight, 1985). The drought in the late 1950's was similar in magnitude but longer in duration than the drought in the early 1960's. All sites had larger annual flows during this time period than the drought in the early 1930's, except for the Fox River at Berlin and the Milwaukee River, which had streamflow similar to, or less than, during the 1930's. The last drought on record extended through 1990. This last drought was less severe than the drought in the early 1930's, especially in the southern streams.

Floods in the study unit are caused by three types of climatic events: rapid snowmelt in March or April, intense thunderstorms in the summer months (May through September), or a combination of snowmelt closely followed by intense storms. Flood-frequency characteristics have been calculated at streams with long-term streamflow records (Krug and others, 1992) (table 8).

Intense thunderstorms in September, 1938 affected the southern part of the study unit more than the northern part. The Fox River at Berlin, the Wolf River near Shawano, and the Milwaukee River have the largest September flow on record in 1938. Only the Wolf River at Shawano appeared to be affected by the record summer rainfalls in 1941 and 1943. Rapid snowmelt followed by thunderstorms in April, 1967 caused the largest April flows ever recorded at the Menominee River. This same situation caused flooding again in 1973 at the Menominee, Oconto, and Fox Rivers. In summary, from 1910 to 1990, extreme fluctuations in climatic patterns tend to be confined to relatively small areas have not affected all areas of the study unit equally.

Rainfall/Runoff Relations

Streamflow can be divided into runoff (derived from precipitation) and baseflow (derived from ground-water discharge). During a rainfall event, precipitation infiltrates the soil until the amount of rainfall exceeds the soil's infiltration capacity. Then, the excess water moves down slopes and into streams via overland flow, subsurface stormflow, and saturation overland flow (Dunne and Leopold, 1978). Thus, the intensity, duration, and timing of precipitation coupled with soil infiltration rates are the major factors that affect runoff.

Soil infiltration rates are variable and are dependent on a variety of factors including: antecedent soil moisture, precipitation, soil temperature, vegetative cover, and soil properties. Intense rains of long duration closely spaced in time can quickly reduce the infiltration capacity of a soil. Rain drop impact from intense rains also can clog soil pores quickly at the surface. Temperature has a direct effect on frozen or frosty ground; water cannot permeate frozen ground, whereas frost cracks sometimes can increase infiltration rates. Snowfall does not immediately affect infiltration rates, but has a variable effect depending on the timing of the snowmelt with respect to rainfall events. Vegetative cover influences infiltration rates by reducing raindrop impact, increases the roughness factor (slows overland flow), and produces organic matter that increases the porosity of the soils and keeps mineral matter from cementing together. Grain size and sorting of sediments directly control the porosity and permeability of soils.

Other physiographic factors of stream basins also affect runoff. The orientation of a stream basin to the direction of storm movement is important. Large drainage areas decrease the variability of peak flows caused by frontal-type precipitation events. Small drainage areas typically have steeper slopes that transport excess precipitation out of the basin more efficiently. Long, linear basins (palmate-shaped) disperse total runoff over time, whereas more circular basins deliver water to a downstream point at about the same time, which can cause flooding. Drainage density also controls how quickly water can be routed by the stream. Young landscapes (recently deglaciated areas typical in the WMIC) and highly permeable surficial deposits have a low density of streams, and flood peaks are typically 2 to 3 times less than those in older landscapes with a higher density of streams. Greater slope and relief in a basin cause quick removal of water from an area.

Land-use practices, such as agriculture, channellization, and urbanization, commonly increase runoff during rainfall events. Agricultural practices typically remove natural vegetative cover and leave the ground

Table 8. Flood frequency characteristics of selected streams in the Western Lake Michigan Drainages study unit

Data from Krug and others, 1992.

Station number	Name	Estimated flood for the given recurrence interval, in years						
		2	5	10	25	50	100	Percent standard error
04063000	Menominee River	7,610	11,100	13,600	16,900	19,400	22,000	13.0
04066500	Pike River	1,010	1,395	1,660	2,000	2,270	2,540	10.4
04068000	Peshtigo River	2,000	2,600	2,980	3,440	3,770	4,080	8.9
04071000	Oconto River	2,490	3,540	4,250	5,150	5,820	6,500	9.0
04073500	Fox River	3,460	4,730	5,510	6,420	7,060	7,660	6.8
04079000	Wolf River	6,720	9,460	11,200	13,400	14,900	16,400	9.1
04081000	Waupaca River	1,060	1,540	1,835	2,175	2,405	2,620	9.9
04084500	Fox River	12,700	17,000	19,200	21,600	23,000	24,200	6.7
04086000	Sheboygan River	3,140	5,000	6,150	7,480	8,380	9,200	13.6
04086500	Cedar Creek	951	1,860	2,600	3,670	4,570	5,530	20.1
04087000	Milwaukee River	4,690	6,990	8,580	10,700	12,300	13,900	10.4

exposed for large parts of a year. Channellization typically increases the slope of the channel and routes water out of the system faster. Smoothing of channel banks reduces the hydraulic roughness and thus increases runoff. Urbanization increases the amount of impervious area in a basin, converts natural channels to storm sewers, and removes natural vegetative cover.

Maps of average annual runoff have been produced for the U.S. (Gebert and others, 1987) and for major river basins in Wisconsin (Olcott, 1968; Oakes and Hamilton, 1973; and Skinner and Borman, 1973). Gebert and others (1987) estimated runoff, including baseflow, as an average depth over the drainage area (Krug and others, 1989) for hydrologic cataloging units (Seaber and others, 1984). The source for these calculations is based on records from USGS streamflow-gaging stations for the time period 1951-80 (Krug and others, 1989). Runoff rates varied from 8 in. per year in the southern part of the basin to 15 in. per year in the northern part of the basin (Gebert and others, 1987) (fig. 24). Runoff across the U.S. ranges from less than 1 inch in the western deserts to greater than 100 in. in the mountains of the Pacific Northwest. Runoff in the WMIC is similar to other areas in the Midwest owing to similarities in topography and vegetative cover.

Runoff from individual streams within the WMIC is quite variable seasonally and over longer periods of time. This is especially important in the WMIC where temperatures are below freezing for a number of months each year. During winter months and periods without rain, a large proportion of flow in streams is derived from ground-water sources.

Runoff was computed for two streams in the WMIC by dividing mean monthly streamflow in acre-feet by drainage area upstream of the site. Runoff for the Oconto River (site 04071000) was coupled with mean monthly precipitation at Oconto, Wis. Runoff from the Fox River basin above Berlin, Wis. (site 04073500) was coupled with rainfall at Oshkosh, Wis. Average monthly rainfall/runoff ratios range from about 2 to 5.

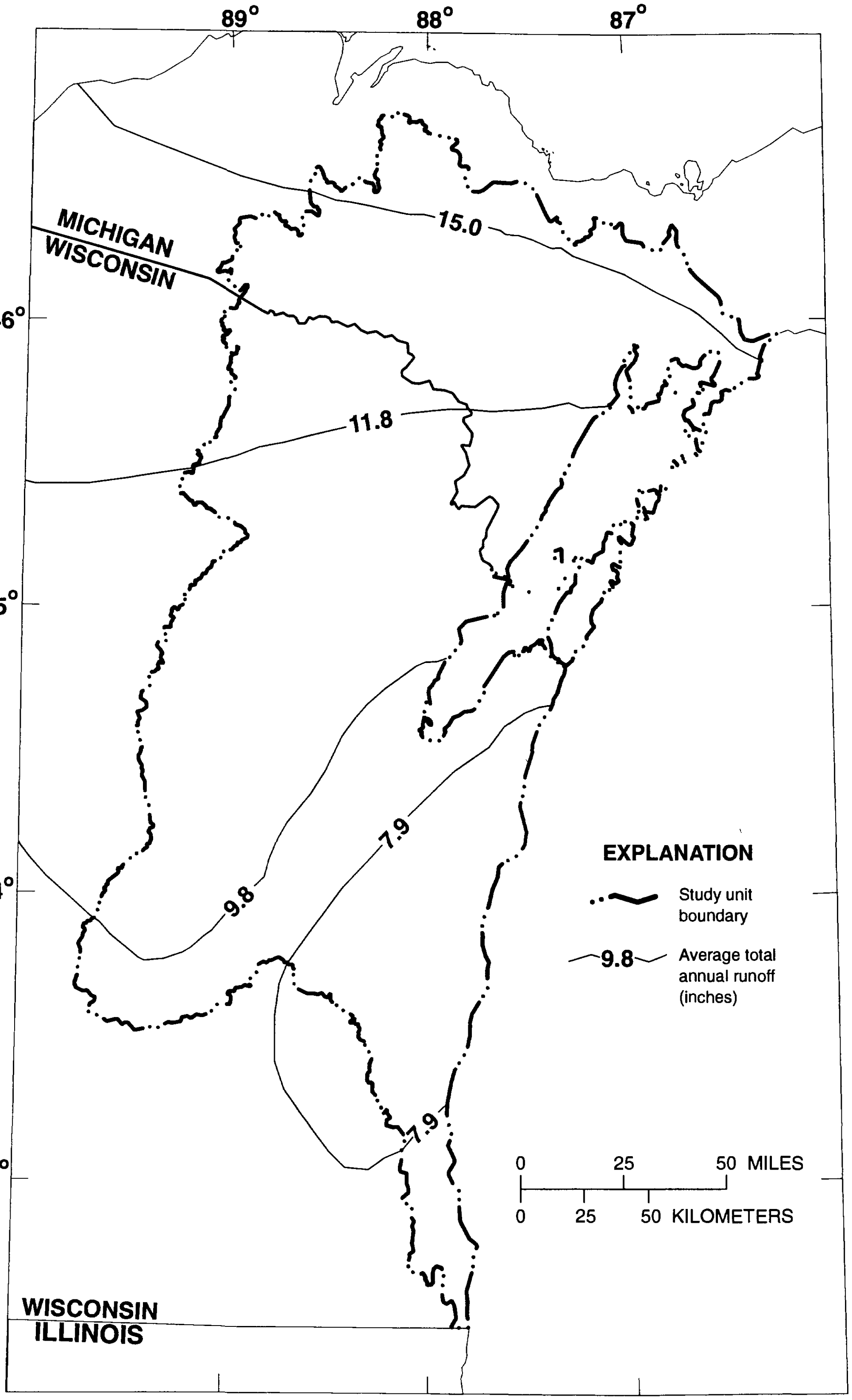


Figure 24. Average annual runoff rates in the Western Lake Michigan Drainages study unit (from Gebert and others, 1987).

Rainfall/runoff ratios for the two sites are similar from about 1920 to 1930 (fig. 25). After 1930, the rainfall/runoff ratios of the Oconto River differ from those for the Fox River near Berlin, especially from about 1960 to the present. Largest rainfall/runoff ratios for the Fox River occurred in the 1960s. Especially noticeable are the low rainfall/runoff ratios that occurred during the 1980s and 1990s in the Fox River that did not occur in the Oconto River to the north.

Many factors could cause variations in the rainfall/runoff ratios. Changes in the seasonality, intensity, duration, and frequency of precipitation in the study unit may contribute to the variations. Reforestation in the Oconto River basin from about 1900 to 1950 could have caused the increase in the rainfall/runoff ratio by decreasing runoff over time. The Oconto River also is less affected by human impacts than the Fox River at Berlin. The Fox River basin was logged somewhat earlier than the Oconto River basin, and was converted to agriculture instead of being reforested. In addition, many wetland areas have been drained. Finally, urban areas are also more common on the Fox River, resulting in decreased rainfall runoff ratios.

Lakes and Reservoirs

Lakes and reservoirs are prevalent features in the WMIC study unit. Several thousand lakes, ranging in size from 0.5 to 138,000 acres, exist within the study unit. In addition, many impoundments were created when large rivers were dammed for navigation, to generate hydroelectric power, or to regulate flow. Many of these impoundments are nested in complicated riverine systems. The lower flow velocities in impoundments and lakes intersecting streams and rivers can greatly influence the water quality of a riverine system as a whole. The types of changes in water quality are dependent on: (1) the location of the impounded system in the drainage basin; (2) the water quality of the inflowing water and impounded water; and (3) the physical characteristics of the impoundment.

Many factors determine how a lake or impoundment affects a river's water quality. A lake can control riverine flow and water quality if the river originates from a lake or if discharge is released from the lake. In this case, the water quality of the river can be almost identical to the upstream lake. A smaller lake intercepting a stream or river can significantly reduce the flow within the lake and result in the loss or deposition of a significant portion of the suspended matter and nutrients from the river. The increased residence time of water in lakes provides plankton the opportunity to take up or remove nutrients from the dissolved phase. Zooplankton fecal pellets and other detritus can be lost downstream; however, most is decomposed in the water column or at the sediment water interface in the lake where it subsequently may be released back to the water column. Lacustrine environments can also significantly alter the biological assemblage of the nearby riverine communities by acting as a continual source of lake species.

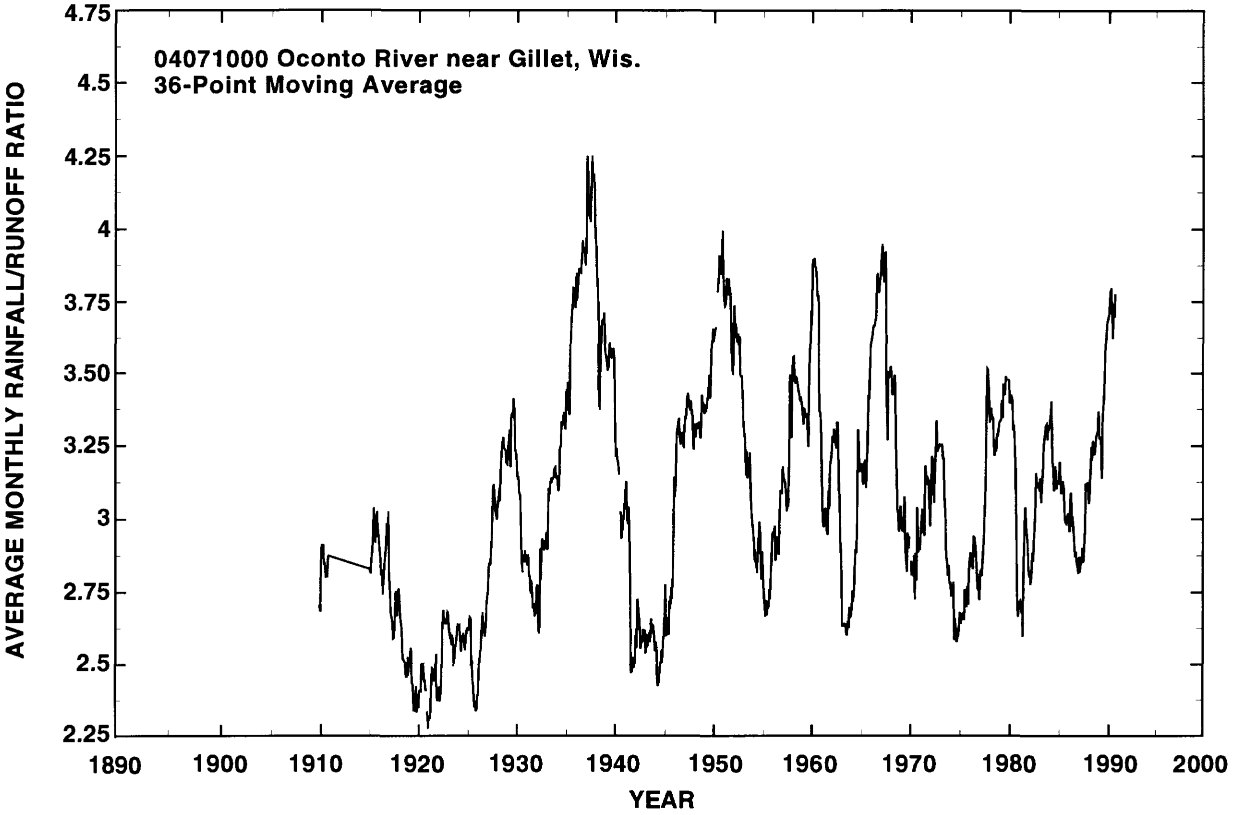
Lakes within the WMIC study unit are diverse, ranging from those that are completely unaffected by rivers to those with water quality that is almost completely controlled by inflowing rivers. Similarly, lakes range from having very little effect on the downstream river system to almost completely controlling conditions downstream. Many lakes were created to regulate the flow from specific drainages. A primary goal of these impoundments is to decrease the flow of the large spring floods and increase the flow during late-summer, fall, and winter low-flow conditions, as described earlier.

Lake Winnebago is the largest lake in the study unit (138,000 acres) and one of the largest natural lakes in the United States. Most of the surface water draining the central region of the study unit enters Lake Winnebago. Lake Winnebago alone contains 61 percent of the open water in the study unit. Large inputs of nutrients drive very high primary production, which is marked by intense algal blooms and fish kills within the lake.

Water Use

Water-use information for the WMIC study unit was obtained from USGS's Water-Use Data System (WUDS) for the year 1990. This information has been aggregated by water-use category. Only water that is withdrawn from its source (that is, pumped to a different location) is included in this discussion. The WMIC study unit has significant non-consumptive, instream uses of water, such as navigation, recreation, and hydroelectric power generation.

About 96 percent (4,654 million gallons per day [Mgal/d] out of 4,842 Mgal/d) of the total water used in the study unit, for all withdrawal water-use categories combined, comes from surface-water sources. The total surface-water use, by category, for the WMIC study unit, is shown in table 9. Probably less than 5 percent of the amount of surface water that is used is actually consumed (U.S. Geological Survey, 1990).The



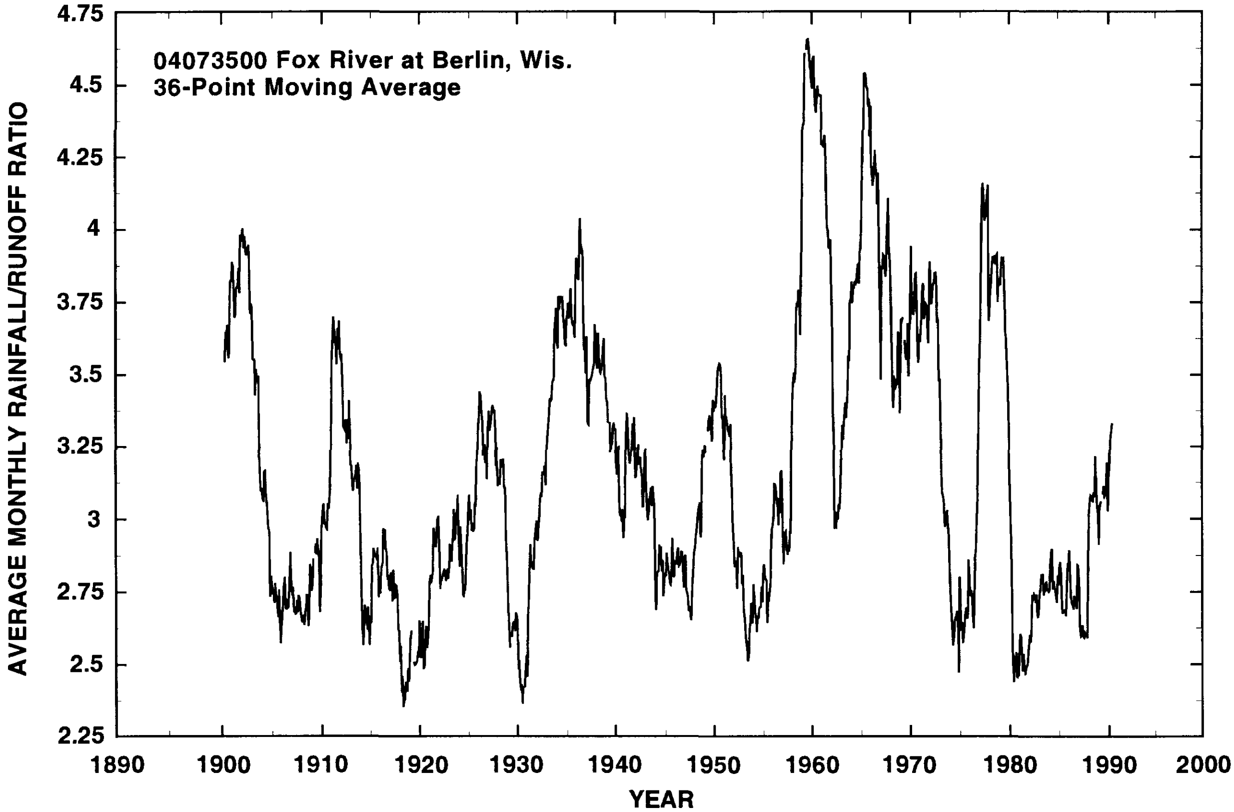


Figure 25. Rainfall/runoff ratios for selected streams in the Western Lake Michigan Drainages study unit.

Table 9. 1990 surface-water use for the Western Lake Michigan Drainages study unit.

[Mgal/d, million gallons per day]

Water-use category	Water use (in Mgal/d)	Percent of total
Thermoelectric, fossil fuel	2483.00	53.40
Thermoelectric, nuclear	1618.00	34.80
Public water supply	306.00	6.50
Industrial use	226.00	4.90
Fish hatcheries	12.40	0.30
Mining	4.41	0.10
Livestock use	2.31	<0.10
Irrigation	0.74	<0.10
Commercial use	.08	<0.10
Domestic use	0.00	0.00
Total	4654.06	100.00

largest single use of surface water (88 percent) in the WMIC study unit is for the generation of thermoelectric power. Most of the water used for this purpose is for cooling. About 99 percent of the water used for thermoelectric power generation is returned to its source and about 1 percent is consumed or lost through evaporation (Ellefson and others, 1987; U.S. Geological Survey, 1990). About 60 percent of the water used for thermoelectric power generation is used at fossil-fuel powered plants. Most of these power plants are in the eastern part of the study unit, primarily along the shore of Lake Michigan. The remaining 40 percent of surface water used for thermoelectric power generation is used at nuclear power plants. There are two nuclear power plants in the WMIC study unit, the Kewaunee Nuclear Power Plant in Kewaunee County, Wis., and the Point Beach Nuclear Power Plant in Manitowoc County, Wis. Both are on the shore of Lake Michigan and withdraw water directly from the lake.

The next largest use of surface water, after thermoelectric, is public-water supply. This accounts for 6.5 percent of total surface-water use. Generally, the communities located on the shores of Lake Michigan and Lake Winnebago use surface water for a part of their water supply (Ellefson and others, 1987). Some of these communities include Milwaukee, Green Bay, Racine, Kenosha, Manitowoc, Sheboygan, Appleton, and Oshkosh, Wis. (USGS Water Use Data System - WUDS) and Menominee, Gladstone, and Escanaba, Mich. (Bedell, 1982).

The third largest use of surface water in the WMIC study unit is for industry. This accounts for 4.9 percent of total surface-water use. Water used by paper, machinery, and oil companies are examples of industrial water use. The largest single industrial use of surface-water is by pulp and paper mills. Many of these companies are located along the Lower Fox River between Lake Winnebago and Green Bay, an area purported to have the highest concentration of pulp and paper mills in the world (Wisconsin Department of Natural Resources, 1992). The remaining uses of surface-water in the WMIC study unit account for less than one percent of total surface-water use. These include water for animal specialties (fish hatcheries), mining, livestock, irrigation, commercial, and domestic use.

Water Quality

The quality of surface waters in the WMIC study unit varies widely, from nearly pristine to highly contaminated. The sparsely populated, heavily forested areas in the northern and northwestern portions of the WMIC generally are characterized by better water quality than those in the southern and southeastern portions of the WMIC. The southern portion of the study unit is more densely populated, with correspondingly higher amounts of industrial and municipal waste discharged to surface waters. In addition, agricultural activities account for a much larger percentage of land use in the south, and contribute a concomitantly larger portion of nonpoint-source pollution to surface waters.

Monitoring Activities

Most current long-term water-quality-monitoring activities in the WMIC are being conducted in the southern two-thirds of the study unit. The USGS has maintained three NASQAN (National Stream Quality Accounting Network) sites and one HBN (Hydrologic Benchmark Network) site in the WMIC which are sampled on a quarterly basis. The WDNR maintains 18 fixed sites and the Michigan Department of Natural Resources (MDNR) maintains one site in the study unit. These sites are sampled approximately monthly. In addition, data on specific conductance and water temperature are collected in conjunction with all streamflow measurements made at USGS stream-gaging stations.

Thirteen of the combined 23 sites monitored by WDNR, MDNR, and USGS are located at the mouths of rivers where they discharge directly to Lake Michigan or Green Bay. The Fox and Wolf River systems are monitored at several points along their channels. One of the sites, the Popple River near Fence, Wis., is a Hydrologic Benchmark Site. This designation is given to rivers that are considered to possess near-pristine water quality. Table 10 contains the name, site number, and the agency responsible for the water-quality-monitoring sites in the WMIC.

The Lake Winnebago system is part of many past and ongoing water-quality studies. Outflow from the lake has strongly influenced the downstream water quality in the Lower Fox River. The quality of the outflow from the lake has been studied in conjunction with the Green Bay Mass Balance Study (U.S. Environmental Protection Agency, 1990). The lake, including inflows and outflows, is also part of the ambient monitoring program of the WDNR.

Characteristics

In general, alkalinity, hardness, dissolved solids, and specific conductance increase from the northwest to the southeast across the study unit. These parameters largely reflect the shallow ground-water quality in much of the WMIC study unit. Exceptions occur in areas where human impacts, such as point-source discharges, dams, or agricultural runoff, change water-quality characteristics. However, much of the large-scale variation can be explained by bedrock and surficial-deposit characteristics, while human impacts have more local effects on water quality.

During low-flow conditions, most of the surface water in the study unit is of the calcium-magnesium-bicarbonate type. Concentrations of other ions, including sodium, sulfate, and chloride, are generally lowest in the northern and northwestern portions of the study unit. In general, concentrations of major ions throughout the study unit are lower in lower-order streams. Thus, the observed concentrations of major ions tend to increase from lower- to higher-order streams. Concentrations of sodium, sulfate, and chloride also are higher in urban areas, and sometimes vary seasonally. Chloride concentrations, for example, increase in streams in urban areas in late winter and early spring due to runoff from highway-salt applications.

In the northern and northwestern portions of the study unit, ground water moves rapidly through highly permeable outwash deposits of sand and sand mixed with gravel overlaying bedrock composed of weathering-resistant igneous/metamorphic rock. In these areas, however, sufficient weathering occurs so that surface waters commonly are very hard (>180 mg/L, as calcium carbonate), although not hard enough to restrict the use of the water for recreation and industry (Oakes and Hamilton, 1973).

Water quality in streams in the southeastern and eastern portions of the WMIC study unit is generally good except locally, where urban and industrial discharges have degraded stream conditions (Skinner and Borman, 1973). A greater percentage of surficial deposits in these areas are clays or silts, through which ground water flows more slowly than in areas with sands and gravels in the north. Also, carbonate bedrock predominates in this portion of the WMIC. This combination of factors yields higher solute contributions in surface water than in the northern and northwestern portions of the WMIC and thus accounts for the higher concentrations of major ions, and higher alkalinities and specific conductance. Surface water in thesestreams, particularly those discharging directly to Lake Michigan, is generally very hard and not used for public supply (Skinner and Borman, 1973).

Table 10. Site name, location, and agency responsible for water-quality-monitoring sites in the Western Lake MIchigan Drainages study unit (Wisconsin Department of Natural Resources, 1992)

[USGS, U.S. Geological Survey; NASQAN, National Stream Quality Account Network; WDNR, Wisconsin Department of Natural Resources]

Site name	Site number	Agency
Popple River near Fence, Wis.	04063700	USGS NASQAN
Fox River at Wrightstown, Wis.	04085000	USGS NASQAN
Manitowoc River at Manitowoc, Wis.	04085427	USGS NASQAN
Milwaukee River at Milwaukee, Wis.	04087000	USGS NASQAN
Fox River at Berlin, Wis.,	243020	WDNR
Kinnickinnic River in Milwaukee, Wis.	413069	WDNR
Milwaukee River at Estabrook Park, Wis.	413640	WDNR
Milwaukee River at North Avenue Dam, Wis.	413073	WDNR
Sheboygan River at Sheboygan, Wis.	603095	WDNR
Fox River at Appleton, Wis.	453226	WDNR
Fox River at DePere, Wis.	053210	WDNR
Fox River at Winnebago outlet, Wis.	713002	WDNR
Kewaunee River near Kewaunee, Wis.	313038	WDNR
Oconto River near Gillett, Wis.	433003	WDNR
Oconto River at Oconto, Wis.	433002	WDNR
Pensaukee River at Bell Bridge, Wis.	433080	WDNR
Peshtigo River at Peshtigo, Wis.	383001	WDNR
East Twin River near Two Rivers, Wis.	363070	WDNR
West Twin River near Two Rivers, Wis.	363071	WDNR
Menominee River at U.S. 141, Wis.	383061	WDNR
Wolf River at Freemont, Wis.	693001	WDNR
Wolf River at New London, Wis.	693035	WDNR
Menominee River at mouth nr. Menominee, Mich.	550038	MDNR

Table 11. Specific water-quality issues of concern for the Ford-Escanaba (FE), Menominee-Oconto-Peshtigo (MOP), Fox-Wolf (FW), and direct Lake Michigan (LM) Basins

Water-quality issue	FE	MOP	FW	LM
Nutrients		X	X	X
Siltation/turbidity		X	X	X
Animal wastes		X	X	X
Ammonia toxicity			X	
Nuisance algal blooms			X	
Low dissolved oxygen			X	
Pesticides		X		X
Heavy metals	X	X	X	X
Polychlorinated biphenyls	X		X	X
Polycyclic aromatic hydrocarbons		X		X
Mercury			X	
Oil and grease		X		
pH		X		X
Fish toxicity	X		X	

In portions of the WMIC with large urban and industrial areas, such as Milwaukee and Green Bay, point-source discharges of pollution cause higher dissolved solids, and thus greater specific conductance. Towns and cities in these areas rely on Lake Michigan for their water supply. In addition, agriculture, which makes up a significant percentage of the land use in the southern and southeastern portion of the study unit, contributes non-point-source pollution to surface waters in these areas. The impact of agriculture may be reflected in increased nutrients and suspended-sediment inputs. A detailed analysis of existing data indicates that land uses, such as agriculture, are the primary factors influencing concentrations of nutrients and suspended sediment in surface waters in the WMIC (Robertson, 1996).

Concerns

Historically, water-quality problems within the WMIC study unit have been attributable to both point- and nonpoint-source pollution. Point sources primarily include discharges from wastewater-treatment plants, dairy producers, and paper mills, whereas non-point sources primarily include runoff from agricultural and urban areas. Hydrophobic organic compounds, some metals, and trace elements that are no longer discharged in the basin have accumulated into streambed sediments, where they may have relatively long residence times and remain as water-quality concerns because of processes such as re-suspension into the water column, and bioaccumulation through uptake by bottom-feeding organisms. In the past, sediment contamination in the study unit was monitored in response to dredging requests. In recent years, more monitoring has been done in order to develop fish-consumption advisories.

Over the past 20 years, Wisconsin has reached full compliance with Federal standards for conventional pollutants, such as suspended sediment and ammonia, from point sources. The primary point sources presently targeted for further control include urban storm-water-drainage systems and septic tank leakage. The primary sources of "new" pollution to waters in the WMIC, however, are non-point sources related to agricultural land uses.

Today, sediment and nutrients are the largest and most widespread non-point-source pollutants in surface water, adversely affecting approximately 40 percent of the streams and threatening another 20 percent in the area (Wisconsin Department of Natural Resources, 1990). The WNDR's efforts to control non-point-source pollution are focused within the Wisconsin Non-point Source Water Pollution Abatement Program which provides grants to individual landowners and communities to implement Best Management Practices (BMPs). Within the WMIC study unit in Wisconsin, 16 priority watershed projects are in various stages of completion (Wisconsin Department of Natural Resources, 1990). Landowners in each of the selected watersheds have up to eight years to voluntarily install BMPs on a cost-sharing basis.

Water-quality issues of concern for specific basins in the study unit are summarized in table 11. This table should not considered exhaustive, although it does contain the primary issues identified to date.

Ground Water

By David A. Saad

An aquifer is defined as a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (Lohman, 1972). The movement of ground water through these aquifers can be divided into two types of flow systems: regional and local. The general direction of deep flow throughout large areas is called regional flow. Regional flow for the WMIC study unit is controlled by the eastward dipping slope of the bedrock surface (LeRoux, 1957; Oakes and others, 1973). Regional flow is generally to the east and discharges to Lake Michigan or the major ground-water pumping centers such as Milwaukee and Green Bay. Some regional flow to the Wisconsin and Rock Rivers may occur in the extreme southwestern part of the study unit (Zaporozec and Cotter, 1985).

Ground water that moves through small, shallow flow systems is called local flow. This type of flow develops where local relief is pronounced (Freeze and Cherry, 1979), and is typical in the WMIC study unit. The lateral boundaries of the local ground-water flow systems generally correspond to the surface-water boundaries of drainage basins. Some recharge to ground water enters the deeper, regional flow system but most stays within the local flow systems and moves toward surface-water discharge points at lakes and streams (Gonthier, 1975; Young and Batten, 1980). The distance from point of recharge to point of discharge in the local flow systems of the WMIC is generally less than 6 mi (Young and Batten, 1980; Oakes and others, 1973).

The four principal aquifers in the WMIC study unit include (in descending order) the Sand and Gravel aquifer, Silurian Dolomite aquifer, Sandstone aquifer, and the Basement Complex (fig. 26) (Kammerer, 1984; U.S. Geological Survey, 1985). These four aquifers have a wide range of water-yields and hydraulic and geologic characteristics that will be discussed in the following section.

Aquifer Characteristics

The Sand and Gravel aquifer primarily consists of permeable unconsolidated Quaternary glacial deposits of highly variable texture. The aquifer is not well mapped but is known to be up to 600 ft thick. Generally, however, the aquifer is 25-200 ft thick, but it may be very thin or absent in some parts of the study unit. Where the Sand and Gravel aquifer is sufficiently thick and saturated, large yields (100 to 500 gallons per minute [gpm]) are possible. Yields as high as 1,750 gpm have been reported (Young and Batten, 1980) although yields generally range from 5 to 200 gpm. The hydraulic conductivity (K) values of the aquifer have a wide range. Published K values for unconsolidated deposits in and around the WMIC study unit range from 4.5×10^{-5} feet per day (ft/d) for tests on eastern Wisconsin tills (Bradbury and Muldoon, 1990) to 1.5×10^{3} ft/d for sand and gravel deposits in Washington and Ozaukee Counties, Wis. (Young and Batten, 1980). Published values of storage coefficients (S) range from 0.10 to 0.23 (Novitski, 1976; Batten, 1987).

The Silurian Dolomite aquifer underlies in the eastern part of the WMIC study unit and consists of eastward dipping Silurian- and Devonian-Age dolomite and limestone strata that are up to 700 ft thick (U. S. Geological Survey, 1985). The aquifer is overlain by the Sand and Gravel aquifer and underlain by the Maquoketa shale, a confining unit, which separates it from the Sandstone aquifer. Well yields from the aquifer generally range from 5 to 300 gpm although rates up to 1,500 gpm has been reported (Hutchinson, 1970). The permeability of this aquifer depends largely on the size, number, and interconnectedness of fractures and solution openings. The amount of water from a given well in this aquifer depends on how many of these

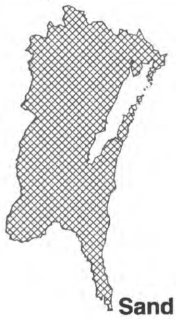
Geologic Age	Geologic Unit	Dominant Lithology	Aquifer
Quaternary	Holocene alluvial and Pleistocene glacial deposits	Unconsolidated sand and gravel; variable amounts of silt, clay, and organic material	 Sand and gravel (thin or absent in parts of the study unit)
Devonian - Silurian	Undifferentiated	Dolomite	 Silurian dolomite
Ordovician - Cambrian	Undifferentiated	Sandstone and dolomite	 Sandstone
Precambrian	Igneous and metamorphic rocks	Granite and metamorphic rocks	 Basement complex

Figure 26. Aquifers in the Western Lake Michigan Drainages study unit (from Kammerer, 1984; and U.S. Geological Survey, 1985.

fractures and solution openings it intersects. Published K values for this aquifer range from 0.01 ft/d (Young and Batten, 1980) to 8,000 ft/d (Emmons, 1987). Storage coefficient values range from $1.6x10^{-6}$ (Geraghty and Miller, Inc., 1979) to $1.0x10^{-2}$ (Emmons, 1987).

The Sandstone aquifer underlies all but the northwestern portion of the WMIC study unit. It is underlain by the Basement Complex and overlain by the Sand and Gravel aquifer. Along the eastern edge of the WMIC it is also overlain by the Silurian Dolomite Aquifer. The aquifer is composed of Cambrian- and Ordovician-Age sandstone and dolomite, but also includes some siltstone and dolomitic sandstone. The maximum thickness of the aquifer is greater than 1000 ft. The aquifer is confined in the eastern part of the WMIC, where it is overlain by the Maquoketa shale. It may be locally confined in other places where it is overlain by unconsolidated materials of low permeability. The highest well yields are obtained from this aquifer where it is overlain by only the Sand and Gravel aquifer (Zaporozec and Cotter, 1985). Well yields are generally between 10 and 500 gpm; however, yields of up to 1,500 gpm have been reported (Skinner and Borman, 1973). Well yields from this aquifer are controlled by the type of rock that the well penetrates. In the dolomite and dolomitic sandstone, the amount of fractures and solution channels dictates the permeability. In the sandstone, the permeability is largely controlled by the amount of intergranular pore space. The range of published K values for this aquifer is 0.10 to 160 ft/d (Harr and others, 1978). Published storage coefficient values range from $1.4x10^{-4}$ (Foley and others, 1953) to $2.0x10^{-3}$ (Krohelski, 1986).

The Basement Complex underlies the entire study unit. It is composed of igneous and metamorphic rocks of Precambrian age and is overlain only by the Sand and Gravel aquifer in the northwestern part of the WMIC. Well yields are relatively low, usually less than 10 gpm. Many holes drilled into the Basement Complex yield little or no water. Most wells that yield water are completed in fractured or weathered zones. These zones are usually less than 20 ft thick and are less permeable with depth (Batten, 1987, 1989). Published K values for this aquifer range from $1.0x10^{-5}$ to 35 ft/d (Batten, 1987). No storage coefficient values for the Basement Complex have been published.

Ground-Water/Surface-Water Interaction

Shallow ground water and surface water in the WMIC study unit are chemically similar because of the relatively short travel distance of most ground water via local flow, especially under low flow conditions. Under natural conditions, almost all of the local ground-water flow in the WMIC is towards surface-water bodies such as lakes and streams. Some streams, however, are known to lose water to the underlying aquifers. Several reaches of Duck Creek and the Suamico River, in Brown County, Wis., lose water to the underlying aquifers. These reaches lose water because they are within the cone of depression caused by pumping of ground water from the Sandstone Aquifer in the Green Bay area (Krohelski, 1986). In general, water in the deep, confined Sandstone Aquifer in the eastern part of the WMIC discharges into Lake Michigan, although Lake Michigan water may enter the aquifer in small, localized areas.

Streamflow can be composed entirely of ground-water discharge up to 90 percent of the time (Olcott, 1966). Also, up to 90 percent of total annual flow can be made up of ground-water discharge (Holt, 1965). This means that poor quality water in a stream possibly could be due to poor quality of ground water discharging to it. The amount of ground-water-supplied streamflow depends on the thickness and permeability of the aquifer material. Where it is thick, permeable, and saturated, an aquifer can maintain higher baseflows for longer periods of than where it is less permeable and thin (Oakes and others, 1973).

Water Use

Information about ground-water use in the WMIC study unit was retrieved from the WUDS for the year 1990. Ground-water use information by aquifer was available only on a county basis in the Wisconsin portion of the WMIC (Bernie Ellefson, U.S. Geological Survey, written commun., 1992). To determine the total water used by each aquifer, the water use for each county was multiplied by the percent of the county that fell within the WMIC study boundary and then summed for the Wisconsin portion of the study unit. Estimates of water use, by aquifer, for the entire WMIC, were therefore based only on the values calculated for the Wisconsin portion.

About 4 percent (188 Mgal/d out of 4,842 Mgal/d) of the water used in the study unit (excluding non-withdrawal uses) comes from ground water, nearly all of which is derived from fresh-water sources. The total ground-water use, by aquifer and water-use category for the WMIC study unit is summarized in table 12. The primary uses of ground water in the WMIC study

Table 12. 1990 ground-water use in the Western Lake Michigan Drainages study unit

[Mgal/d, million gallons per day; --, data not available

Water-use catergory	Amount supplied by aquifer[1] (in Mgal/d)					
	Sand and Gravel	Silurian Dolomite	Sandstone	Basement Complex	Total	Percent of total
Public water supply	16.70	14.20	39.00	0.07	69.97	37.18
Commercial use	7.18	14.90	12.20	.00	34.28	18.21
Domestic use	10.60	10.40	10.80	.80	32.60	17.32
Livestock use	5.32	5.92	6.42	.55	18.21	9.68
Irrigation	14.90	0.59	2.50	.00	17.99	9.56
Industrial	3.50	3.97	5.39	.00	12.86	6.83
Mining[2]						
fresh	--	--	--	--	1.13	0.60
saline	--	--	--	--	0.01	<0.10
Animal						
specialties	1.08	.00	0.00	.00	1.08	.57
Thermoelectric, nuclear	0.00	.08	.00	.00	.08	<0.10
Total	59.28	51.19	76.31	1.42	188.21	100.00

[1]Percent from each aquifer is estimated. Estimates are based on county data and the portion of each county that falls within the WMIC study boundary.
[2]Data not available to calculate percent supplied by each aquifer for this category.

unit are public-water supply, commercial, and domestic use. Collectively these account for about 73 percent of all ground water used in the WMIC. The only use of saline water in the study unit is for mining, where it accounts for less than 1 percent of the total amount of ground water used for mining purposes.

The Sand and Gravel aquifer supplies about 31 percent of the total ground water used in the study unit. The largest use of water from this aquifer is public supply. Water supply wells tapping this aquifer are located in all parts of the WMIC. In the northwestern part of the WMIC, where the Basement Complex is unproductive and the other aquifers are absent, the Sand and Gravel aquifer is the most important source of ground water (Patterson, 1989; Spicer, 1988).

The Silurian Dolomite Aquifer supplies about 27 percent of the total ground water used in the study unit. The primary uses of this aquifer are commercial and pubic supply. Water from this aquifer is used primarily along the eastern portion of the WMIC. In some areas it is the most important aquifer because the overlying Sand and Gravel Aquifer is thin and/or unproductive and the underlying Sandstone aquifer is too deep and/or produces saline water (Zaporozec and Cotter, 1985). The Sandstone Aquifer supplies about 40 percent of the ground water used in the study unit. Public supply is the single largest use of water from this aquifer. Water from the Sandstone aquifer is used primarily in the central part of the WMIC, where the aquifer is relatively thick and not overlain by the Maquoketa Shale. The Basement Complex Aquifer provides less than one percent of the ground water used in the study unit, with most of the water being used for domestic and livestock use. The Basement Complex is a source of supply mainly in the northern part of the WMIC, where other aquifers are absent or too thin to be productive (Vanlier, 1963a and b).

Water Quality

The natural quality of ground water in the WMIC study unit varies greatly. The primary reason for this is the variety of materials that make up the aquifers. The dominant ions in the ground water are usually calcium, magnesium, and bicarbonate (Vanlier, 1963a and b; Kammerer, 1984).

Several chemical constituents are generally recognized as indicators of poor water quality. Elevated concentrations of dissolved solids, chloride, sulfate, iron, manganese, nitrate, and trace inorganic elements in ground water may indicate that the water is unsuitable for certain uses (Kammerer, 1984). Some of these and other chemical constituents, and associated water-quality problems, will be discussed for each aquifer in the context of various ground-water monitoring programs.

Monitoring activities

Most of the ground-water monitoring activities conducted by various agencies throughout the WMIC study unit are short term efforts that generally focus on a specific issue. Ground waters have been widely sampled for nitrates and pesticides by several agencies, but samples were collected only once at most sites. Certain volatile organic chemicals (VOCs) and other hazardous wastes may be sampled for more often at landfills and suspected leaky underground storage tanks. No extensive, long term ground-water-quality monitoring networks are currently being sampled in the WMIC study unit.

Characteristics

The Sand and Gravel aquifer is the shallowest aquifer with generally the shortest residence time for ground water. Water typically moves quickly through this aquifer, allowing relatively little time to dissolve the constituent minerals. Thus, water from this aquifer generally has low dissolved solids concentrations as compared to that from the bedrock aquifers. The water type in this aquifer ranges from calcium-bicarbonate, in the western part of the study unit, to calcium-magnesium-bicarbonate type, in the eastern part of the study unit.

The geometric mean values of some of the poor-water-quality 'indicator' constituents, are summarized in table 13, by aquifer, for parts of Wisconsin in and around the WMIC study unit. In general, most of the natural 'indicator' constituents in the Sand and Gravel aquifer have smaller concentrations than those found in the bedrock aquifers. In some areas, high iron concentrations are a problem. This generally occurs in areas of poor drainage, including wetlands (Holt and Skinner, 1973). In areas underlain by the Silurian Dolomite and/or Sandstone aquifers, nitrate concentrations are slightly elevated in the Sand and Gravel aquifer. This is probably due to the fact that the Sand and Gravel aquifer is closest to potential sources of contamination at the land surface, such as those from agricultural practices. Excess nitrate can cause methemoglobinemia in infants and health problems in livestock. The thickness and permeability of this aquifer determines, to some extent, the contamination potential within it and to the underlying aquifers. Where the Sand and Gravel aquifer is thickest and least permeable, contamination potential is lowest.

Water from the Silurian Dolomite aquifer is commonly very hard and has higher concentrations of dissolved solids than the other aquifers. The dominant ions are calcium, magnesium, and bicarbonate. In some parts of the study unit, other constituent ions include chloride, iron, and sulfate. Some highly mineralized water from this aquifer is categorized as the calcium-sulfate type. In most parts of the study unit, the aquifer is overlain by the Sand and Gravel aquifer that can act as a buffer zone for potential contamination. In areas where the Sand and Gravel aquifer is thin or absent and the Silurian Dolomite aquifer contains fractures and solution openings, there is a high potential for ground-water contamination. Such is the case in Door County, Wis. where bacterial contamination of ground water is the most widespread problem (Sherrill, 1978). The problem originates in areas where septic systems are closely spaced. Bacteria from the septic systems can travel long distances in the fractured dolomite with little attenuation, resulting in large areas of contamination. In addition, turbidity, which usually occurs after

Table 13. Geometric mean values of some poor-water-quality 'indicator' constituents for aquifers in and around the Wisconsin portion of the Western Lake Michigan Drainages study unit

[modified from Kammerer, 1984; mg/L, milligrams per liter]

Aquifer	Dissolved solids (mg/L)	Chloride (mg/L)	Sulfate (mg/L)	Iron (mg/L)	Manganese (mg/L)	Nitrate (mg/L)
Sand and Gravel	142[1]/341[2]	3.4[1]/5.2[2]	7.7[1]/21[2]	182[1]/328[2]	41[1]/22[2]	0.6[1]/0.6[2]
Silurian Dolomite	417	6.8	48	217	21	0.5
Sandstone	334-387[3]	6.1-8.0[3]	25-34[3]	244-520[3]	8.0-27[3]	0.4-0.5[3]
Basement Complex	180[4]	5.3[4]	7.1[4]	91[4]	28[4]	1.5[4]

[1]Represents geometric mean for the Sand and Gravel aquifer overlying Basement Complex.

[2]Represents geometric mean for the Sand and Gravel aquifer overlying Silurian Dolomite and/or Sandstone aquifers.

[3]The range of values represents the range of geometric means determined for three components of the Sandstone aquifer. The components are: undifferentiated Ordovician units, Sinnipee Group, and undifferentiated Cambrian units.

[4]Represents geometric mean for Basement Complex that directly underlies the Sand and Gravel aquifer.

heavy rains, is also a problem in some wells in this aquifer. Turbidity in ground water indicates a rapid movement of precipitation to the water table along fractures and solution openings. Additionally, contaminants such as nitrates and certain pesticides introduced at the land surface can and do move quickly into the ground water under these conditions.

The water type in the Sandstone aquifer generally ranges from calcium-bicarbonate to calcium-magnesium-bicarbonate. Sodium-sulfate, sodium-bicarbonate, and calcium-sulfate type waters are also found in some areas. The sodium-sulfate and sodium-bicarbonate waters probably originate from poor-quality water in the Maquoketa Shale. Dissolved solids are found in relatively high concentrations in this aquifer. Concentrations of dissolved solids are highest in the eastern part of the study unit where the aquifer is deepest and residence time of the ground water is longest. In some areas along the eastern edge of the WMIC, the water is so highly mineralized that it is unfit for human use. This highly mineralized water may be encroaching into fresh-water-zones in areas where the Sandstone aquifer is heavily pumped.

Some natural water-quality problems in this aquifer include the presence of dissolved hydrogen sulfide gas and high concentrations of iron, sulfate, and radium. The source of the hydrogen sulfide is not fully understood but is indicative of anoxic conditions. Some of the formations in the Sandstone aquifer contain significant amounts of the mineral pyrite (FeS_2). Chemical reduction of the pyrite could result in the production of hydrogen sulfide. The St. Peter Sandstone Formation of the sandstone aquifer appears to be a significant contributor of radium in ground water, especially where it is overlain by the Maquoketa Shale. This is very important because the St. Peter Sandstone is also one of the principal sources of water within the Sandstone aquifer.

Not much is known about the quality of water in the Basement Complex, especially where it is overlain by the Silurian Dolomite and/or Sandstone aquifers. Water from this aquifer is usually the calcium-magnesium-bicarbonate type. In areas where it is overlain by only the Sand and Gravel aquifer, water from the Basement Complex generally has lower concentrations of dissolved solids compared to the other bedrock aquifers. In areas where the Basement Complex is fractured and near the land surface, there is a high potential for contamination of the ground water (similar to the Silurian Dolomite aquifer). In central Wisconsin, just outside of the study unit, high nitrate concentrations are found locally in the Basement Complex where it is near the land surface. This is believed to result from infiltration of water from barnyards and fertilized fields in agricultural areas.

Concerns

Most of the cities and villages in the WMIC study unit get all or part of their drinking water from ground-water sources. Many factors, both natural and anthropogenic, that can adversely affect the quality of ground water and result in restrictions on its use. The most common natural constituents that affect ground-water quality are hardness, iron, radon gas, dissolved solids, manganese, sulfate, and radium (Wisconsin Department of Natural Resources, 1990). These constituents are derived from the aquifer material, and their concentrations depend largely on the types of minerals present as well as the length of time the water is in contact with the aquifer material.

The major anthropogenic contamination sources for ground water in the WMIC study unit include agricultural activities, municipal landfills, underground storage tanks, abandoned hazardous waste sites, and spills (Wisconsin Department of Natural Resources, 1990; Michigan Department of Natural Resources, 1990). Nitrates (mostly from fertilizers and animal waste) and pesticides (typically aldicarb, atrazine, and alachlor) are the most significant contaminating substances, and are associated with agricultural activities. VOCs leaking from landfills are the most significant contaminating substances associated with non-agriculture sources.

Aquatic Biological Characteristics

By Barbara C. Scudder, Stephen J. Rheaume, *and* Daniel J. Sullivan

The biological characteristics of concern for the NAWQA program include information on the spatial distribution, community structure, and relative abundance of fishes, benthic invertebrates, algae, and macrophytes. This information can be used in conjunction with physical and chemical measurements of water quality to determine the sources and trends in water-quality and how they relate to natural conditions and anthropogenic factors.

Fish

Fish-community analysis has been found to be an effective tool for large-scale water-quality assessments (Meador and others, 1993). Fish communities integrate the current physical and chemical characteristics of a stream with historical conditions. In addition, analyses of fish flesh for bioaccumulative contaminants may determine that some contaminants, which have low concentrations in sediments or water, reach levels of concentrations that provide health risks to the organism or possibly to humans if consumed.

The streams in the WMIC study unit are home to a wide variety of fish species and communities ranging from cold-water fisheries with species such as brook trout and sculpin to warm-water fisheries dominated by species such as sunfish. A few species, such as the white sucker (*Catastomus commersoni*), can tolerate a wide variety of temperature and water-quality conditions and thus are almost universally distributed in the basin.

The fact that the study unit extends over a wide latitudinal range results in a wide variety of stream types. The northern portion of the study unit has a greater percentage of cold-water streams than the southern portion. Some headwater streams in the southern portion of the study unit may support cold-water species for short stretches, particularly if the stream is spring-fed. Throughout the study unit however, as drainage area and stream order increase, most streams in the WMIC study unit become cool- or warm-water fisheries.

Historically, the distribution of fishes in the study unit was influenced by the passing of the last glaciers. These Wisconsin-aged glaciers not only defined the physical appearance and the boundaries of the basin itself, but it is commonly accepted that they also extirpated all fishes therein, by a forced southward migration of fishes (Becker, 1983). Reintroduction of fishes occurred through both migration from non-glaciated areas to the south and west, and, more recently, from intentional and non-intentional introductions by humans.

Natural connections between the Mississippi drainage basin and the WMIC study unit have occurred in several places at various times as the Wisconsin-age glaciers retreated and drainage-basin boundaries formed and re-formed, allowing the passage of fish between basins. Examples of human activities that have influenced fish communities include stocking of both native and exotic species by both individuals and official agencies, and by fish rescue and transfer operations, which sometimes moved species into basins in which they previously did not exist (Becker, 1983). Other species made their way into the basin indirectly, as the result of human disturbances to physical characteristics of basins. For example, the parasitic sea lamprey moved into the Great Lakes after the completion of the Welland Canal that connects the Atlantic Ocean to the Great Lakes via the St. Lawrence Seaway. A canal connecting the Wolf and Wisconsin Rivers near Portage, Wis., has been in existence off and on over the years, allowing migration of fishes between these two basins. These and other natural and anthropogenic activities, as well as water-quality conditions, have combined to influence the composition of the fish communities that exist today in the WMIC study unit.

Twenty-four families of fishes currently inhabit the Wisconsin inland waters of the WMIC study unit. The distribution maps and descriptions in Becker (1983) indicate that 112 species inhabit the inland streams. The largest family, in terms of numbers of species, is that of the minnows and carps, with 35 species represented; followed by the perch, with 14 species; and the suckers and sunfish, with 10 species each. A statewide survey of the inland waters of Wisconsin was initiated in 1974 by the Bureau of Research, WDNR to establish a comprehensive data base on the distribution and relative abundance of all fish species (Fago, 1992). In the WMIC, only the streams in the southeastern portion have been sampled to date (1993).

Aquatic Invertebrates

Currently there are at least 12 phyla, and approximately 150 families of aquatic invertebrates in the WMIC study unit (Edmondson, 1959; Pennak, 1978; Throp and Covich, 1991; Michigan Academician, 1991). This great diversity of invertebrates adds up to several thousand aquatic species in the basin's inland streams; however, the vast majority of these are in the class Insecta. The distribution of these aquatic invertebrates is influenced by an interaction of physical, chemical, and biological characteristics. State and Federal agencies are in the process of trying to understand the effects of biotic and abiotic factors influencing invertebrate populations, and their relations to community structure, relative abundance data, and exiting water-quality conditions (Hilsenhoff, 1982; Plafkin and others, 1989; Michigan Department of Natural Resources, 1992; Gurtz, 1993).

Of the many invertebrate phyla encountered in the study unit, the four most commonly used in water-quality studies are the mollusks, crustaceans, worms, and insects. These benthic invertebrates live in or on streambed sediments, where many hydrophobic contaminants tend to concentrate and toxic responses are most likely to occur. These organisms are continuously exposed to changing environmental conditions and are well suited for use in comparing spatial patterns of water quality because of their non-migratory nature.

Aquatic mollusks are relatively long-lived invertebrates, and therefore reflect relatively long-term water-quality conditions. Mollusks in the study unit are divided into two classes: freshwater gastropods and freshwater bivalves (Burch, 1991). The gastropods are represented by the orders Mesogastropoda (6 families, 24 species) and Lymnophila (4 families, 66 species). The bivalves are represented by the orders Veneroida (2 families, 31 species) and Unionoida (1 family, 46 species).

Crustaceans are an ecologically important group of aquatic invertebrates. Although they are more mobile than the mollusks, crustaceans can not escape the affects of changing water-quality conditions. Crustacean are an important food source for fish, making them an important organism in toxic bioaccumulation studies (Crawford and Luoma, 1993). Common aquatic crustaceans in the study unit include the orders Isopoda (sow bugs) 1 family, 5 species; Anostraca and Conchostraca (fairy shrimp and clam shrimp), 2 families, 5 species; Decapoda (prawns and crayfish), 2 families, 8 species; and Amphipoda (scuds), 3 families, 8 species.

Of the many phyla of worms, the Annelida (segmented worms) are the most studied among benthic invertebrates. The freshwater annelids are comprised of the familiar earthworms (Oligochaeta) and the leeches (Hirudinea). Four families (about 15 species) of Oligochaetes are found in the lakes and streams of the study unit. Their varied density and distribution response to different kinds of pollution and toxic substances make them very useful as water-quality indicator organisms. Four families of Hirudinea (43 species) are found in the study unit. Their distribution is determined by environmental factors, such as composition of substratum, lentic or lotic water, depth, hardness, pH, water temperature, dissolved oxygen, and turbidity (Klemm, 1991).

Aquatic insects are the most numerous invertebrates in the study unit and are described in detail by Hilsenhoff (1980) and Merritt and Cummins (1984). They offer several advantages to water-quality studies in that they are relatively easy to collect, they are commonly abundant, they have limited mobility, and some live long enough and become large enough for tissue analysis (Crawford and Luoma, 1993). Many aquatic insects have been assigned pollution tolerance values (table 14) and can be used as water-quality indicators (Hilsenhoff, 1982).

Stoneflies (Order Plecoptera) are represented by 9 families (about 70 species) in the study unit. Stonefly nymphs are usually found in stream areas with relative

Table 14. Invertebrate water-quality indicator groups

Water quality	Invertebrate group	Pollution tolerance[1]
Good	Stonefly nymphs, mayfly naiads, caddisfly larvae, hellgrammites, and *Unionoida* clams	Very sensitive
Fair	Sowbugs, scuds, fingernail clams, blackfly larvae, snails, dragonfly nymphs, leeches, caddisfly larvae, and damselflies	Intermediately tolerant
Poor	Blood worms or midge larvae, sludgeworms, rat-tailed maggots, and sewage flies	Very tolerant

[1]"Pollution tolerance" refers primarily to low-oxygen conditions related to excessive nutrient concentrations as opposed to toxic conditions from organic pollutants.

high levels of dissolved oxygen, and they are relatively intolerant of nutrient (nitrogen and phosphorus) pollution. These characteristics may account for their absence from most streams in agricultural areas of southern Wisconsin. Additionally, fourteen families (about 150 species) of mayflies (Order Ephemeroptera) are present. Nymphs of most mayfly species also require high levels of dissolved oxygen, though many are more tolerant of lower levels than are stoneflies.

Dragonflies and damselflies (Order Odonata) are represented by at least 8 families (130 species) primarily in ponds, marshes, and lake margins, but some species are present in streams. Approximately 6 aquatic families (75 species) and 5 semiaquatic families (30 species) of true bugs (Order Hemiptera), including striders, water bugs, treaders, water boatmen, water scorpions, and backswimmers are present.

About 16 families (290 species) of caddisflies (Order Trichoptera) are distributed throughout the study unit. Most caddisfly larva and pupa inhabit streams but some may be found in other aquatic habitats, and some species are relatively tolerant of organic pollution. Larvae of fishflies and alderflies (Order Megaloptera) occur commonly in both streams and lake habitats and are represented by 2 families (20 species). One Family (5 species) of spongilla fly larva (Sisyridae, Order Neuroptera) is likely to be found in streams and lakes where the host species of sponge occurs. One family (15 species) of aquatic moths (Pyralidae, Order Lepidoptera) is fairly common in some lakes and streams.

Twelve aquatic families (more than 350 species) of beetles (Order Coleoptera) occur in the study unit, most in the families Dytiscidae, Gyrinidae, Haliplidae, Elmidae, Curculionidae, and Hydrophilidae. About 20 families (over 400 species) of aquatic flies and midges (Order Diptera) are found in the area's streams and lakes. The taxonomy of larvae in the numerous species of aquatic flies and midges is poorly known which leaves species lists fairly tentative.

Aquatic Plants

Aquatic plants have been used extensively in investigations of water quality because they are relatively easy and inexpensive to sample, transport, preserve, and store. As with other organisms mentioned above, they also are capable of accumulating certain contaminants above ambient concentrations in water, integrating contaminant concentrations over time, and are a direct measure of the bioavailable fraction of contaminants to plants in the environment. Two groups of aquatic plants are of interest to NAWQA for water-quality assessment: macrophytes and algae. Macrophytes refers to the larger (macroscopic) aquatic plants and includes vascular plants, mosses, liverworts, and larger algae (Sculthorpe, 1967). Several characteristics, in addition to size, make macrophytes better suited for tissue sampling and analysis; however, differences in species abundance of macrophytes and algae can also be valuable indicators of environmental change.

Macrophytes

Aquatic vascular plants, or macrophytes, provide food and cover for many fish and aquatic invertebrates. Many birds and fish feed directly on the aquatic invertebrates and algae attached to macrophytes. In addition, some birds, fish, and invertebrates use macrophytes in their reproductive cycle during nesting, spawning, and emergence. Rooted plants help stabilize shorelines, gravel bars, and stream banks. Healthy stands of macrophytes in rivers and lakes compete with algae for nutrients and light and can therefore reduce nuisance algal blooms.

About 51 families of macrophytes are represented in Wisconsin and the Upper Peninsula of Michigan and many also may be found in streams and rivers of the WMIC study unit. The pondweed family, Potamogetonaceae, is represented by the largest number of submersed species and a wide variety of growth forms. Growth forms of macrophytes vary from submerged, emergent, or floating depending on the species and maturity of the plant.

Several introduced macrophytes such as Eurasian watermilfoil appear to be having an impact on the ecology of aquatic communities in the WMIC. Purple loosestrife, an introduced emergent with tall purple "spike" flowers, has invaded many lakeshore and wetland areas in the study unit by outcompeting native species. Excessive growth of this species may impede water flow and may also replace native plants that provide greater benefits to other aquatic organisms (Wisconsin Department of Natural Resources, 1988; Walters, 1992).

Algae

Algae may be either attached (periphyton) or free-floating (phytoplankton), and may be single-celled, colonial, or in filaments or chains. Information on changes in species composition and abundance of algae is often valuable for use as an indicator of water quality. As the degree of pollution increases, in an area, the number of species decreases (diversity decreases) and the number of individuals of certain species increases. Phytoplankton, such as some blue-green (Division Cyanophyta) and green (Division Chlorophyta) algae, may increase greatly in number to form nuisance blooms in polluted waters. Because they are attached to a substrate, periphyton such as some diatoms (Division Chrysophyta) can reflect water-quality conditions at a specific location. In large non-wadable rivers and lakes, however, phytoplankton are more easily sampled than periphyton. A number of such studies have been conducted on phytoplankton in the WMIC study unit, most in the Winnebago Pool lakes (Marsh, 1903; Sager, 1971 and 1991; Sloey and others, 1976; Sloey and Spangler, 1977; Sloey and Brosseau, 1985). Marsh (1903) observed large blooms of several blue-green species followed by a bloom of the green algae *Cladophora* during summers in Lake Winnebago. In addition, the USGS collected data on phytoplankton species and abundance for its national NASQAN program during 1974 through 1981 at six sites in the WMIC. These six sites are Menominee River near McAllister (04067500), Fox River at Rapide Croche Dam near Wrightstown (04084500), Fox River at Wrightstown (04085000), Manitowoc River at Manitowoc (04085427), Milwaukee River at Milwaukee (04087000), and Cedar Lake near Kiel (435527087562701 and 435534087561101).

IMPLICATIONS OF ENVIRONMENTAL SETTING ON WATER QUALITY

By Charles A. Peters *and* David W. Hall

The quality of water in the Western Lake Michigan area rivers and aquifers is determined by innumerable combinations of natural factors and human activities. Natural factors influencing water quality include climate, geology, vegetation, and physiography. While most headwater and associated upland-lake areas in the 19,900 mi^2 WMIC study unit typically contain abundant water of high quality, much of the water that discharges into Lake Michigan from the ten major rivers in the study unit has been impacted by human activities. Contamination of these waterways, and thereby Green Bay and Lake Michigan, has the potential to alter water uses and biological cycles in many ways and is of great concern to industrial and private consumers, environmentalists, and resource managers in the United States and in Canada.

Natural Factors

Water in the WMIC study unit originates as rain and snow, and therefore the temperature, quantity, quality, and any subsequent evaporation of precipitation affect the volume and quality of recharge to ground water and runoff to surface water. These climatic factors determine not only the initial chemical composition of study-area waters, but also affect geologic weathering reactions that result in soil formation and contribute dissolved and particulate matter to surface and ground waters.

Climatic characteristics, in combination with geologic properties, typically provide the setting for characteristic plant communities within different lithologies and latitudes (Hem, 1985). Additionally, geologic formations affect water quality because rocks are the source of many chemical constituents in the water. The physical and chemical features of the bedrock, surficial deposits, and soils influence the surface- and ground-water hydrology and also physiographic characteristics of each basin.

Streams and rivers in the topographically rugged northern parts of the WMIC are in general large and perennial, whereas those in the south are smaller and consist of both intermittent and perennial streams and rivers. Increased annual runoff in the northern part of the WMIC is a result of a combination of more frequent and larger rainfall, snow, and snowmelt events and less evapotranspiration. Thus, the streams and rivers in the northern part of the study unit have the capacity to transport larger loads of sediment than do streams and rivers in the south. Increased runoff in the northern part of the WMIC relative to southern areas is further facilitated by areas of relatively impermeable igneous and metamorphic, Precambrian rocks that are present near the land surface in the northwest (fig. 4) and by "lake effect" enhanced rainfall (fig. 13) and snowfall (fig. 14) in areas proximate to Lake Superior and Lake Michigan.

In the northwestern Northern Lake and Forest ecoregion (fig. 8), impermeable and weathering-resistant bedrock of volcanic origin has been exposed over large areas (fig. 4), and in places is overlain with a thin mantle of glacial deposits. Ground-water typically flows rapidly through the coarse-grained glacial deposits in this area along the upper bedrock surface. Most of the surface water and shallow ground water in the WMIC area is of a calcium-magnesium-bicarbonate type.

Thick glacial sand and gravel materials mantle the bedrock over much of the North Central Hardwood Forests and Southeastern Wisconsin Till Plains. Surficial and shallow aquifer materials in the North Central Hardwood Forest and in the Southeastern Wisconsin Till Plain are largely clay and silt over sandstone, shale, limestone, and dolomite bedrock. Ground water flows more slowly through these materials than through the coarser deposits to the north, causing a greater contact time between geologic materials and water. Relatively slow ground-water flow and resultant increased contact time of water with geologic materials also cause elevated solute concentrations of water in the small area of the Central Corn Belt prairie which is situated at the southern tip of the Till Plain. This small area of the WMIC consists primarily of loess and interbedded till overlying permeable Cambrian sandstones (fig. 4). Thus, slower moving surface and ground waters in the southern part of WMIC typically contain less sediment but greater concentrations of alkalinity, hardness, dissolved solids, and specific conductance than northern waters because of the local geology and intensive agricultural and urban land uses in the south.

Acidic precipitation in the WMIC (fig. 19) enhances weathering of rocks and soils, thereby increasing concentrations of many naturally-occurring soluble or partially soluble substances including sulfate, iron, and manganese in WMIC surface and ground water. Areas where carbonate-bearing (dolomite or limestone) soils and bedrock are present (figs. 4A., 4B, and 26) typically have surface and ground water that are buffered against acidic precipitation; however, noncarbonate areas such as those in the northern WMIC contain lakes and streams that may be subject to acute and chronic acidification. Although carbonate bedrock materials are the predominant source of hardness in study unit waters, acid precipitation also contributes to hardness in all areas of the WMIC. In the poorly buffered northern study unit waters, iron is mobilized under acidic conditions causing iron hardness. In the well-buffered southern waters of carbonate-rock areas, acidic precipitation contributes to hardness because the acid consumes alkalinity and accelerates dissolution of calcium- and magnesium-bearing materials in water.

Large floods have occurred at irregular intervals in all parts of the study unit (table 7). Large floods typically cause massive erosion and can deliver anomalously large loads of sediment in any part of the WMIC at any time of the year. Most floods in the north are caused by snowmelt runoff in the spring, whereas floods in the south may be caused by spring snowmelt but also large rain storms occurring from spring until fall.

Human Activities

Human activities contribute numerous contaminants to surface and ground water in the WMIC through both point and nonpoint source pathways. Anthropogenic contaminants present in the western Lake Michigan drainage systems include nutrients, polychlorinated biphenyls (PCB's), pesticides, other synthetic organic compounds, and trace elements (including metals) in bottom sediments of rivers and harbors. Point sources of pollution in the study unit include mining operations, industrial activities including paper mills, unlined agricultural manure-storage facilities, barnyards, and large point-source discharges of wastes from sewage plants and industrial operations that are typically associated with densely-populated (table 4) and urban areas (fig. 9). Antiquated combined sewer and storm overflow systems are present in many older urban areas of the WMIC and can cause large point-source contaminant loading during periods of rainfall and snowmelt.

Concern about the potential effects of certain chemicals and metals has increased as the presence of contaminants and carcinogenicity in fish, genetic defects in fish-eating birds, and other reproductive disorders in biota have been observed. The primary route of human exposure to toxic substances in WMIC waters is through fish consumption, and numerous fish-consumption advisories are in effect to reduce this hazard. Additional routes of human exposure to these toxic substances include air inhalation, water consumption from public and private sources, and skin exposure through swimming.

Areas of Concern (AOC) are so designated where pollutants have caused impairment of beneficial use and support of aquatic life, as defined by the International Joint Commission (IJC; International Joint Commission, 1979). Four out of 43 AOCs defined by the IJC in the Great Lakes region are in the WMIC study unit: the lower Milwaukee River, the lower Sheboygan River, the lower Fox River, and the lower Menominee River. These areas were designated as AOCs after many beneficial uses of water had become impaired by contaminants (table 11). While the most severe water-quality problems exist within the defined AOCs, water resources of each basin are commonly affected by point- and nonpoint-source contaminants originating upstream. Remedial Action Plans (RAPs) have been developed and partially implemented by the U.S. and Canadian governments and numerous state and local agencies to ameliorate water quality in each AOC.

Nonpoint sources are diffuse discharges of pollutants that are difficult to trace to single or multiple point sources. Most major waterways in the WMIC study unit are severely impacted by nonpoint-source pollutants, which enter waterways in runoff and from the atmosphere, and may be dispersed from contaminated sediments. Common nonpoint pollutants include nutrients, sediment, and many materials from both urban and rural areas that are released into the atmosphere and subsequently infiltrate with recharge to ground water or are carried with runoff into surface waters.

Some nonpoint-source contaminants are wastes directly associated with human activities occurring in the proximate area, however, significant amounts of atmospheric material from distant areas may also be deposited in the WMIC. As previously discussed, precipitation (rain and snow) in the WMIC is acidic, with an average pH of about 4.7. The acidity is primarily a result of sulfur- and nitrogen-bearing compounds discharged into the atmosphere from coal-fired power plants in the midwestern U.S and also automobile exhaust emissions in, and upwind of the WMIC area. Atmospheric mercury in precipitation and dryfall has caused bioaccumulation of mercury in the food chain in sufficient amounts to require fish consumption advisories in some WMIC waterways. Atmospheric wetfall and dryfall have contributed substantial quantities of synthetic toxic chemicals to waters in the WMIC area (Eisenreich and others, 1981), including PCBs, pesticides, dioxins, furans, hexachlorobenzene, benzene, trichloroethylene, carbon tetrachloride, mercury, sulfate, nitrate, nitric acid, sulfur dioxide, ammonia, and alkylated lead.

Agricultural land occupy approximately 37 percent of the total land area in the WMIC. Puckett (1994) states that in most midwestern areas of the United States where agricultural activities are similar to those in the WMIC, nonpoint-source loading of nitrogen to waterways is commonly 4 to 5 times greater than point source loading. Nonpoint-source nitrogen loading from the atmosphere to the land surface commonly accounts for between 60 and 75 percent of the total load of nitrogen contaminants in midwestern waterways, and an unidentifiable percentage of this airborne nitrogen (Langland, 1992) and most of the remainder of the nitrogen contamination originates primarily as agricultural manures and fertilizers. Nitrate concentrations in ground water in agricultural areas of the WMIC with permeable soils frequently exceed 10 mg/L. The herbicide atrazine and its metabolites have been detected so frequently and in concentrations sufficiently high in both surface and ground water to have required atrazine application bans in many WMIC counties.

Various land uses including agriculture, silviculture, industrial, and residential lands frequently cause the release of nonpoint-source pollutants, including sediment, phosphorus, and pesticides. Some sources of nonpoint-source contamination of surface and ground water from these land uses in the WMIC include holding ponds for storage of agricultural animal wastes, landfills, and leaking underground storage tanks.

Nonpoint source sediment loading to streams in the WMIC is frequently caused by erosion associated with logging operations in the northern part of the study unit and by agricultural activities such as disking and plowing in the south. Pesticide (herbicide, fungicide, insecticide, and rodenticide) applications to forested lands, farm fields, residential land, urban areas, and golf courses have caused many pesticides and pesticide degradation products to be present in waters of the WMIC. In addition to atrazine and its metabolites, pesticides frequently detected in water samples collected in agricultural areas of the WMIC include alachlor, metolachlor, and cyanazine (Kammerer, 1986).

Considerations for Water-Quality Monitoring

The NAWQA Program is designed to provide a nationally consistent description of surface- and ground-water quality and aquatic life for the majority of the Nation's major river basins, and to identify and attempt to explain any significant factors affecting water-quality conditions. Because of costs associated with data collection, a carefully designed approach is required to accurately describe water-quality conditions over a large area from relatively few samples in each of the 59 past, present, or planned NAWQA study units.

Because data generated from the study units will be integrated nationally, a consistent approach to the design and implementation of data collection in each NAWQA study unit is planned to facilitate valid comparisons and interpretations of data collected in all, or any of the study units.

The WMIC study unit was subdivided into "relatively homogeneous units" (RHUs) to facilitate identification of relations between physiographic features and water quality in the predominant land-use areas of each basin. Land use and cover, surficial deposit, and bedrock type were selected as being the most useful factors to define spatial variations in water-quality of the WMIC area, therefore, unique combinations of these three factors were used to divide the WMIC study unit into 28 RHUs. Areas with similar land use, surficial deposits, and underlying bedrock were defined by overlaying digital coverages of each factor in a geographic information system (GIS).

The primary land-uses and land covers that were used to characterize the WMIC study unit into RHUs included forest, agriculture, wetlands, urban, and open-water areas. The major surficial deposits are sand and gravel, sand, loam, clay, and peat, therefore, these were used in RHU definition. Areas underlain by the major igneous/metamorphic, sandstone, carbonate, or shale aquifers were defined by these types of bedrock.

The properties defining each RHU were generalized to varying extents to define contiguous areas that can be monitored to successfully identify and assess of the predominant factors affecting water-quality conditions in each RHU of the WMIC. Thus, areas where the land use was classified as being predominately agricultural may also have smaller inclusion areas of forest, wetlands, urban, and/or open water. Similarly, an area classified as having predominately clay surficial deposits may include smaller areas of other surficial materials. These generalizations were judged to be appropriate given the large size of the WMIC study unit and budgetary limitations.

In addition to analyzing and characterizing the water quality of large areas, evaluations of significant and representative smaller-scale factors affecting water-quality will be conducted at selected sites. For example, an investigation of movement of agricultural chemicals along a ground-water flowpath from an upland farm field to a receiving stream is planned to identify and assess important processes associated with agricultural nonpoint-source water contamination in the WMIC study unit.

The RHUs will be used to design the stream-water, ground-water, and biological-sampling networks of the WMIC study unit, in accordance with the uniform protocols established for all study units in the National NAWQA network (Hirsch and others, 1988). Monitoring of individual RHUs may facilitate identification of the water-quality effects of different land uses, surficial deposits, or bedrock type. Monitoring of larger streams and rivers that drain multiple RHUs may be used to characterize the quality of waters discharging into Lake Michigan and also provide a basis for inter-regional water-quality comparisons. Additionally, rivers draining large areas (containing multiple RHUs) have historically been sites of long-term data collection. Continued monitoring of the sites with historical records may lead to recognition of trends or other changes in water quantity or quality that may have occurred over time.

SUMMARY

In 1991, the U.S. Geological Survey began to implement its National Water-Quality Assessment (NAWQA) program. The Western Lake Michigan Drainages (WMIC) was one of 20 study units selected for investigation to begin in 1991. The study-unit investigation will include an assessment of surface- and ground-water quality. The WMIC study unit drains a 19,900-square-mile area in eastern Wisconsin and the Upper Peninsula of Michigan. Ten major rivers drain the basin including the Escanaba River and Ford River in the Upper Peninsula of Michigan, the Menominee River, which defines part of the state boundary for Wisconsin and Michigan, the Peshtigo and Oconto Rivers in northeastern Wisconsin, the Fox/Wolf River complex which drains into Green Bay, and the Manitowoc, Sheboygan, and Milwaukee Rivers that drain directly into Lake Michigan from the southeastern part of the study unit.

The morphological and geochemical characteristics of streams as well as ground-water movement, storage, and chemistry are controlled by consolidated and unconsolidated rock lithologies and structure in the WMIC. Consolidated rocks in the basin include Precambrian crystalline rock, Cambrian sandstones, Ordovician dolomite, sandstone, and shale, Silurian dolomite, and Devonian dolomite. These units are overlain by Pleistocene glacial deposits, outwash, and glacio-lacustrine deposits, and Holocene alluvium, colluvium, lacustrine, and eolian deposits. Soils are developed in the glacial deposits and alluvium, or bedrock residuum where the unconsolidated deposits are thin or missing. The depth to the bedrock surface is highly variable and ranges from 0 to greater than 100 ft below land surface.

Landforms in the WMIC are controlled by underlying bedrock lithology and structure, which have been modified by Pleistocene glacial processes. They consist of erosion-resistant bedrock uplands, glacial terminal and recessional moraines, ground moraines, drumlin fields, outwash plains and valleys, dunes, and ancient lake beds. These landforms influence the patterns of drainages and hydraulic characteristics of surface- and ground-water flow.

Four principle aquifers underlying the WMIC study unit: the Sand and Gravel aquifer, Silurian Dolomite aquifer, Sandstone aquifer, and the Basement Complex. These four aquifers have a wide range of water-yields and hydraulic and geologic characteristics.

The WMIC study unit has a temperate, continental climate associated with a large annual range in air temperature and little monthly variation in precipitation. The study unit is also located in the mid-latitude belt, marked by large seasonal changes in the solar-zenith angle and day length, which together produce a significant north-south temperature gradient. The north-south gradient and the seasonal range in temperature, however, are modified by the neighboring Laurentian Great Lakes. Mean annual precipitation ranges from approximately 28 to 34 in. per year across the study unit. Evaporation plus evapotranspiration varies from less than 18 in. per year in the north to over 24 in. in the southern regions. Runoff rates vary from approximately 8 in. per year in the southern part of the WMIC to 15 in. per year in the northern part.

The WMIC is composed of four ecoregions: Northern Lakes and Forests, North Central Hardwood Forests, Southeastern Wisconsin Till Plains, and Central Corn Belt Plains. The major plant groups include mixed coniferous-deciduous forest, deciduous forest, upland prairie and brush, boreal forest, and wetland vegetation. Ten federally endangered or threatened species of plants and animals may be found in the WMIC.

Forested land accounts for approximately 40 percent of the WMIC, agricultural land accounts for approximately 37 percent, wetlands account for approximately 15 percent, and about 3 percent of the study unit has the classification of 'water'. Several thousand lakes, ranging in size from 0.5 to 138,000 acres, exist within the study unit. Large areas of urban or built-up land are located near the major cities in the southeastern portion of the study unit and account for about 3 percent of the areas.

About 96 percent (4,654 out of 4,842 Mgal/d) of the total water used in the study unit, for all withdrawal water-use categories combined, comes from surface-water. The largest single use of surface water (88 percent) is for the generation of thermoelectric power. The next largest use of surface water is public supply, which accounts for about 6.5 percent of total surface-water use. About 4 percent (188 Mgal/d) of the water used comes from ground water.

The quality of surface waters in the WMIC study unit varies widely, from nearly pristine to highly contaminated. The sparsely populated, heavily forested regions in the northern and northwestern portions of the WMIC generally are characterized by better water quality than those in the southern and southeastern

areas. The southern portion of the study unit is more densely populated than the northern areas, with correspondingly higher amounts of industrial and municipal waste discharged to surface waters. In addition, agricultural activities account for a much larger percentage of land use in the south, and contribute a concomitantly larger portion of nonpoint-source pollution to surface waters.

During low-flow conditions, most of the surface water in the study unit is of the calcium-magnesium-bicarbonate type. Concentrations of other ions, including sodium, sulfate, and chloride, are generally lowest in the northern and northwestern portions of the study unit. In general, concentrations of major ions are lower in lower-order streams. Concentrations of sodium, sulfate, and chloride are higher in urban areas, and sometimes vary seasonally.

The natural ground-water quality varies greatly in the WMIC study unit. The primary reason for this is the variety of materials that make up the aquifers. The dominant ions in the ground water are usually calcium, magnesium, and bicarbonate. Most of the cities and villages get all or part of their drinking water from ground-water sources. Many factors, both natural and man-made, can adversely affect the quality of ground water and result in restrictions on its use. The most common natural constituents that affect ground-water quality are hardness, iron, radon gas, dissolved solids, manganese, sulfate, and radium.

The streams in the WMIC are home to a wide variety of fish species and communities ranging from cold-water fisheries characterized by species such as brook trout and sculpin to warm-water fisheries dominated by species such as bass and sunfish. Currently 24 families of the fishes that represent 112 species are known to inhabit the inland streams in Wisconsin. About 51 families of macrophytes may be found in streams and rivers of the WMIC.

Human activities contribute numerous contaminants to surface and ground water in the WMIC through both point and nonpoint source pathways. Anthropogenic contaminants present in the western Lake Michigan drainage systems include polychlorinated biphenyls (PCB's), pesticides, other synthetic organic compounds, and trace elements (including metals) in bottom sediments of rivers and harbors. Point sources of pollution in the study unit include mining operations, paper mills and other industrial activities, unlined agricultural manure-storage facilities, barnyards, and large point-source discharges of wastes from sewage plants and industrial operations.

Most major waterways in the WMIC are also adversely affected by nonpoint-source pollutants that enter the waterways in runoff, from the atmosphere, and from contaminated sediments. Nonpoint-source sediment loading to streams in the WMIC is frequently caused by erosion associated with logging operations in the northern part of the study unit and by agricultural activities in the south. Pesticide (herbicide, fungicide, insecticide, and rodenticide) applications to forested lands, farm fields, residential land, urban areas, and golf courses have caused many pesticides and pesticide degradation products to be present in study-unit waters. In addition to atrazine and its metabolites, pesticides frequently detected in water samples collected in agricultural areas include alachlor, metolachlor, and cyanazine.

The WMIC study unit was subdivided into "relatively homogeneous units" (RHUs) to facilitate identification of relations between physiographic features and water quality in the predominant land-use areas of each basin. Land use and cover, surficial deposit, and bedrock type were selected as being the most useful factors to define spatial variations in water-quality of the WMIC area. Therefore, unique combinations of these three factors were used to divide the study unit into 28 RHUs.

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