SOURCES AND TRANSPORT OF SEDIMENT, NUTRIENTS, AND OXYGEN-DEMANDING SUBSTANCES IN THE MINNESOTA RIVER BASIN, 1989-92

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Conversions Factors, Abbreviated Water-Quality Units, and Abbreviations

Multiply	By	To obtain:
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	.1894	meter per kilometer
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
foot per second (ft/s)	.3048	meter per second
cubic foot per second (ft^3/s)	.02832	cubic meter per second
tons, short	.9072	megagram
degrees Fahrenheit (°F)	5/9 x (°F - 32)	degrees Celsius

In this report, chemical concentrations in water are expressed in milligrams per liter (mg/L) or micrograms per liter (µg/L); 1,000 µg/L = 1 mg/L. Chemical oxygen demand is expressed as COD. Biochemical oxygen demand for 5 days at 20°C is expressed as Bod_5.

GIS--Geographic Information Systems

LCMR--Legislative Commission of Minnesota Resources

LMIC--Land Management Information Center

MDNR--Minnesota Department of Natural Resources

MPCA--Minnesota Pollution Control Agency

MRAP--Minnesota River Area Project

EWI--equal-width increment (method of collecting samples for analyses of suspended sediment)

Abstract

The Minnesota River, 10 major tributaries, and 21 springs were sampled to determine the sources and transport of sediment, nutrients, and oxygen-demanding substances. The study was part of a four-year assessment of non-point source pollution in the Minnesota River Basin. Runoff from tributary watersheds was identified as the primary source of suspended sediment and nutrients in the Minnesota River mainstem. Suspended-sediment, phosphorus, and nitrate concentrations were elevated in all major tributaries during runoff, but tributaries in the south-central and eastern part of the basin produce the highest annual loading to the mainstem because of higher annual precipitation and runoff in that part of the basin. Particle-size analyses showed that most of the suspended sediment in transport consisted of silt- and clay-size material. Phosphorus enrichment was indicated throughout the mainstem by total phosphorus concentrations that ranged from 0.04 to 0.48 mg/L with a median value of 0.22 mg/L, and an interquartile range of 0.15 to 0.29 mg/L. Nitrate concentrations periodically exceeded drinking water standards in tributaries draining the south-central and eastern part of the basin. Oxygen demand was most elevated during periods of summer low flow. Correlations between levels of biochemical oxygen demand and levels of algal productivity suggest that algal biomass comprises much of the oxygen-demanding material in the mainstem. Transport of sediment, nutrients, and organic carbon within the mainstem was found to be conservative, with nearly all tributary inputs being transported downstream. Uptake and utilization of nitrate and orthophosphorus was indicated during low flow, but at normal and high flow, inputs of these constituents greatly exceeded biological utilization.

Introduction

The Minnesota River drains nearly 17,000 square miles in southwestern Minnesota and parts of eastern South Dakota, northern Iowa, and southeastern North Dakota (fig. 1). A study by the Minnesota Pollution Control Agency (MPCA) demonstrated that the Minnesota River and its tributaries are affected by non-point source pollution (Minnesota Pollution Control Agency, 1982). High concentrations of suspended solids, nitrate, phosphorus, and fecal coliform bacteria impair industrial, domestic, and recreational use of the river, as well as the esthetics of the river. A waste-load allocation study in the Lower Minnesota River Basin (Minnesota Pollution Control Agency, 1985) identified a need for a basin-wide program to control surface-runoff related non-point source pollutants.

The MPCA coordinated a multiagency effort to study the Minnesota River and its tributaries. The Minnesota River Assessment Project (MRAP) was a four-year study (1989-92) to assess the potential for non-point source pollution, to inventory information about physical characteristics of the basin, and to identify areas of non-point source pollution and the effect of non-point source pollution on water quality. This was done by (1) physical and chemical monitoring, (2) biological and toxicological monitoring, and (3) land-use assessment. This project was initiated by the Minnesota Legislature as recommended by the Legislative Commission on Minnesota Resources (LCMR). The MPCA was delegated the responsibility to manage this project. Federal, State, and local agencies, and colleges and universities collected and assembled data. The U.S. Geological Survey (USGS), in cooperation with the MPCA and the LCMR, monitored selected physical characteristics and chemical constituents of river water as part of the study.

The specific objectives of the USGS efforts were to:

1. Identify source areas of suspended sediment, major nutrients, biochemical oxygen demand (BOD), and organic carbon in the Minnesota River, and the effects of specific source areas on water quality in the Minnesota River.

2. Determine the relation of suspended sediment to major nutrients, BOD, algal productivity, and organic carbon in the Minnesota River.

3. Quantify the transport of sediment, nutrients, and oxygen-demanding substances in the Minnesota River.

4. Identify areas of bank and bed erosion and sediment deposition to determine the relative significance of instream sediment sources and non-point sources in the Minnesota River Basin.

Purpose and Scope

This report presents the findings of the physical and chemical monitoring of the Minnesota River. Information pertaining to the physical and chemical characteristics of the river is from data collected for this study by the MPCA and the USGS. A discussion of the results of physical and chemical monitoring relative to each of the study objectives is presented in this report. This report describes the hydrologic setting of the Minnesota River Basin, identifies source areas of sediment, nutrients, and oxygen-demanding substances, and quantifies transport of these constituents in the Minnesota River and its major tributaries.

Approach and Methods

The water sampling approach during 1989-90 was designed to provide information about both areal and temporal variability in water quality. Twelve mainstem water-quality sampling sites were established on the Minnesota River at intervals ranging from 13 to 33 miles. Water sampling included measuring suspended-sediment and chemical concentrations at the mouths of 10 major streams that are tributaries to the Minnesota River. Twenty-one springs, selected to characterize ground-water inputs to the Minnesota River, also were sampled.

Water samples were collected over a range of stream discharge conditions to characterize the change in water quality as the streams responded to both dry and wet conditions. Accordingly, water samples were collected at all spring and stream sites during low stream discharge in late summer (August 1989), in winter (January-February 1990), and in late summer (August 1990). These samples were collected during a short time period (2-3 weeks), progressing from upstream to downstream to obtain a synoptic appraisal of water quality during low stream discharge. Samples were collected at selected tributary and mainstem water-quality sampling sites during snowmelt (March-April) and during runoff from summer rainfall (May-July).

The water sampling approach was modified during 1991-92 to provide more detailed information about the origin, transport, and transformation of water-quality constituents. Seven water-quality sampling sites were added in the Blue Earth and Redwood River Basins and sampling efforts were redirected to address the study objectives as more data were collected. The locations of all water-quality sampling sites are shown on figure 1 and listed in tables 1 and 2.

Table 1.--Stream water-quality sampling sites for the Minnesota River Assessment Project

Site identification number (figure 1)	USGS identification number	Stream Site	Distance upstream from mouth of the Minnesota River, in miles
1	05301000	Minnesota River near Lac qui Parle, Minn.	288
2	05305400	Chippewa River at Montevideo, Minn.	
3	05311000	Minnesota River at Montevideo, Minn.	271
4	05313510	Yellow Medicine River on Highway 67 near Granite Falls, Minn.	
5	05314550	Hawk Creek at mouth near Sacred Heart, Minn.	
6	05314560	Minnesota River near Sacred Heart, Minn.	238
7	05314740	Minnesota River near Delhi, Minn.	219
8	05316470	Redwood River near Seaforth, Minn.	
9	05316490	Judicial Ditch 5 near Redwood Falls, Minn.	
10	05316500	Redwood River near Redwood Falls, Minn.	
11	05316541	Redwood River below Ramsey Creek at Redwood Falls, Minn.	
12	05316580	Minnesota River at Morton, Minn.	203
13	05316685	Minnesota River near Fairfax, Minn.	176
14	05316760	Minnesota River near New Ulm, Minn.	151
15	05317000	Cottonwood River near New Ulm, Minn.	
16	05317250	Minnesota River at Courtland, Minn.	134
17	05317500	Minnesota River at Judson, Minn.	120
18	05318135	Blue Earth River above South Creek near Winnebago, Minn.	
19	05318140	South Creek near Winnebago, Minn.	
20	05318141	Blue Earth River at County Road 5 near Winnebago, Minn.	
21	05318290	Blue Earth River near Good Thunder, Minn.	
22	05319500	Watonwan River near Garden City, Minn.	
23	05320500	Le Sueur River near Rapidan, Minn.	
24	05322000	Blue Earth River at Mankato, Minn.	
25	05325000	Minnesota River at Mankato, Minn.	107
26	05325200	Minnesota River at St. Peter, Minn.	91
27	05326400	Rush River near Henderson, Minn.	
28	05326450	Minnesota River at Henderson, Minn.	67
29	05327000	High Island Creek near Henderson, Minn.	

Table 2.--Spring water-quality sampling sites for the Minnesota River Assessment Project

Site identification (figure 1)	USGS identification number	Spring
D	444750095332001	Baker Spring near Granite Falls, Minn.
P	441827093573301	Seepage face at St. Peter, Minn.
C	445425095402301	Seepage face at Wehrspann Spring, near Montevideo Minn.
G	443631095094801	Seepage Cedar Rock Spring near Delhi, Minn.
F	443921095203301	Boiling Spring near Belview, Minn.
A	450026095514001	Seepage face at Baldwin Farm near Lac qui Parle, Minn.
U	444132093383201	Seepage face near Jordan, Minn.
R	442204093532301	Rogers Creek Spring near St. Peter, Minn.
K	441636094272701	Flandrau Spring at New Ulm, Minn.
L	441531094203001	Courtland Bridge Spring near Courtland, Minn.
N	440230094101001	Birr Spring near Garden City, Minn.
H	443317095073401	Redwood Spring near Redwood Falls, Minn.
Q	442006093545601	Paulson Spring near St Peter, Minn.
T	443418093552201	Seepage face at High Island Creek Spring near Henderson, Minn.
J	442859094490301	Peterson Spring near Fairfax, Minn.
B	445630095462101	Seepage at Envoldsen Farm near Montevideo, Minn.
E	444413095251701	Seepage face at Hawk Creek Spring near Sacred Heart, Minn.
I	443110094530001	Seepage face at Franklin Spring near Franklin, Minn.
S	443129093530501	Spring near Henderson Station, Minn.
O	440558094072301	Davis Hole Spring near Rapidan, Minn.
M	441206094115101	Seepage face at Spring near Judson, Minn.

The Minnesota River at Montevideo (site 3) and the Blue Earth River at Mankato (site 24) were sampled frequently throughout 1989-92 (weekly from March through July, and monthly from August through February) to determine short-term changes in water quality. Suspended-sediment samples were collected daily from March through November 1989-92 at the Minnesota River at Mankato (site 25) and at the Blue Earth River at Mankato (site 24). During the course of the study (August 1989 through September 1992), 404 water samples from streams and 36 water samples from springs were collected for chemical analysis.

Water samples were collected according to methods adopted by the USGS that are described by Buchanan and Somers (1969), Edwards and Glysson (1988), Ward and Harr (1990), and Britton and Greeson (1989). Streams were sampled using an equal-width increment (EWI) method across the stream using discharge weighting samplers to obtain water samples that were representative of total stream discharge. Stream discharge was determined at the time of each sample to calculate constituent loads. Stream discharge was determined by current-meter measurements or derived from stage-discharge relations at USGS gaging stations at or near the sampling sites.

Water samples and bottom-material samples were analyzed for chemical constituents at the USGS National Water-Quality Laboratory at Arvada, Colorado using methods described by Fishman and Friedman (1989), Wershaw and others (1983), and Britton and Greeson (1989). Water samples for suspended-sediment concentrations and particle-size determinations for suspended sediment, and bottom material were analyzed by the USGS Sediment Laboratory at Iowa City, Iowa using methods described by Guy (1969).

Specific conductance, pH, temperature, and dissolved-oxygen concentration were measured in the field using portable meters that were calibrated at the beginning and end of each sampling day. Five-day BOD and bacteria counts were determined in field laboratories. BOD analyses were performed on natural (unseeded) water samples; some water samples required dilution with deionized water.

Physical properties and chemical constituents sampled and analyzed for this study are shown in table 3. Data collected during this study are published in Water Resources Data for Minnesota (Gunard and others, 1989, 1990, 1991, 1992, and in press).

Table 3.--Physical properties and chemical constituents determined for water samples collected in the Minnesota River Basin, August 1989-September 1992

[ft^3/s, cubic foot per second; µmhos/cm, micromhos per centimeter; °C, degrees Celsius; mg/L, milligrams per liter; col/100ml, colonies per 100 milliliters; mg/kg, milligrams per kilogram; µg/L, micrograms per liter; mm, millimeter; NA, not applicable]

Constituent or physical property	Reporting unit	Minimum reporting level
Discharge, instantaneous, stream	ft^3/s	$0.01 ft^3/s$
Specific conductance (micromhos/cm at 25°C)	micromhos/cm	1 µmhos/cm
pH	units	0.1 unit
Water temperature	°C	0.1°C
Dissolved oxygen (DO)	mg/L	0.1 mg/L
Chemical oxygen demand (COD)	mg/L	10 mg/L
Biochemical oxygen demand, five-day at 20°C (BOD)	mg/L	0.1 mg/L
Coliform, fecal, membrane filter	col/100 ml	1/100 ml
Streptococci, fecal, membrane filter, KF agar bacteria	col/100 ml	1/100 ml
Residue total (total suspended solids)	mg/L	1 mg/L
Residue volatile (total volatile suspended solids)	mg/L	1 mg/L
Nitrite, total as N	mg/L	0.01 mg/L
Nitrite, dissolved as N	mg/L	0.01 mg/L
Nitrite plus nitrate, total as N	mg/L	0.01 mg/L
Nitrite plus nitrate, dissolved as N	mg/L	0.05 mg/L
Nitrite plus nitrate, total in bottom material as N	mg/kg	2.0 mg/L
Nitrogen, ammonia, total as N	mg/L	0.01 mg/L
Nitrogen, ammonia, dissolved as N	mg/L	0.01 mg/L
Nitrogen, ammonia, in bottom material as N	mg/kg	0.2 mg/L
Nitrogen, ammonia plus organic, total as N	mg/L	0.1 mg/L
Nitrogen, ammonia plus organic, dissolved as N	mg/L	0.2 mg/L
Nitrogen, ammonia plus organic, in bottom material as N	mg/kg	20 mg/kg
Phosphorus, total as P	mg/L	0.01 mg/L
Phosphorus, dissolved as P	mg/L	0.01 mg/L
Phosphorus, total ortho as P	mg/L	0.01 mg/L
Phosphorus, dissolved ortho as P	mg/L	0.01 mg/L
Phosphorus, total in bottom material as P	mg/kg	40 mg/kg
Dissolved organic carbon	mg/L	0.1 mg/L
Carbon, organic suspended as C	mg/L	0.1 mg/L
Carbon, inorganic in bottom material as C	gm/kg	0.1 gm/kg
Carbon, total in bottom material as C	gm/kg	0.1 gm/kg
Chlorophyll *a*	µg/L	0.1 µg/L
Chlorophyll *b*	µg/L	0.1 µg/L
Sediment, suspended, concentration	mg/L	1.0 µg/L
Sediment, suspended, fall diameter, percent finer than 2.00 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 1.00 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.500 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.250 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.125 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.062 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.031 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.016 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.008 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.004 mm	percent	NA
Sediment, suspended, fall diameter, percent finer than 0.002 mm	percent	NA
Sediment, suspended, sieve diameter, percent finer than 0.062 mm	percent	NA

Hydrologic Setting

The 17,000 square mile Minnesota River Basin comprises 12 tributary-river basins that range in size from 700 square miles (Redwood River Basin) to 2,090 square miles (Upper Minnesota River Basin) (tab. 4). The 12 tributary-river basins in the Minnesota River Basin, as defined by the USGS and the U.S. Water-Resources Council (U.S. Geological Survey, 1976), are shown in figure 1. The basin boundaries were defined on the basis of topographic divides as determined from USGS 1:24,000-scale topographic maps. GIS data bases of basin boundaries are available from the USGS.

Table 4.--Areas of tributary-river basins in the Minnesota River Basin

Subbasin	Area, in square miles
Upper Minnesota River	2,090
Pomme de Terre River	870
Lac qui Parle River	1,100
Chippewa River	2,080
Hawk Creek--Yellow Medicine River	2,070
Redwood River	700
Cottonwood River	1,310
Little Cottonwood River--Middle Minnesota River	1,350
Watonwan River	880
Le Sueur River	1,110
Blue Earth River	1,550
Lower Minnesota River	1,820

Climate and Weather

Due to the wide range of weather conditions, water samples were collected during dry, normal, and wet periods. Average annual precipitation for the Minnesota River Basin is shown in figure 2. Average precipitation generally increases from west to east across the basin. Average annual runoff is shown in figure 3. Average annual runoff is calculated from stream discharge records at gaging stations and is expressed as the depth to which the drainage area would be covered if all the runoff was evenly distributed. As shown in figure 3, runoff also increases from west to east across the basin. The range in runoff is large, increasing from one inch at the western edge of the basin to six inches in the eastern part of the basin. The higher runoff values mean that watersheds in the eastern part of the basin deliver more water to the Minnesota River per unit area than do watersheds in the western part of the basin. Higher runoff also means that the watersheds in the eastern part of the basin have a greater loading potential for non-point source constituents.

The timing and areal distribution of precipitation ranged widely during the study period. Drought conditions prevailed when the study began in August 1989. Runoff, as determined from stream-discharge records for the Minnesota River near Jordan, Minnesota, had been below normal for three consecutive months and remained below normal through April 1990. Runoff was near normal from May 1990 through April 1991, but reached above-normal levels during May 1991. Runoff remained above normal through March 1992, returned to normal during April through June 1992, and was above normal from July through September 1992 (U.S. Geological Survey, Minnesota District, unpublished data, 1989-1992). Stream discharges are classified normal if they fall within the interquartile range of stream discharge determined for each month for the reference period 1951-80. Stream discharges above the interquartile range are classified above normal. Stream discharges below the interquartile range are classified below normal (U.S. Geological Survey, 1992).

Geologic and Physical Features

Magner and Alexander (1993) provide a detailed overview of geologic influences on stream discharge and water quality in the Minnesota River Basin. In the western and central parts of the basin, Cretaceous deposits overlie crystalline Precambrian rock. The eastern part of the basin has layers of Cambrian and Ordovician sandstones, limestones, and shales. Extensive sand and gravel deposits (alluvium) are in the valleys of the major streams (fig. 4). Magner and Alexander evaluated the results of analyses of water samples collected from 21 springs during this study. They also reviewed findings of earlier studies conducted by Novitzki and others (1969), Van Voast and others (1970 and 1972), Brousard and others (1973), Anderson and others (1974a and 1974b), and Adolphson and others (1981). Magner and Alexander (1993) found that basin geology is an important determinant of water quality in the Minnesota River, especially during low-flow periods. Their review of water chemistry in the springs and streams showed that the river receives its base flow from various ground-water sources, deep as well as shallow, each having a characteristic chemical composition that indicated a probable source and pathway. Ground-water sources include bedrock aquifers, valley alluvium, surficial aquifers and ground-water flow to field tiles and ditches.

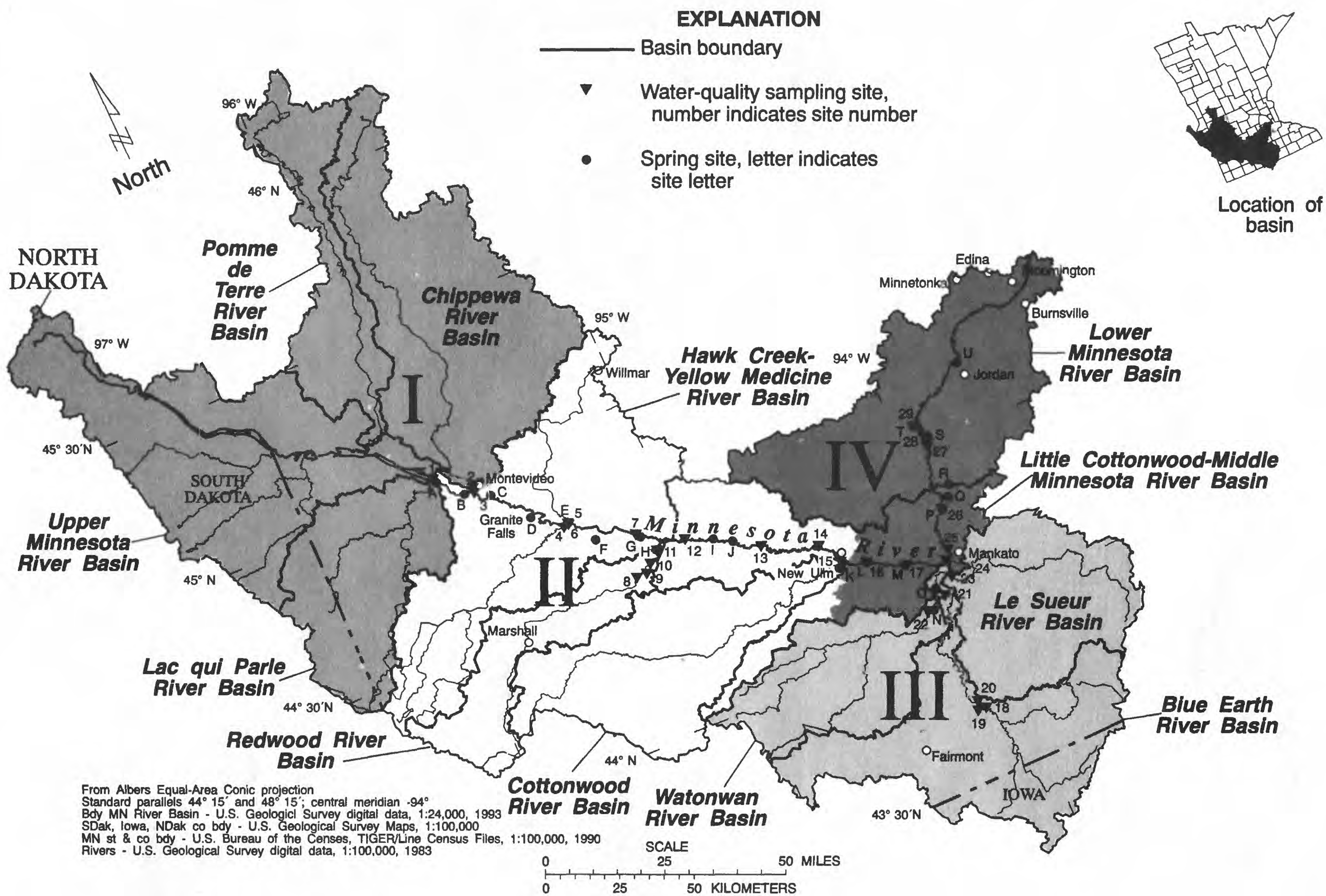


Figure 1.--Location of the Minnesota River Basin Source Regions (I - IV) and water-quality sampling sites.

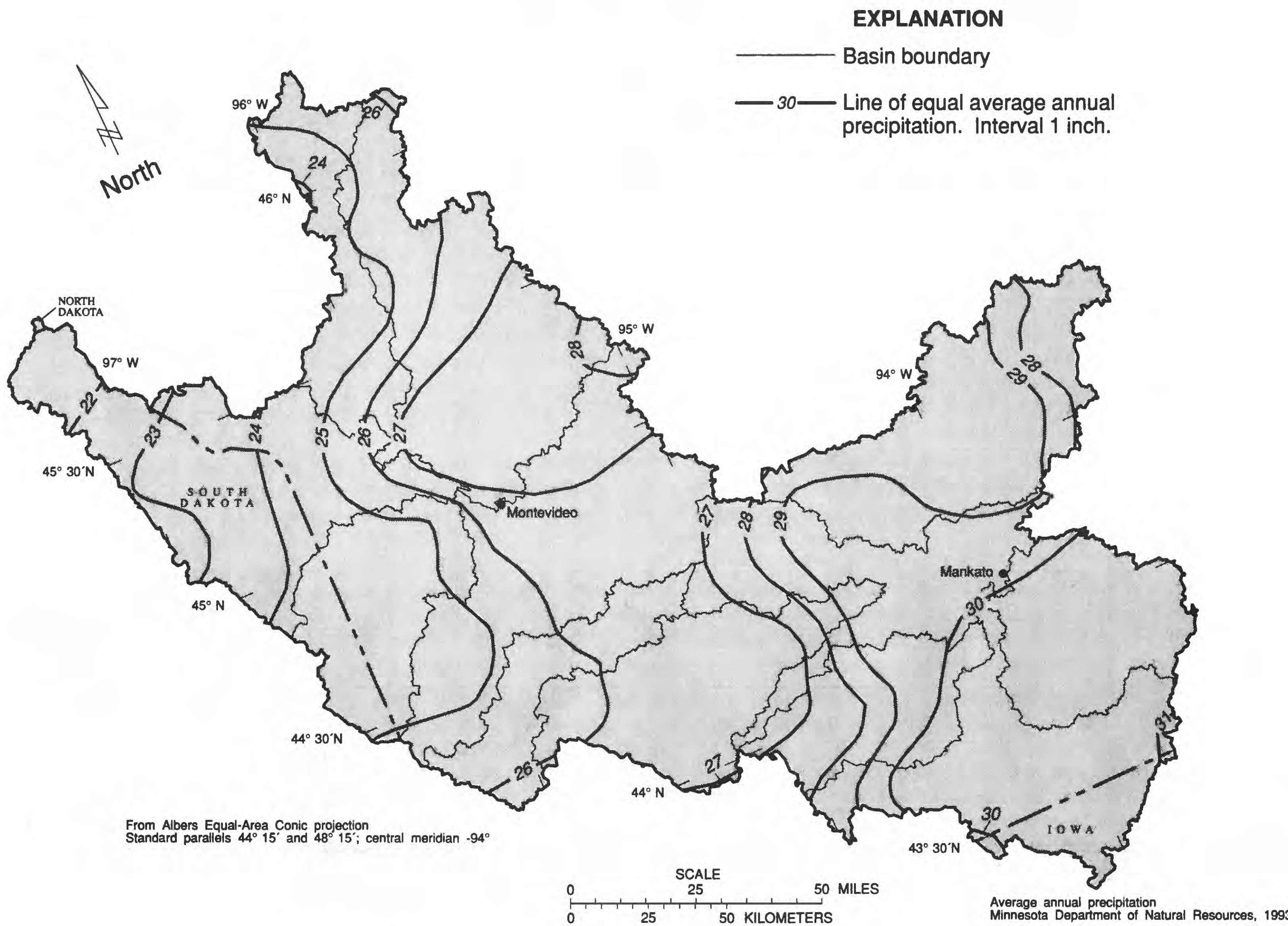


Figure 2.--Average annual precipitation for the Minnesota River Basin, 1961-90.
(Copyright 1990 to Minn. Dept. of Natl. Resources, 1990.)

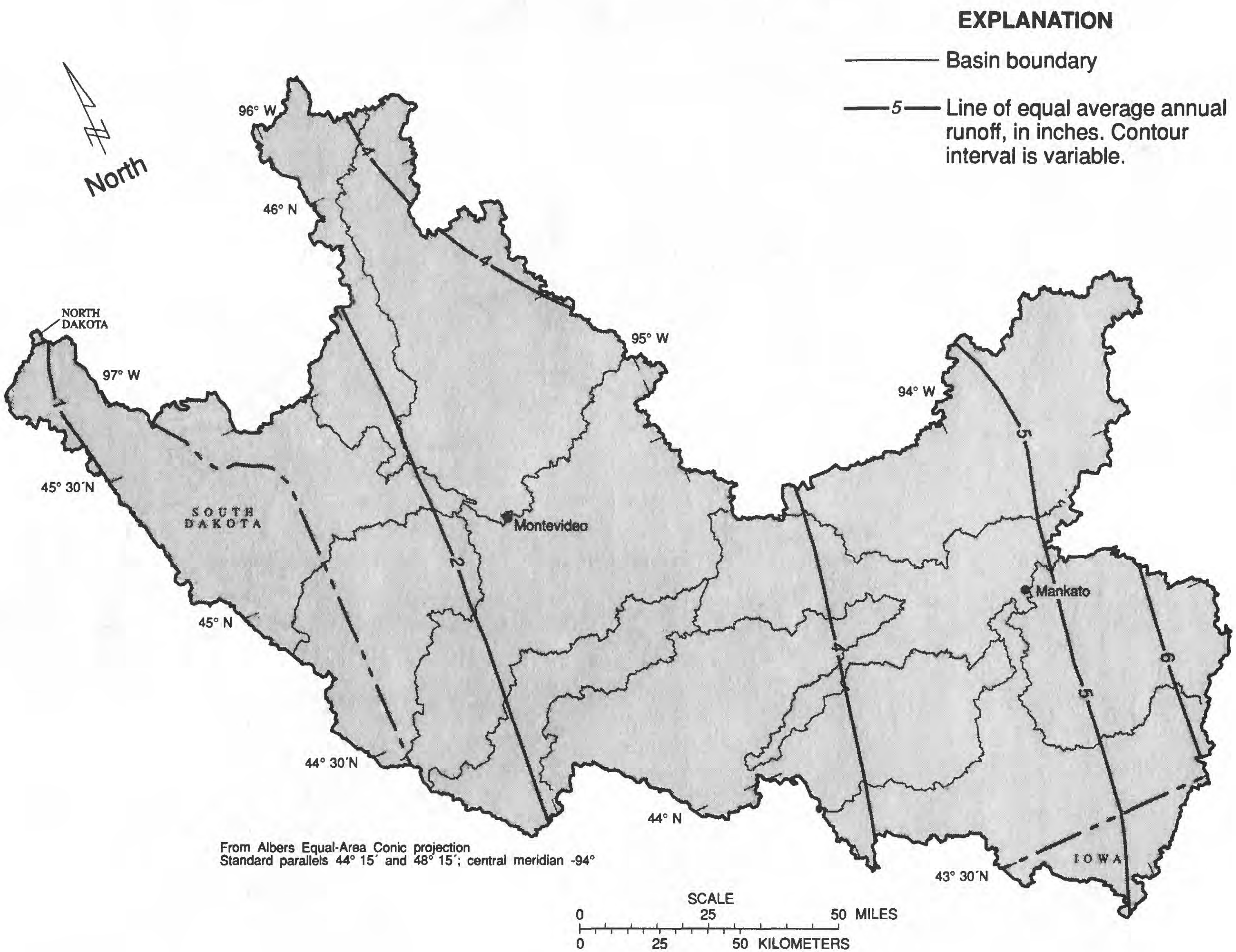


Figure 3.--Average annual runoff in the Minnesota River Basin, 1951-80.

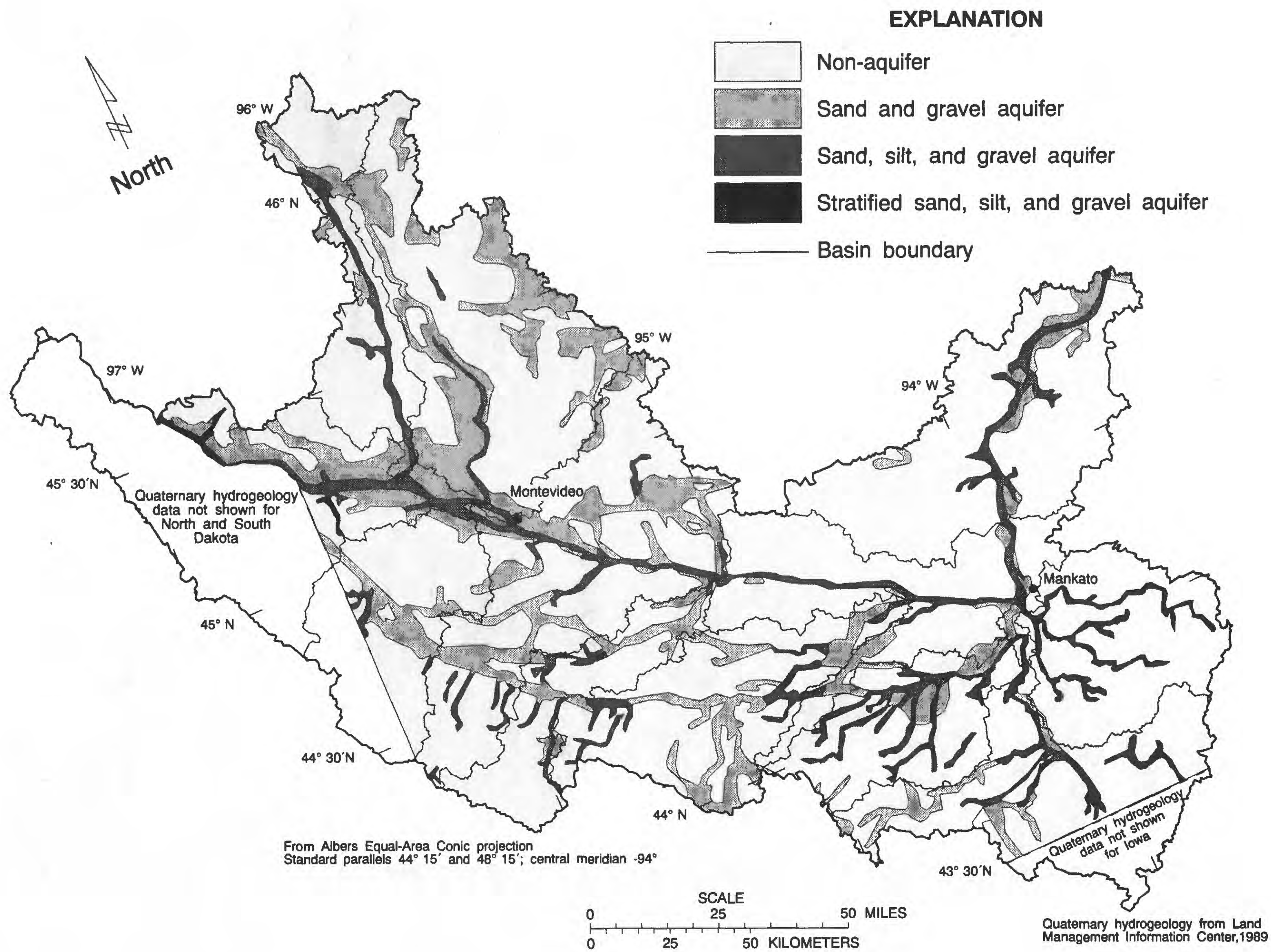


Figure 4.--Quaternary hydrogeology in the Minnesota River Basin.

Water movement through glacial deposits is influenced by physiography. The surface physiography of the Minnesota River Basin was shaped by the Des Moines lobe of the Wisconsin glaciation. Moraines, till plains, and lake beds provide the basic framework for the basin's surficial hydrologic setting. As the ice retreated, meltwater formed glacial Lake Agassiz to the north and west of the basin. Outflow from Lake Agassiz, carried by the ancient River Warren, carved the valley occupied by the present-day Minnesota River about 9,000 years ago and left a landscape that is of relatively recent origin in terms of geologic time. As a result, the tributary basins have not developed the dendritic stream patterns that are characteristic of older stream systems. A major physiographic feature of the Minnesota River Basin is the Coteau des Prairies, a morainal area that occupies the headwater regions of the Upper Minnesota, Lac qui Parle, Yellow Medicine, Redwood, and Cottonwood Basins (fig. 5). The altitude of the land surface rises abruptly in the Coteau des Prairies, from 960 feet at Big Stone Lake at the base of the Coteau des Prairies to more than 2000 feet near the summit. The Coteau des Prairies area has not been extensively drained and contains numerous lakes and wetlands, many of which are located in closed, noncontributing subbasins. Annual precipitation is lower in the Coteau des Prairies area than in other parts of the basin (fig. 2), as is annual runoff (fig. 3). The headwater regions of the Pomme de Terre and Chippewa Basins (fig. 5) are also located in a moraine. This area, while not as prominent a terrain feature as the Coteau des Prairies, also contains numerous lakes and wetlands.

Human Influences on the Hydrologic Setting

At the time of European settlement (mid 1800's) most of the basin contained numerous lakes and wetlands (Anderson and Craig, 1984). Upstream reaches of the tributaries often were typified by poorly-defined channels connecting a linearly-arranged series of wet prairie meadows. The undulating glacial terrain also contained catchments that had no outlet streams and therefore contributed virtually no surface-water runoff to the Minnesota River. Settlement of the basin began after 1860 and was nearly complete by 1900. The rich prairie soils proved to be very productive for agricultural purposes. Much of the land, however, was too poorly drained to be farmed efficiently, and artificial drainage was initiated as early as the 1880's. Drainage was accomplished by constructing ditches and subsurface drainage tile. The channels of many of the small, shallow, and meandering prairie streams were straightened and deepened. Lateral ditches and tiles were extended from the primary ditches to drain isolated depressional wetlands. Construction of watershed-scale drainage projects, often encompassing several square miles, continued into the 1960's. Estimates vary, but about 80 percent of the wetlands in the Minnesota River Basin were drained and converted to other uses (Leach and Magner, 1992). At present, 90 percent of the land in the basin is used for agriculture, primarily row crops such as corn and soybeans (Southern Minnesota River Basin Commission, 1977).

The network of tiles and ditches extends over much of the Minnesota River Basin. Quade and others (1980) inventoried drainage systems in four southern Minnesota counties, three of which are located wholly within the Minnesota River Basin. Their research showed that ditch construction had more than doubled the length of the surface fluvial system. They also compared the ditch system to the first- and second-order categories of the stream-ordering system developed by Strahler (1950). They stated, "The closeness of fit of the drainage ditch systems to the low-order Strahler classification scheme suggests that man has taken an immature lake-marsh environment and within 100 years created a geomorphically mature fluvial landscape" (Quade and others, 1980, p. viii).

Subsurface tiles further enhance the drainage capability afforded by the ditches, especially when surface intakes are installed in depressional areas to allow surface runoff to flow directly into the tile lines. Effects of artificial drainage on the hydrologic setting of the Minnesota River Basin were addressed by Magner and others (1993). Magner and others proposed that, prior to artificial drainage, much of the precipitation falling on the basin infiltrated the soil and was contained in shallow, localized ground-water flow systems that discharged to wetlands where much of the water evaporated. They concluded that artificial drainage has regionalized the flow system by collecting surface and subsurface flows and delivering them to the Minnesota River. This modified hydrologic system has enhanced potential for surface-water transport of non-point source constituents to the Minnesota River.

Concrete dams have been constructed at the outlets of Big Stone Lake, Marsh Lake, and Lac qui Parle to control floodwaters and lake levels. The Big Stone-Whetstone Reservoir was constructed in the Minnesota River Valley between Big Stone Lake and Marsh Lake during the 1970's. These lakes and the reservoir receive all tributary flow from the Upper Minnesota, Pomme de Terre, and Lac qui Parle Basins. In addition, a significant portion of flow from the Chippewa River Basin is diverted to Lac qui Parle Reservoir. During spring and summer floods, Chippewa River flow in excess of 1000 ft^3/s is diverted to Lac qui Parle. When flow in the Chippewa River is less than 1000 ft^3/s, one half of its flow is diverted to Lac qui Parle.

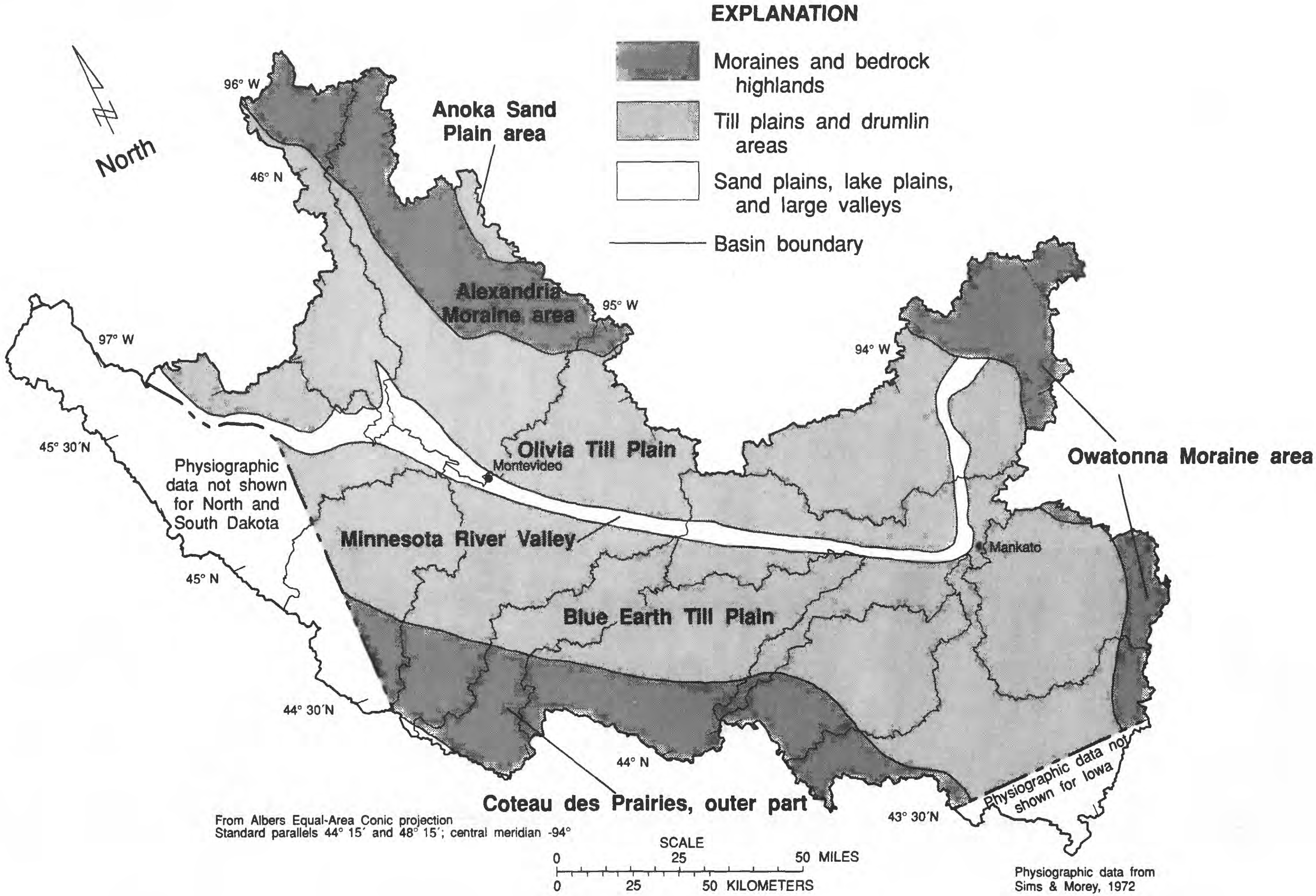


Figure 5.--Physiographic provinces in the Minnesota River Basin.

Sources of Sediment, Nutrients, and Oxygen-Demanding Substances

The term sources, as used in this report, refers to geographical source regions rather than to specific localized sources, such as an eroding hillside or a feedlot. This section of the report describes regional differences in non-point source loading and evaluates the relative importance of instream and watershed sources. The load of a particular chemical constituent in a stream is calculated by multiplying the concentration of a constituent by stream discharge. The resulting value is the amount (load) of that constituent transported by the stream during a specified time period.

Geographic Source Regions

The regional variation of physiography, geology, and the temporal variation in rainfall distribution within the basin were considered to be natural factors that would have effects on water quantity and quality. The natural hydrologic influences were identified so they could be differentiated from anthropogenic effects such as land-use practices. The west to east precipitation gradient, for example, could cause the eastern part of the basin to have more runoff-producing storms, therefore, producing higher sediment loading, irrespective of land-use activity.

Regional variability of basin water quality is defined by four broad geographic source regions (figs. 1, 6a-6c). These regions are (I) Minnesota River headwater basins, (II) Hawk Creek-Yellow Medicine, Redwood, Cottonwood, and Little Cottonwood-Middle Minnesota River Basins upstream of New Ulm, (III) Watonwan, Blue Earth, and Le Sueur River Basins, and (IV) Little Cottonwood-Middle Minnesota River Basins downstream of New Ulm and the Lower Minnesota River Basin. These basin divisions, while based on findings from this study, are somewhat arbitrary, and the distinctions between regions are, in some instances, gradational.

Source Region I (fig. 6a) consists of the Upper Minnesota, Pomme de Terre, Lac qui Parle, and Chippewa Basins. The effect of low average precipitation combined with evaporation from the four headwater reservoirs results in this region having the lowest annual runoff in the basin. During the initial planning phase of this study, it was hypothesized that the headwater reservoirs would accumulate the inflows of the tributaries and that significant biochemical processing of that inflow would occur within the reservoirs. Outflow from the most downstream reservoir, Lac qui Parle, would represent the end result of processes in all four reservoirs. It was expected that water quality of outflow from Lac qui Parle would tend to be less variable than water quality at river locations elsewhere in the basin.

There are two hydroelectric dams downstream of Lac qui Parle; one is located in the city of Granite Falls and the other is located 2.5 miles downstream from Granite Falls. Neither of these dams impound large reservoirs. Downstream from Granite Falls, the relative influence of the headwater reservoirs diminishes as the Minnesota River receives inflow from two major tributaries, the Hawk Creek and Yellow Medicine River.

The Hawk Creek-Yellow Medicine Basin, Redwood River Basin, Cottonwood River Basin, and the Little Cottonwood-Middle Minnesota River Basin upstream of New Ulm, form the second source region as defined for this study (fig. 6b). The Minnesota River in this region undergoes more rapid fluctuations in flow rate and water quality as tributaries in this source region respond to snowmelt and heavy rainfall. Continuous stage records for the Yellow Medicine, Redwood, and Cottonwood Rivers show rises in stage within one to four hours after the onset of rainfall. Hawk Creek is not gaged for collection of continuous stream discharge data, but stage measurements of Hawk Creek during runoff indicated that it also responds rapidly to rainfall.

In addition to the four major tributary rivers, parts of Source Region II contain other streams that are direct tributaries to the Minnesota River. About twenty tributaries enter the Minnesota River between Granite Falls and New Ulm. The watersheds of these tributaries support intensive agriculture and their upstream reaches are drainage ditches and improved natural channels. The rapid response to rainfall recorded for one of these tributaries, the Little Cottonwood River, suggests that the other tributaries may have similar rainfall-runoff responses. This source region, like Source Region I, experienced fewer runoff periods during the study compared to the eastern part of the Minnesota River Basin. This region is differentiated from the Source Region I in that non-point source constituents in stream runoff are delivered directly to the Minnesota River.

The Watonwan, Blue Earth, and Le Sueur River Basins form Source Region III (fig. 6c). The Watonwan and Le Sueur Rivers join the Blue Earth River near its mouth. These three river basins drain the area of highest rainfall and runoff in the Minnesota River Basin (figs. 2, 3). Long-term (1903-93) stream discharge records show that the Blue Earth River accounts for 46 percent of the flow of the Minnesota River at Mankato. During the study (August 1989-September 1992) the Blue Earth River delivered 46 percent of the flow of the Minnesota River at Mankato. The Blue Earth River drains about 40 percent

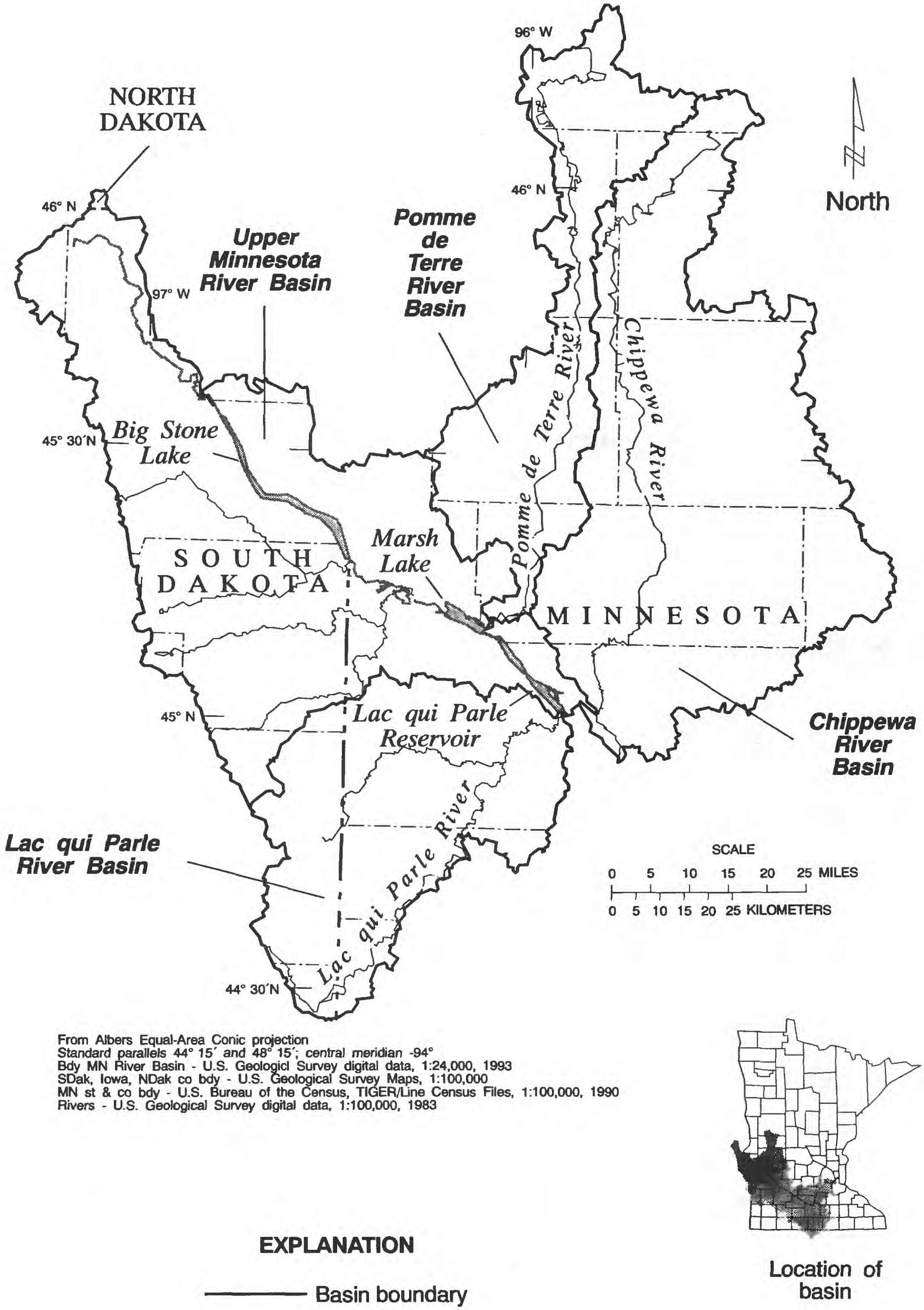
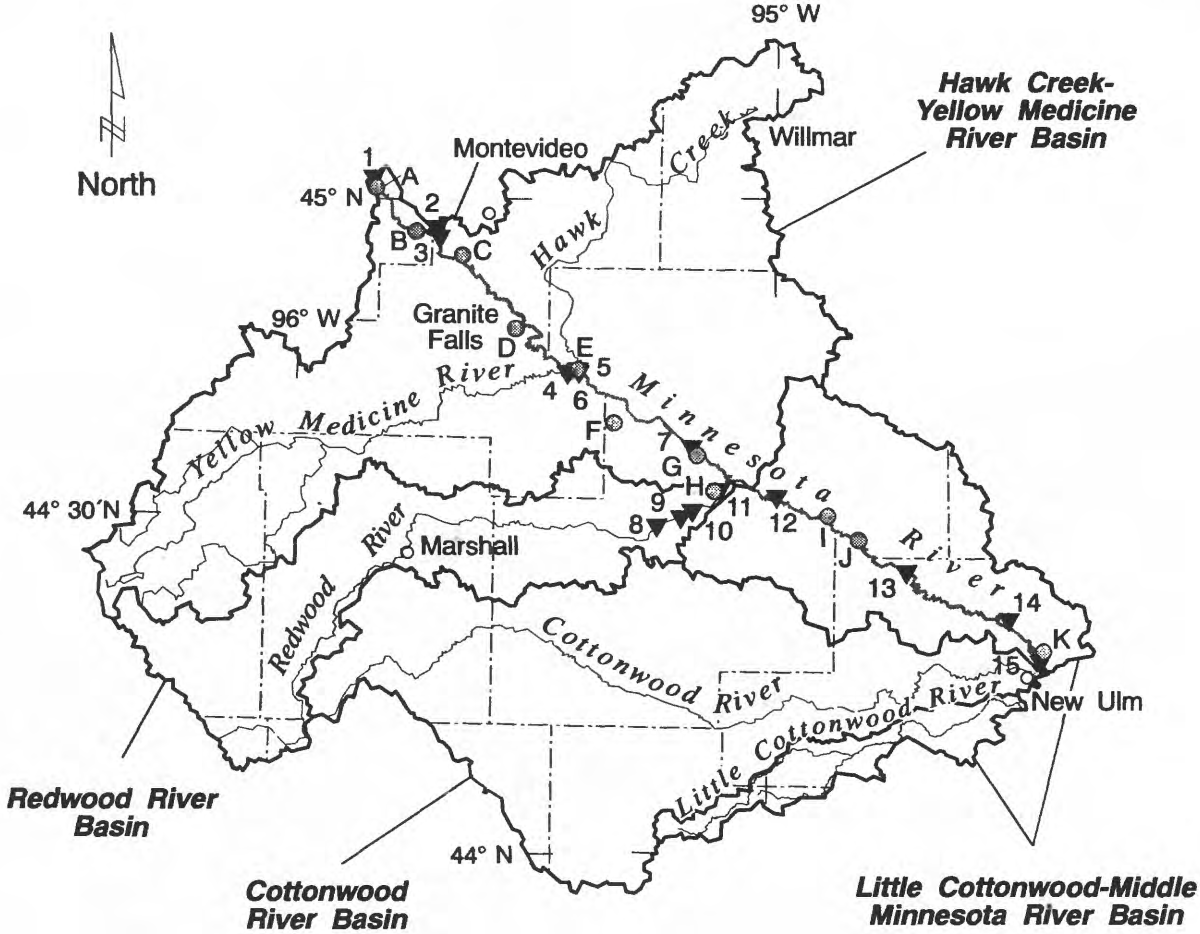


Figure 6a.--Basins and rivers in Source Region I.



From Albers Equal-Area Conic projection
Standard parallels 44° 15′ and 48° 15′; central meridian -94°
Bdy MN River Basin - U.S. Geologicl Survey digital data, 1:24,000, 1993
SDak, Iowa, NDak co bdy - U.S. Geological Survey Maps, 1:100,000
MN st & co bdy - U.S. Bureau of the Census, TIGER/Line Census Files, 1:100,000, 1990
Rivers - U.S. Geological Survey digital data, 1:100,000, 1983

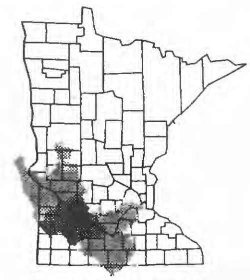
SCALE
0 5 10 15 20 25 MILES
0 5 10 15 20 25 KILOMETERS

EXPLANATION

——— Basin boundary

▼ Water-quality sampling site, number indicates site number

◉ Spring site, letter indicates site letter



Location of basin

Figure 6b.--Basins, rivers, and water-quality sampling sites in Source Region II.

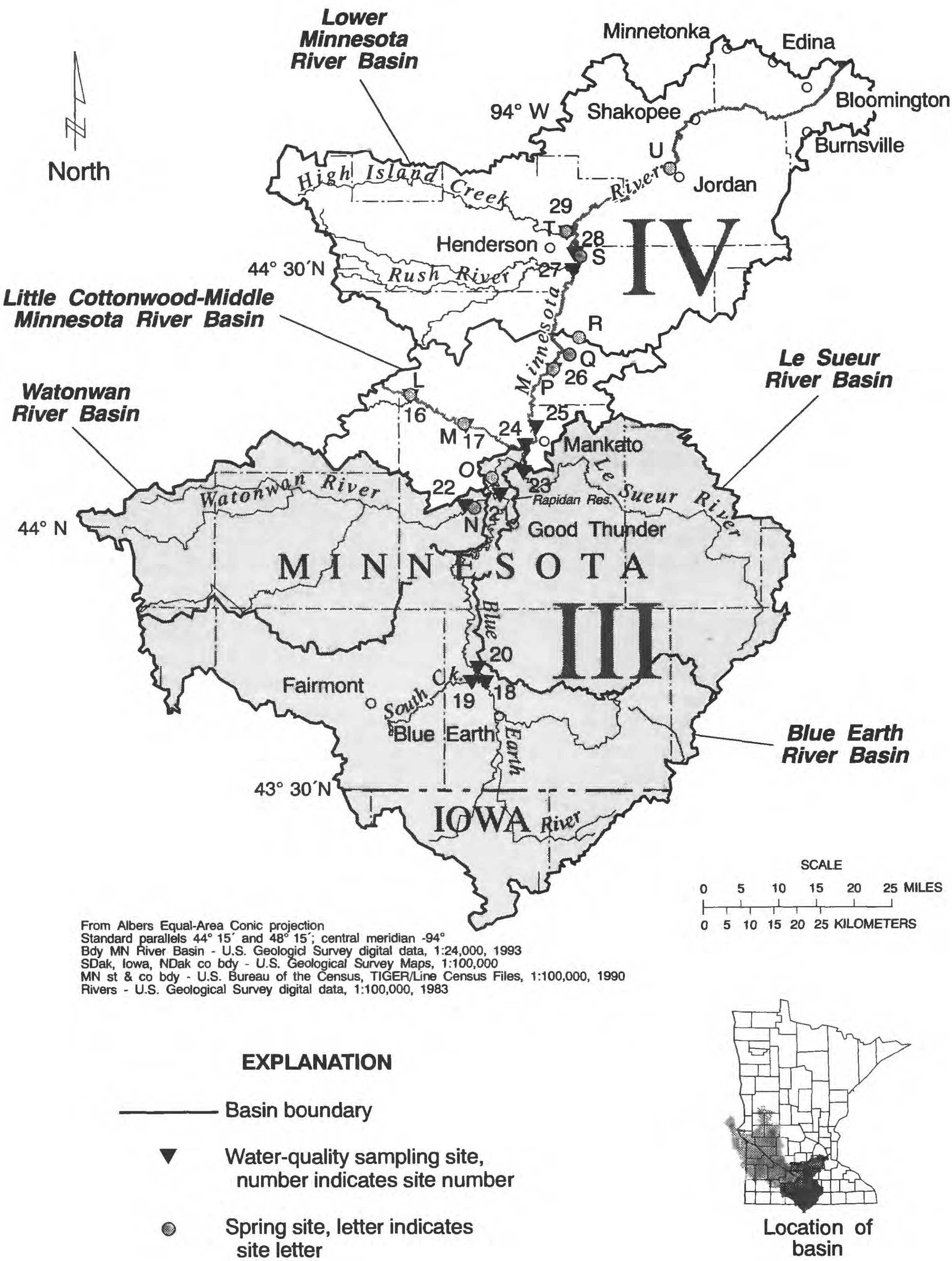


Figure 6c.--Basins, rivers, and water-quality sampling sites in Source Regions III and IV.

less area than Source Region I, but delivers more than three times as much water to the Minnesota River. There is a hydroelectric dam located about 11 miles upstream from the mouth of the Blue Earth River. The dam creates a relatively small reservoir (about 400 acres). The dam is operated for power generation and the reservoir is not used for retention of flood waters. Because the water yield of this source region was known to be high, it was hypothesized at the beginning of the study that this region would contribute a large part of the Minnesota River's non-point source load.

Source Region IV comprises the Little Cottonwood-Middle Minnesota River Basins downstream of New Ulm and the Lower Minnesota River Basin (fig. 6c). This source region contains more than 15 tributaries that drain directly to the Minnesota River. Two of these streams, Rush River and High Island Creek, were sampled during this study. This source region also is located in the part of the Minnesota River Basin that has higher rainfall and runoff (figs. 2, 3). Runoff characteristics of this source region were similar to Source Region III drained by the Blue Earth River and its tributaries.

Suspended Sediment

The suspended-sediment sampling on the mainstem and at tributary sites was undertaken to gain an understanding of the nature and extent of suspended sediment delivery and transport. It was hypothesized that suspended sediment is derived from erosional processes throughout the basin and that the tributary streams deliver a portion of the suspended sediment to the Minnesota River. It was also hypothesized that settling and resuspension of suspended sediment could occur during the transport process. An alternative hypothesis was that most of the suspended sediment is derived from bank and bed erosion.

Minnesota River mainstem

Figure 7 shows suspended-sediment load data from five synoptic samplings conducted on the Minnesota River mainstem. The water samples were collected during periods of stable discharge and covered a wide range of discharges. Stream discharge was considered stable if river stage was steady or changing slowly and no runoff had occurred within a 10-day period prior to sampling. The discharge rates during six synoptic samplings are shown in figure 8. There is about a 100-fold difference between the lowest and highest discharge rates sampled. It was difficult to execute a complete water sampling of the mainstem during stable discharge because of the large expanse of the basin. There were few extended time periods when runoff was not occurring in one or more parts of the basin.

The synoptic samplings were conducted over all or parts of the mainstem from the outlet of Lac qui Parle (site 1) to Henderson (site 28). The data in figure 7 show the increase in the amount of suspended-sediment load carried by the mainstem as it flows downstream. In general, there was about a 10-fold increase in sediment load from Lac qui Parle (site 1) to Henderson (site 28) during stable flow conditions. One notable exception is the August 1990 sampling period (fig. 7). Two rainfalls occurred in separate parts of the basin while sampling was underway. The effects of runoff from these rains are most apparent in the portion of the mainstem between sites 7 and 12 and also between sites 14 and 26. The tributary runoff resulted in about a 40-fold increase in water discharge and a 300-fold increase in sediment load between Lac qui Parle (site 1) and Henderson (site 28). The decrease in load at site 28 resulted because the peak of the runoff had not yet reached site 28 when it was sampled. Tributary runoff was the primary source of suspended-sediment load to the Minnesota River during the August 1990 sampling period.

Suspended-sediment concentration data for the synoptic samplings are shown in figure 9. The data in figure 9 show that suspended-sediment concentrations at sites in the upstream portion of the mainstem were less than 100 mg/L during the synoptic samplings. Suspended-sediment concentrations below 100 mg/L in the upstream part of the study reach likely reflect settling of sediment in the headwater reservoirs.

Source Region I was routinely monitored by collecting samples from the Minnesota River at Montevideo (site 3). The suspended-sediment data for this site are shown in figure 10. The results of frequent sampling at this site are consistent with the results from the synoptic sampling in that about 85 percent of the water samples from this source region have suspended-sediment concentrations less than 100 mg/L. About 15 percent of the samples, however, had concentrations near or exceeding 200 mg/L. Stream discharge is plotted with the suspended sediment data in figure 10. A comparison of the suspended-sediment concentrations with the stream discharge shows that most of the higher concentrations occurred during periods of increasing stream discharge during runoff. The exceptions occurred when flow rates at Montevideo (site 3) increased because of release of relatively sediment-free water from the dam at Lac qui Parle (site 1). The effects of such a release are shown in the June 30, 1992 synoptic sampling (figs. 8, 9). At the time of the June 30, 1992 sampling, a relatively large discharge (4,670 ft^3/s), carrying little sediment (46 mg/L), was being released.

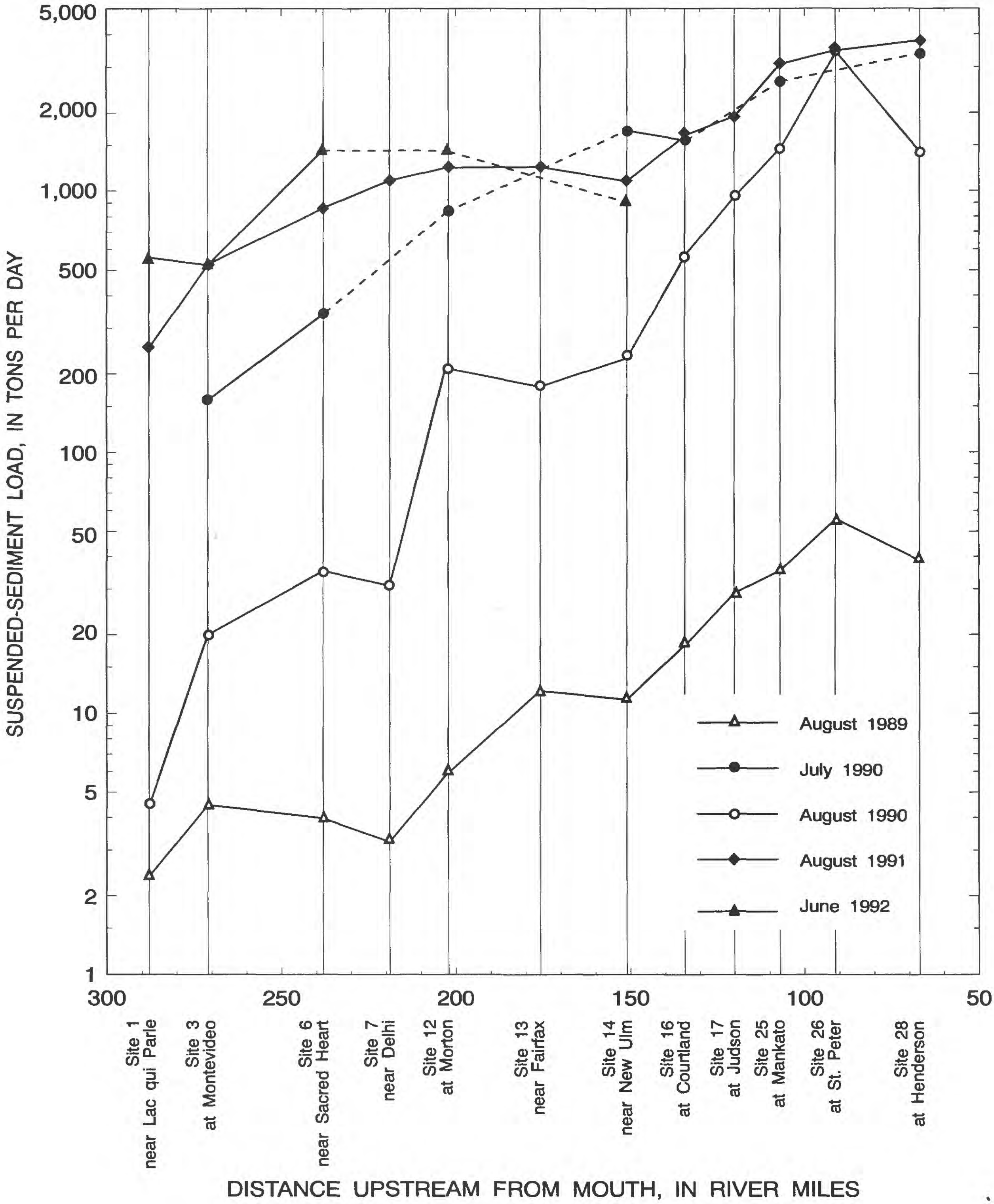


Figure 7.--Suspended-sediment load at time of sampling, by river mile, for Minnesota River water-quality sampling sites, August 1989-June 1992.

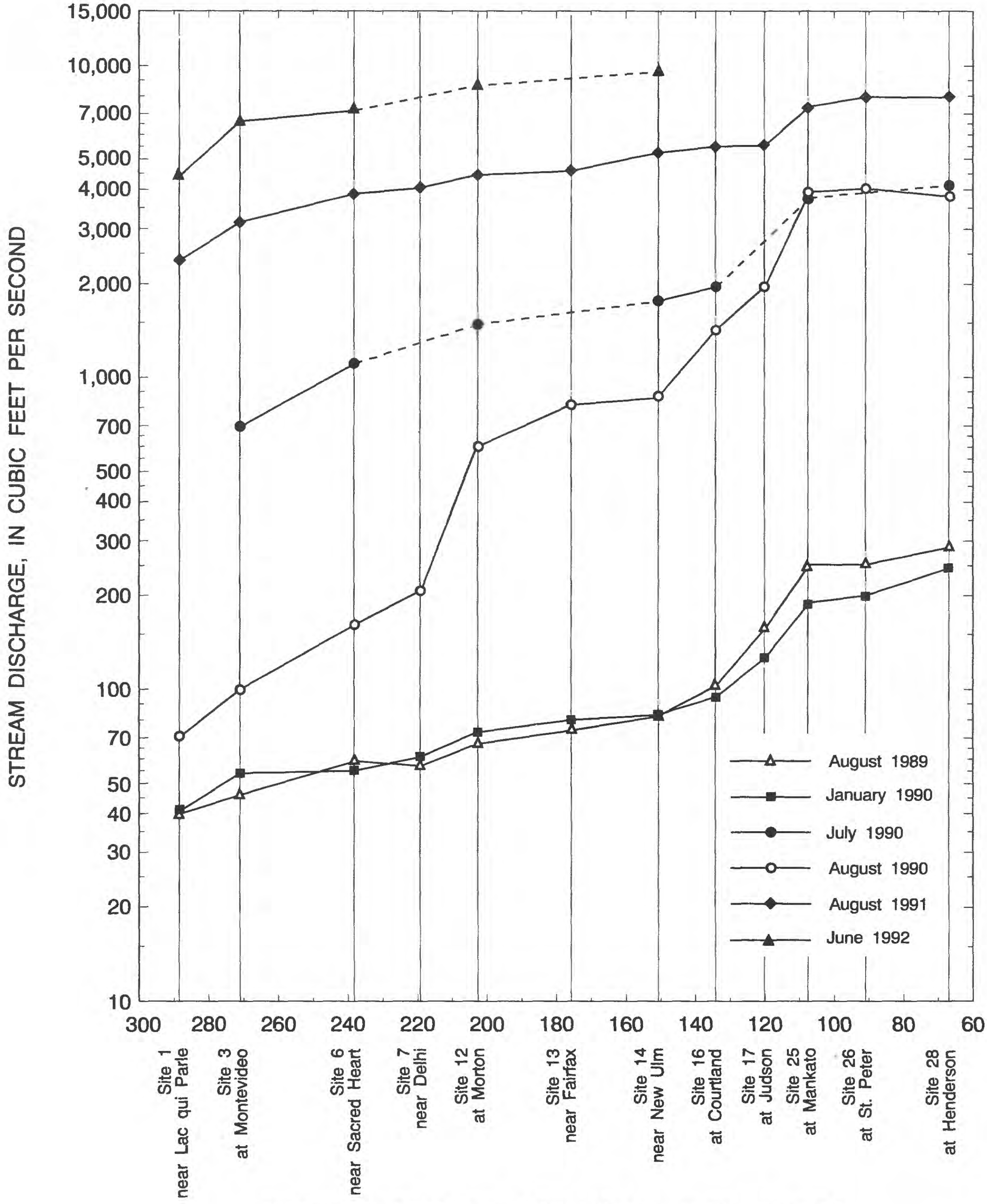


Figure 8.--Stream discharge at time of measurement, by river mile, for Minnesota River water-quality sampling sites, August 1989-June 1992.

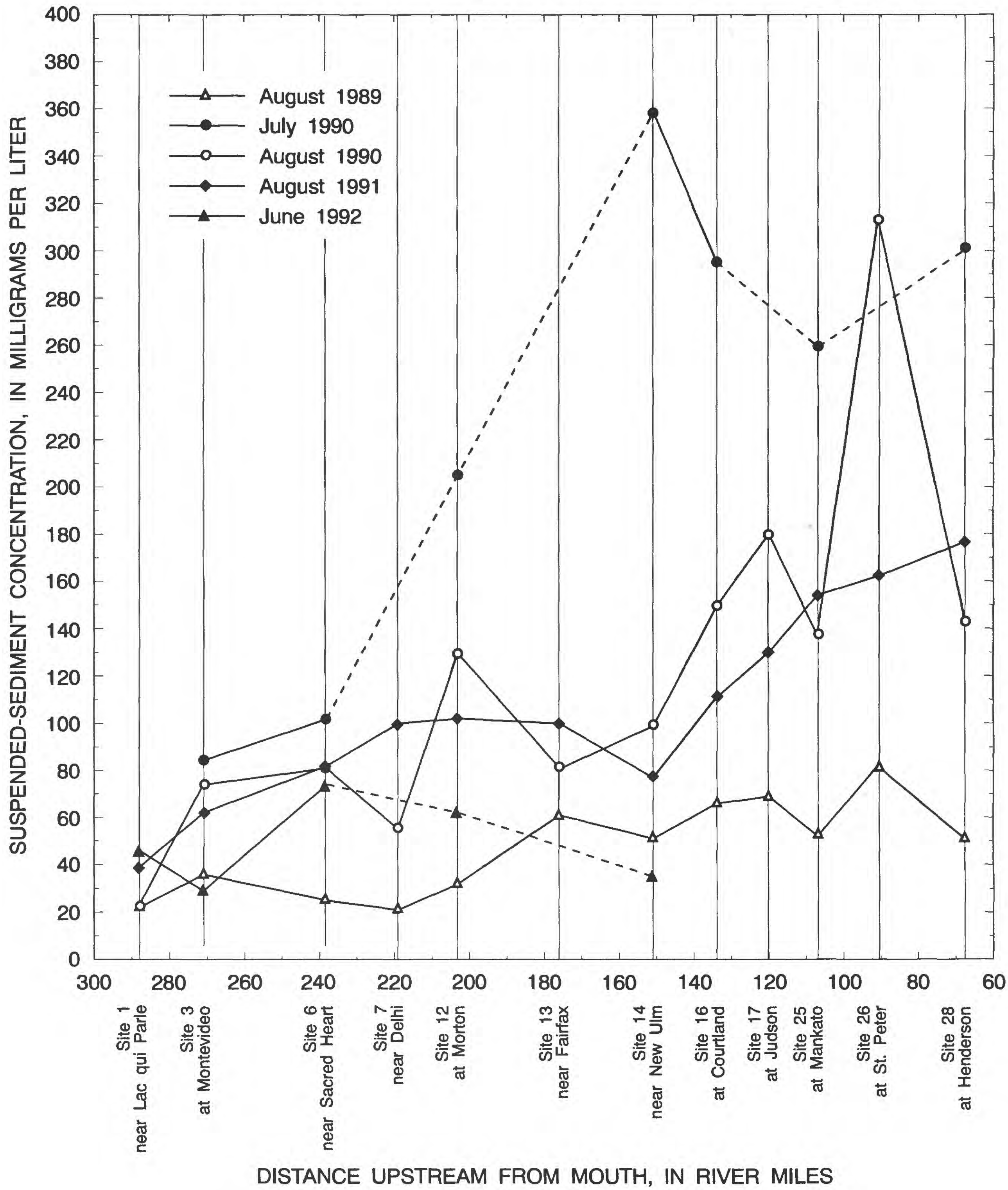


Figure 9.--Suspended-sediment concentrations at time of sampling, by river mile, for Minnesota River water-quality sampling sites, August 1989-June 1992.

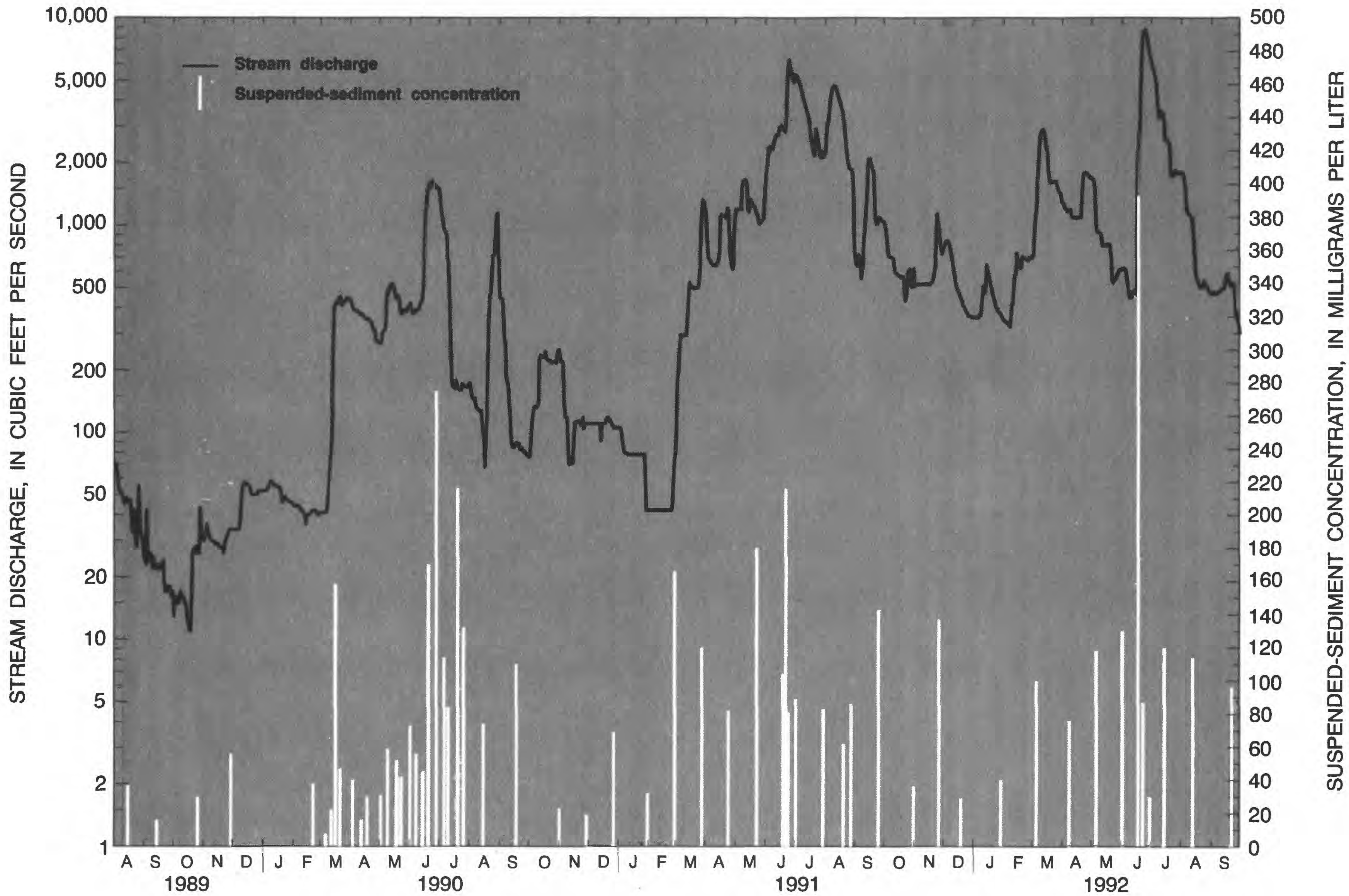


Figure 10.--Daily-mean stream discharge and suspended-sediment concentration for the Minnesota River at Montevideo (site 3), August 1989-September 1992.

As the Minnesota River flows out of Source Region I, suspended-sediment concentrations in the mainstem increase. When runoff is not a substantial part of stream discharge sediment concentrations can increase moderately or can decrease because of sediment deposition or dilution by tributary discharges or sediment-free ground water. These conditions are illustrated by the data from the August 1989, and August 1991 synoptic samplings shown in figure 9. When the tributaries carry runoff to the mainstem, suspended-sediment concentrations increased as shown by data for sites 12, 17, and 26 during the August 1990 sampling. These concentrations were measured in the parts of the reach affected by runoff-producing rainfall. Downstream from the headwater reservoirs, the frequency of elevated suspended-sediment concentrations is controlled by tributary inflow. This is shown by the data collected in the mainstem at Mankato (site 25), located 164 river miles downstream from the Montevideo (site 3) sampling site (fig. 11). Suspended-sediment samples have been collected daily at the Mankato site (site 25) since 1968. The stream discharge data and daily suspended-sediment concentration for the period corresponding to the MRAP study are shown in figure 11. In contrast to the mainstem at Montevideo (site 3), suspended sediment-concentrations at Mankato (site 25) frequently exceeded 200 mg/L and at times exceeded 1000 mg/L.

Tributaries

Ten major tributaries were sampled near their confluence with the Minnesota River mainstem. Efforts were made to sample each tributary near its peak sediment concentration during runoff of various magnitudes. In addition, multiple water samples were collected during runoff at four tributary sites to determine and characterize the change in concentration and load during the rise and fall in river stage that accompanied each runoff.

Because of the strong west to east rainfall and runoff gradient, there were fewer opportunities to sample runoff in tributaries in the western part of the basin. As a result, only two runoff periods were sampled in the Chippewa, Hawk Creek, and Yellow Medicine Rivers, whereas, six or more runoff periods were sampled in the Watonwan, Le Sueur, and Blue Earth Rivers. Figure 12 shows the range of suspended-sediment concentrations at each tributary site. The data plotted in figure 12 represent samples from runoff as well as samples collected at low flow concurrent with three of the synoptic samplings on the mainstem.

Suspended-sediment concentrations increase rapidly as river stage rises in response to runoff. A typical rise in concentration with increasing stream discharge is shown in figure 13. Peak suspended-sediment concentrations are present before the stream discharge peak. As stream discharge peaks and diminishes, suspended-sediment concentrations decline. Two factors may explain this phenomenon.

The first factor is the available sediment becomes depleted before the water discharge peak. Part of the sediment that is available is supplied from the impact of raindrops that dislodge soil particles. This process stops when the rainfall stops. Another source of material is the sediment that has accumulated within channels and other drainage courses. This is sediment that was deposited in the channels during the recessions of previous runoff periods. In addition, wind-eroded topsoil accumulates in sheltered areas such as channels, and in road and drainage ditches. For each runoff, the amount of accumulated channel sediment is finite, and once the sediment is removed, the contribution to runoff declines.

The second factor affecting the concentration decline during the recession is related to the source of the stream discharge. During the recession of stream discharge, a greater proportion of the flow is supplied by shallow, subsurface drainage carried by drain tiles and ditches. Water that has reached the stream through a subsurface pathway will be virtually free of suspended sediment. The outcome of these processes is that the tributaries deliver the most highly-concentrated sediment during rising stages. During this study maximum concentrations of suspended sediment occurred within a few hours to a few days depending on the duration of the runoff.

Intensive sampling during runoff on the Blue Earth River and its tributaries provided information about suspended-sediment delivery from the tributaries. Four sampling sites in the Watonwan, Le Sueur, and Blue Earth Basins were used (sites 21-24 in fig. 6c). The objective of the detailed sampling was to measure the contribution of each tributary and determine how much of the sediment was transported to the mouth of the Blue Earth River at its confluence with the Minnesota River. The suspended-sediment load data are shown in table 5. The first event, March 16-April 9, 1991, was a snowmelt runoff. During this runoff, 16 percent more sediment was delivered to the mouth of the Blue Earth River at Mankato (site 24) than was supplied by the Watonwan (site 22) and Le Sueur Rivers (site 23) and the Blue Earth River near Good Thunder (site 21). Analysis of the daily sediment data showed that most of the additional sediment was supplied during the first 10 days of the runoff when river stages were rising. A possible source of the additional sediment is material that had accumulated in the Blue Earth River channel. Another source is the upstream end of the Rapidan Reservoir below the mouths of the Watonwan and Blue Earth River. During field reconnaissance,

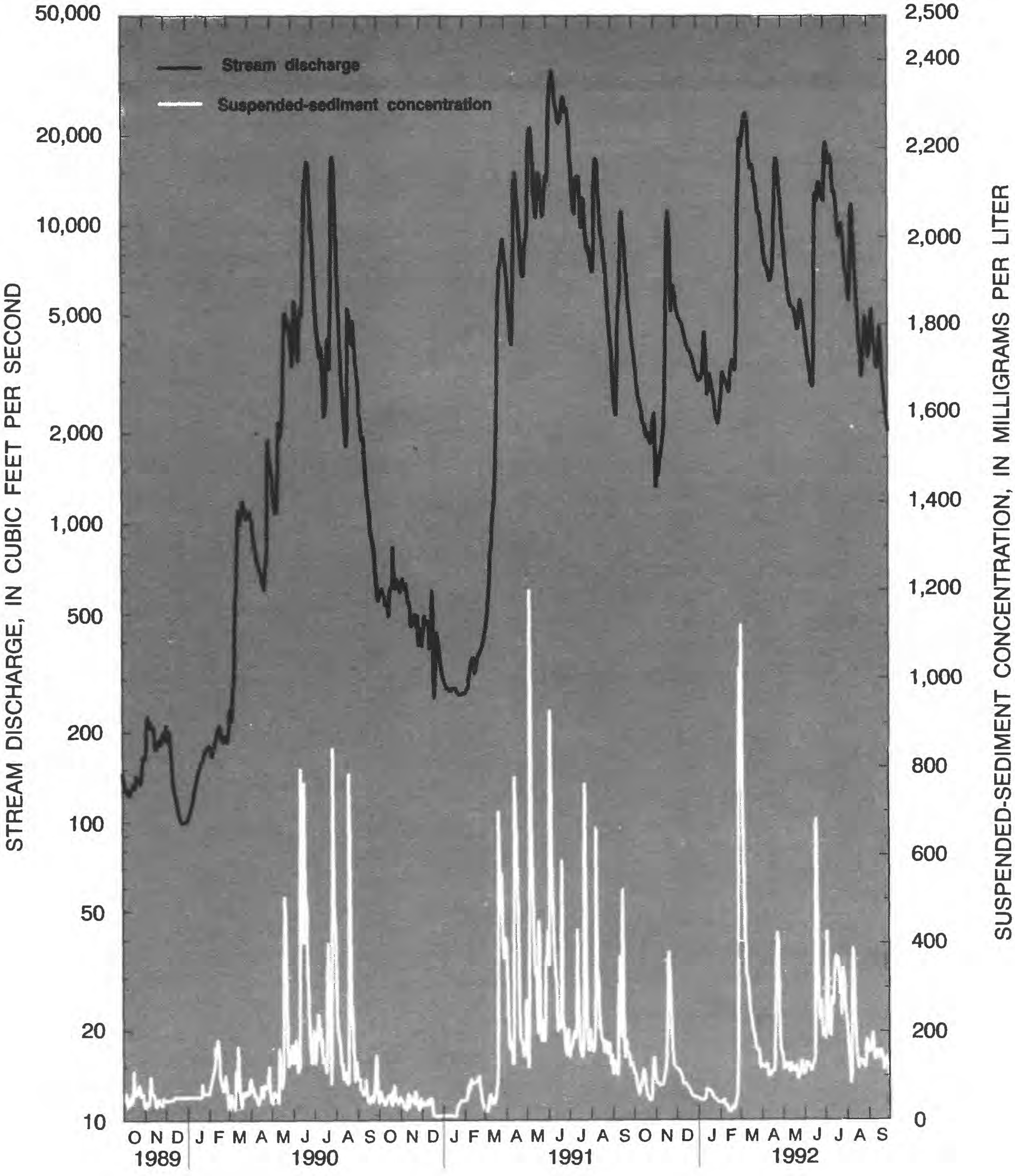


Figure 11.--Daily-mean stream discharge and suspended-sediment concentration for the Minnesota River at Mankato (site 25), October 1989-September 1992.

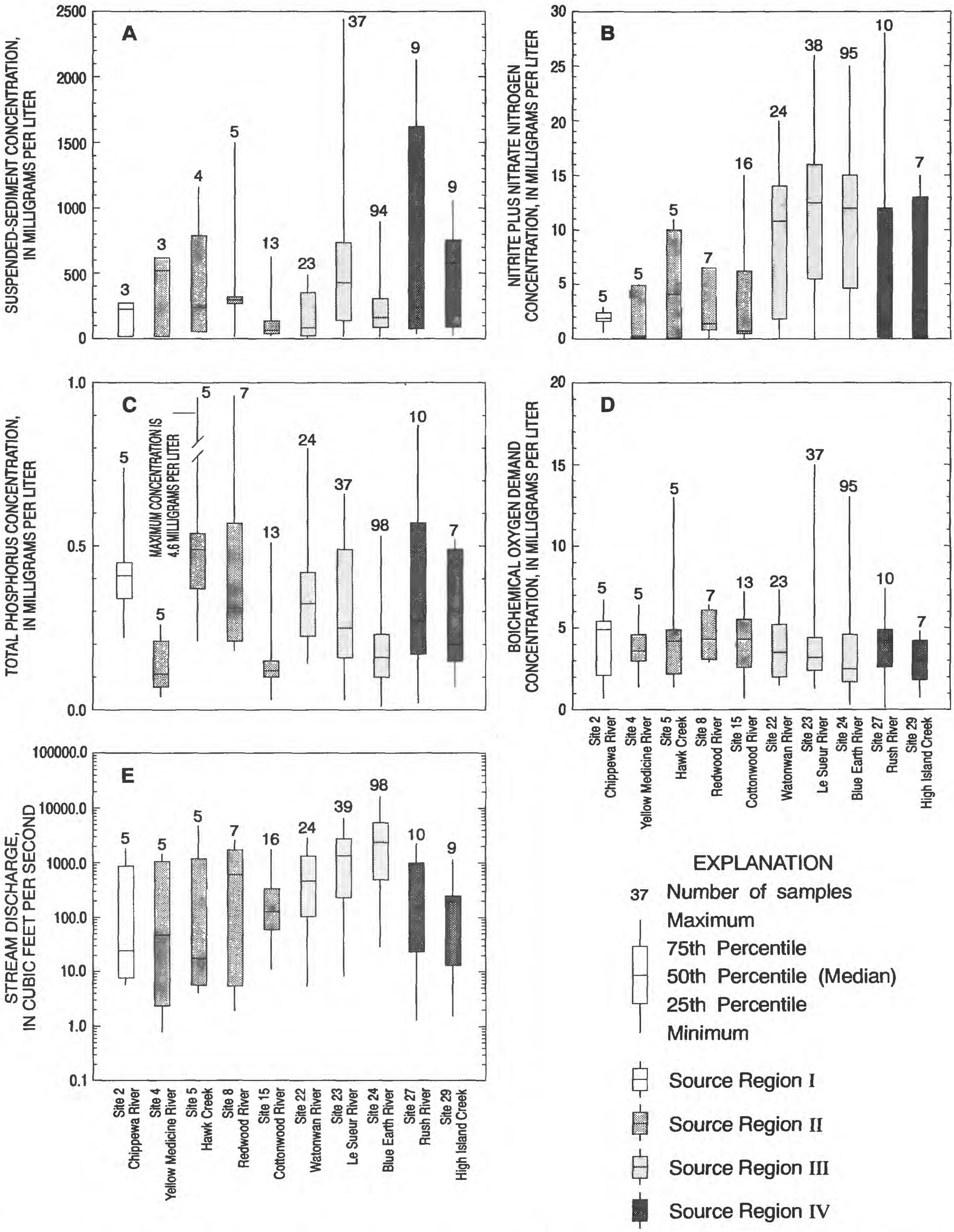


Figure 12.--Concentrations of (A) suspended-sediment, (B) dissolved nitrite plus nitrate nitrogen, (C) total phosphorus, (D) biochemical oxygen demand, and (E) stream discharge for water-quality sampling sites at ten major Minnesota River tributaries.

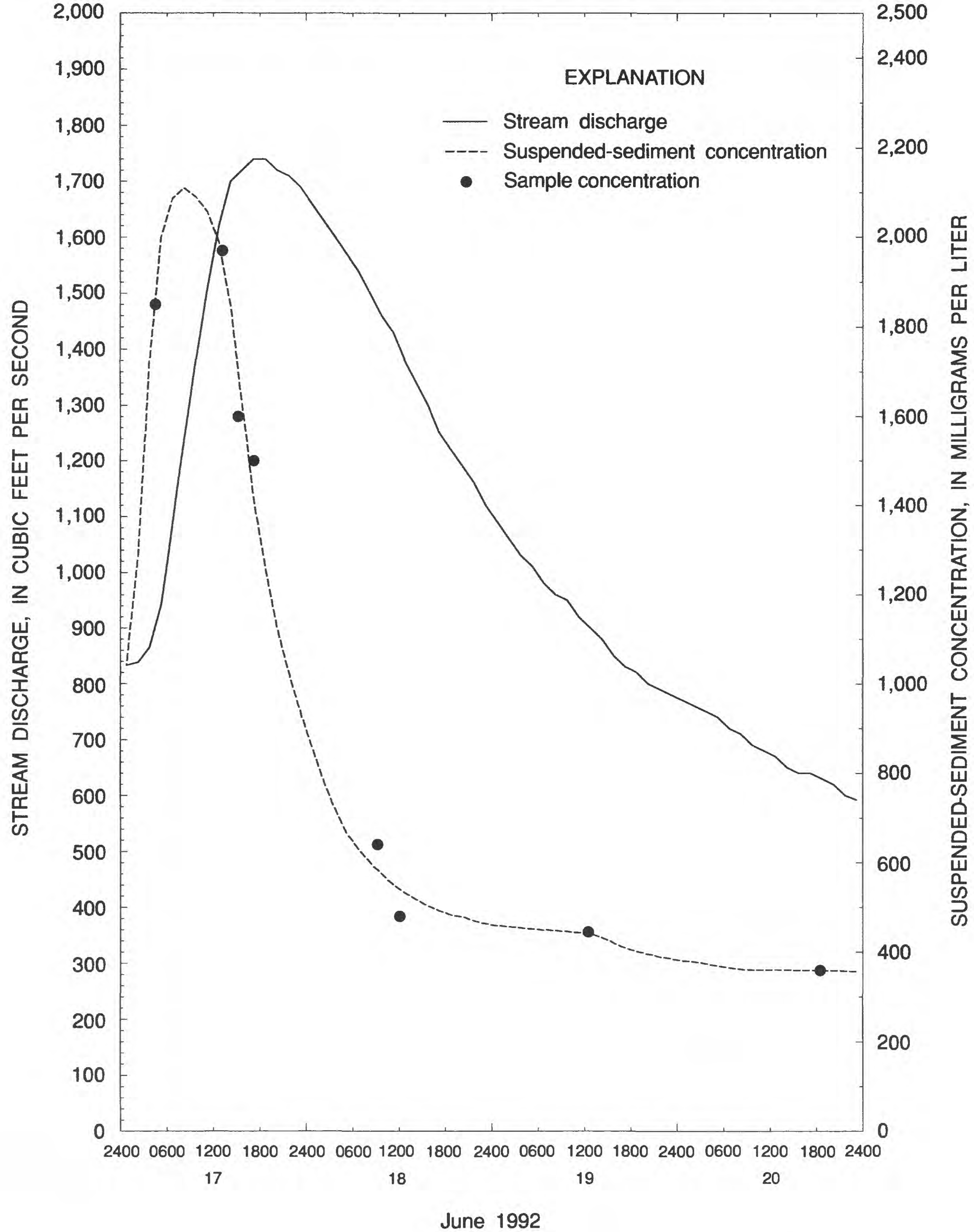


Figure 13.--Stream discharge and suspended-sediment concentration for Redwood River near Redwood Falls (site 10), June 17-20, 1992.

accumulations of fine sediment were observed at these locations when the reservoir was in drawdown during late summer 1989. Sediment from the reservoir may have been scoured and resuspended as water re-entered the reservoir. During the last nine days of the runoff, the Watonwan (site 22) and Le Sueur Rivers (site 23) and the Blue Earth River near Good Thunder (site 21) were delivering more sediment than the Blue Earth River was delivering at its mouth. This occurred as river stages were in recession and suggests that sediment was being deposited in the river channel or reservoir during the runoff.

The second event, May 5-13, 1991, was caused by runoff from rainfall. During this runoff, the amount of sediment transported into the Blue Earth River by the Watonwan (site 22) and Le Sueur Rivers (site 23) and the Blue Earth River near Good Thunder (site 21) was almost evenly balanced by the amount delivered by the Blue Earth River at its mouth. Daily suspended-sediment totals for each site show that during the last four days of the runoff, more sediment was coming into the Blue Earth River than was being transported at its mouth, suggesting a net deposition of sediment within either the Rapidan Reservoir or the Blue Earth River channel downstream of the reservoir or in both. The deposition represents six percent of the total sediment in transport. This value is within the error associated with measurement of sediment discharge.

The third event, July 22-26, 1991, was caused by rainfall. The Watonwan River (site 22) Basin received less rainfall during this period and did not produce significant runoff. The Le Sueur River (site 23) and the Blue Earth River near Good Thunder (site 21) did respond, and collectively delivered about 50,000 tons of sediment. This amount of sediment was about the same as the amount measured at the mouth of the Blue Earth River.

The results obtained by sampling these three runoff periods indicate that about all the sediment delivered to the Minnesota River by the Blue Earth River originates in the Watonwan (site 22) and Le Sueur Rivers (site 23) and the Blue Earth River near Good Thunder (site 21). The 16 percent sediment gain that was calculated for the snowmelt period probably can be attributed to scouring of previously-deposited sediment or to bank and bed erosion in the portion of the Blue Earth River upstream of Good Thunder. These results, based on three runoff periods, represent runoff derived from both snowmelt and rainfall and were calculated from peak stream discharges at the mouth of the Blue Earth River that ranged from 5,270 ft^3/s during snowmelt to 15,200 ft^3/s during the May runoff from rainfall.

An important aspect of the results from the runoff sampling is that the relative contribution of the three major streams varied significantly between runoff periods. During snowmelt, the largest sediment load was measured at Blue Earth River near Good Thunder, whereas, during the May runoff, the largest sediment load was measured at the Le Sueur River (tab. 5). This variability is indicated by the differences in sediment yield (tons of sediment per square mile of drainage area) (tab. 5).

Suspended-sediment loads

The periodic sampling in the tributary streams provided information to characterize sediment delivery to the mainstem. The highly variable temporal and spatial loading patterns, however, make estimation of annual loads difficult unless all runoff periods are sampled. Daily suspended-sediment samples were collected from 1989 to 1992 at the mouth of the Blue Earth River at Mankato (site 24) to provide an assessment of sediment transport. The Blue Earth River at Mankato (site 24) was chosen for this sampling because long-term stream discharge monitoring (1903-93) had shown that it provided a significant amount of flow to the Minnesota River. This site is about one mile upstream from a long-term (1968-93) daily suspended-sediment sampling site operated by the USGS on the Minnesota River mainstem at Mankato (site 25). The establishment of a daily sampling site at the mouth of the Blue Earth River at Mankato (site 24) provided for direct comparison of Blue Earth River sediment loads with those calculated for the Minnesota River at Mankato (site 25).

Daily-mean suspended-sediment concentrations and daily sediment loads for both sites are shown in figures 11, 14, 15, and 16. The daily-mean stream discharge for both sites is shown in figure 17. As shown in figure 17, peaks and recessions of daily-mean stream discharge in the Minnesota River at Mankato (site 25) closely follow the peaks and recessions of stream discharge in the Blue Earth River at Mankato (site 24). This is a reflection of the large amount of the total flow in the Minnesota River at Mankato (site 25) that is supplied by the Blue Earth River. During the study, the Blue Earth River contributed about 46 percent of the total flow of the Minnesota River at Mankato (site 25). This percentage was nearly constant, at 45 percent during 1990, 44 percent during 1991, and about 48 percent during 1992. Annual flow in both rivers during 1992 was three times higher than it was in 1990, indicating that the relative amount of flow contributed by the Blue Earth River to the Minnesota River can remain constant over widely varying hydrologic conditions.

Table 5.--Suspended-sediment loads and yields for water-quality sampling sites in the Watonwan (site 22), Le Sueur (site 23), and Blue Earth River (sites 21 and 24) Basins for three runoff periods

[Suspended-sediment load, in tons]

Date (mm/dd/yy)	Blue Earth River near Good Thunder (site 21)	Watonwan River near Garden City (site 22)	Le Sueur River near Rapidan (site 23)	Blue Earth River at Mankato (site 24)
Snowmelt-runoff period March 16-April 9, 1991				
03/16/91	28	5	18	101
03/17/91	33	5	23	126
03/18/91	68	5	37	149
03/19/91	146	6	89	353
03/20/91	475	19	233	275
03/21/91	2140	90	529	2210
03/22/91	3290	269	1070	6120
03/23/91	3360	759	2450	7850
03/24/91	3900	1040	3340	13000
03/25/91	4940	1280	3290	11400
03/26/91	4830	1420	2710	10500
03/27/91	4050	1340	2640	7600
03/28/91	3300	1160	2590	7100
03/29/91	2890	1090	2560	7120
03/30/91	2500	916	2340	7330
03/31/91	2180	788	1900	6910
04/01/91	1880	748	1610	6520
04/02/91	1650	696	1270	3720
04/03/91	1380	550	1000	2460
04/04/91	1070	379	789	2050
04/05/91	944	265	631	1760
04/06/91	1020	193	506	1770
04/07/91	1150	135	420	1680
04/08/91	1160	100	358	1620
04/09/91	960	77	304	1180
Total load[a]	49344	13335	32689	110904
Percent[b]	44.5	12.0	29.5	100
Sediment yield[c]	32	16	29	31
Rainfall-runoff period May 5-13, 1991				
05/05/91	3870	1960	11300	16700
05/06/91	11400	2560	25000	31700
05/07/91	10500	1380	19800	32400
05/08/91	9020	817	18600	31800
05/09/91	11900	640	16100	30600
05/10/91	12100	536	10700	22000
05/11/91	10300	435	7330	15900
05/12/91	8000	346	5380	11700
05/13/91	6250	274	4300	6620
Total load[a]	83340	8948	118510	199420
Percent[b]	41.8	4.5	59.4	100
Sediment yield[c]	54	10	107	56

Table 5.--Suspended-sediment loads and yields for water-quality sampling sites in the Watonwan (site 21), Le Sueur (site 22), and Blue Earth River (sites 21 and 24) Basins for three runoff periods--Continued

Date (mm/dd/yy)	Blue Earth River near Good Thunder (site 21)	Watonwan River near Garden City (site 22)	Le Sueur River near Rapidan (site 23)	Blue Earth River at Mankato (site 24)
Rainfall-runoff period July 22-26, 1991				
07/22/91	4380	not sampled	7400	13300
07/23/91	8180	not sampled	10100	18000
07/24/91	4330	not sampled	6760	11300
07/25/91	2310	not sampled	3550	4790
07/26/91	1310	not sampled	2240	2580
Total [a]	20500		30000	50000
Percent [b]	40		60	100
Sediment yield[c]	13		27	14

[a] Load contributions from tributaries do not equal total load at the mouth of the Blue Earth River because of losses caused by deposition or gains from other sediment sources such as bank and bed erosion and channel scour.

[b] Percent of total load at mouth of Blue Earth River.

[c] Yield in tons per square mile for runoff period.

The data collected during the study show that about 55 percent of the suspended-sediment load in the Minnesota River at Mankato was contributed by the Blue Earth River, which drains only 24 percent of the total basin. The suspended sediment contributed to the Minnesota River at Mankato (site 25) by the Blue Earth River was relatively constant during each year of the study (57 percent during 1990, 55 percent during 1991, and 55 percent during 1992). Mean-monthly suspended-sediment concentrations and monthly load data for both rivers are shown in figures 18 and 19. Mean-monthly suspended-sediment concentrations in the Blue Earth River exceeded those in the Minnesota River during most months, especially during months when mean concentrations were above 100 mg/L.

The daily suspended-sediment records provide a means to calculate and compare suspended-sediment yields for each of the rivers on a yearly basis, by subtracting the annual suspended-sediment load of the Blue Earth River at Mankato (site 24) from the annual suspended-sediment load for the Minnesota River at Mankato (site 25), the suspended-sediment load of the Minnesota River upstream of its confluence with the Blue Earth River can be computed. The basin upstream of the confluence yielded 19.9, 78.5, and 62.1 tons per square mile (tons/mi^2) during 1990, 1991, and 1992, respectively. The yields from the Blue Earth River Basin were significantly higher at 84.2, 313, and 241 tons/mi^2. The total yields for the Minnesota River at Mankato (site 25) were 35.2, 134, and 105 tons/mi^2 during 1990, 1991,and 1992, respectively. The long-term suspended-sediment yields for the Minnesota River at Mankato (site 25) ranged from a low of 11.6 tons/mi^2 (1988) to a high of 242 tons/mi^2 (1969) and averaged 73.8 tons/mi^2 during the past 25 years (fig. 20).

The total drainage area at Mankato, however, includes about 6,100 mi^2 in Source Region I upstream from Montevideo. As previously discussed, this source region delivers little sediment relative to source regions downstream of Montevideo. Comparisons between yields of the Blue Earth River Basin and the Minnesota River Basin upstream of the Blue Earth River are, therefore, more meaningful if the drainage area upstream of Montevideo is subtracted before calculating suspended-sediment yields. After this subtraction, the Blue Earth River's drainage area becomes 40 percent of the total drainage area of the Minnesota River at Mankato. The yields for the part of the Minnesota River Basin upstream of the Blue Earth River using this adjustment are 43.4, 171, and 135 tons/mi^2 during 1990, 1991, and 1992, respectively. After this adjustment, the yields for the Minnesota River above the confluence with the Blue Earth River are still less than the yields for the Blue Earth River Basin. These data illustrate the effect the Blue Earth River has on the suspended-sediment load of the Minnesota River at Mankato.

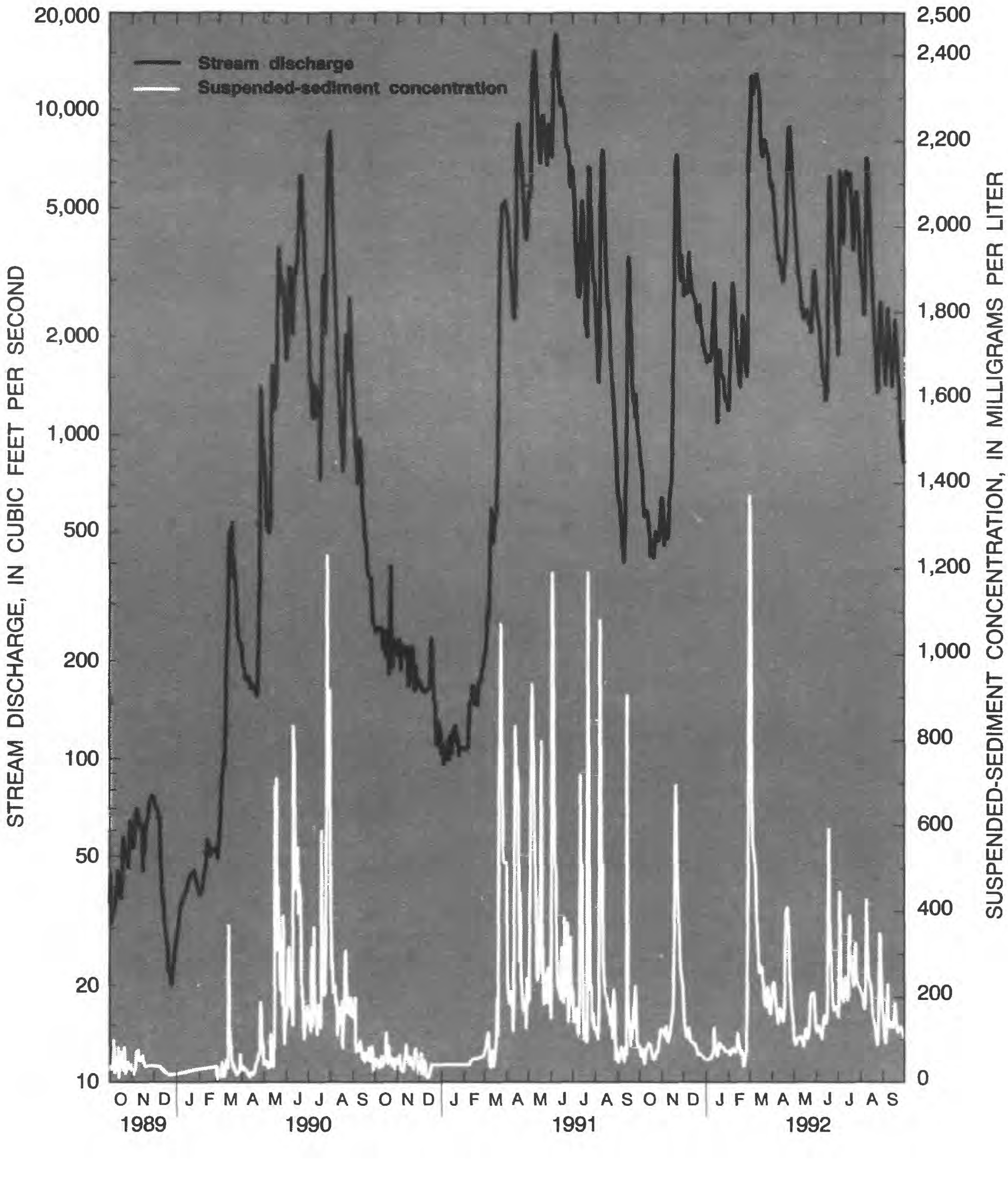


Figure 14.--Daily-mean stream discharge and suspended-sediment concentration for the Blue Earth River at Mankato (site 24), October 1989-September 1992.

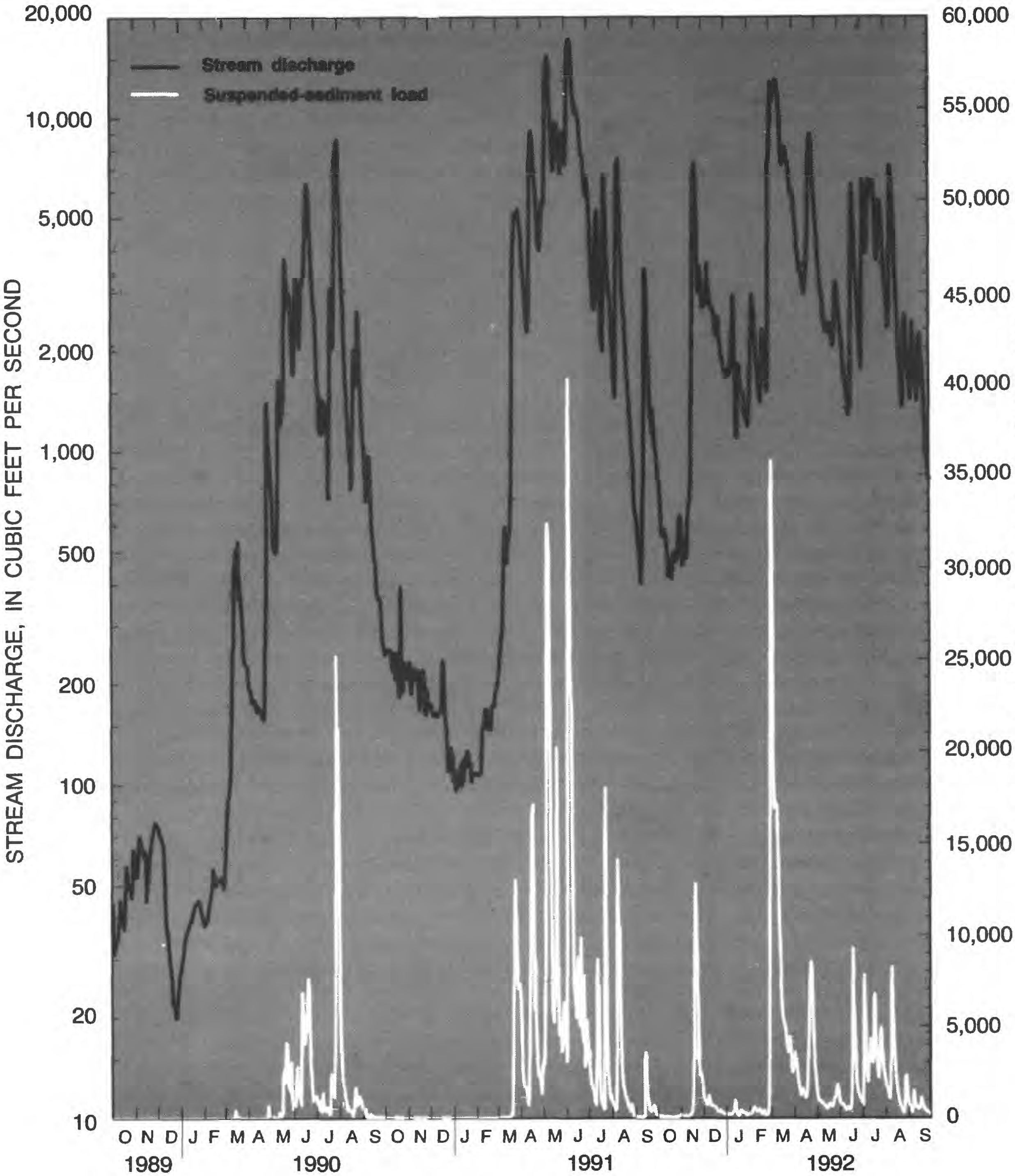


Figure 15.--Daily-mean stream discharge and suspended-sediment load for the Blue Earth River at Mankato (site 24), October 1989-September 1992.

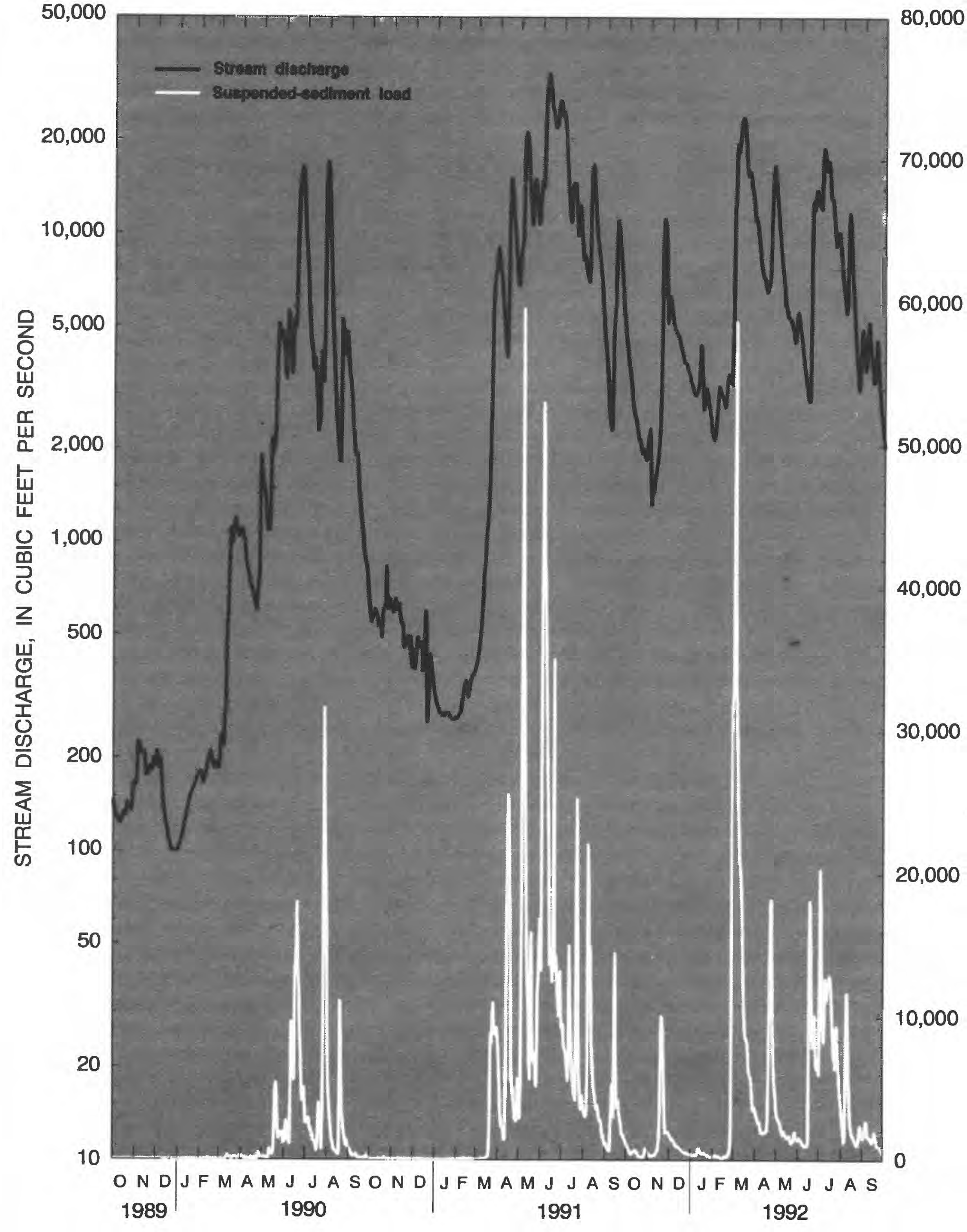


Figure 16.--Daily-mean stream discharge and suspended-sediment load for the Minnesota River at Mankato (site 25), October 1989-September 1992.

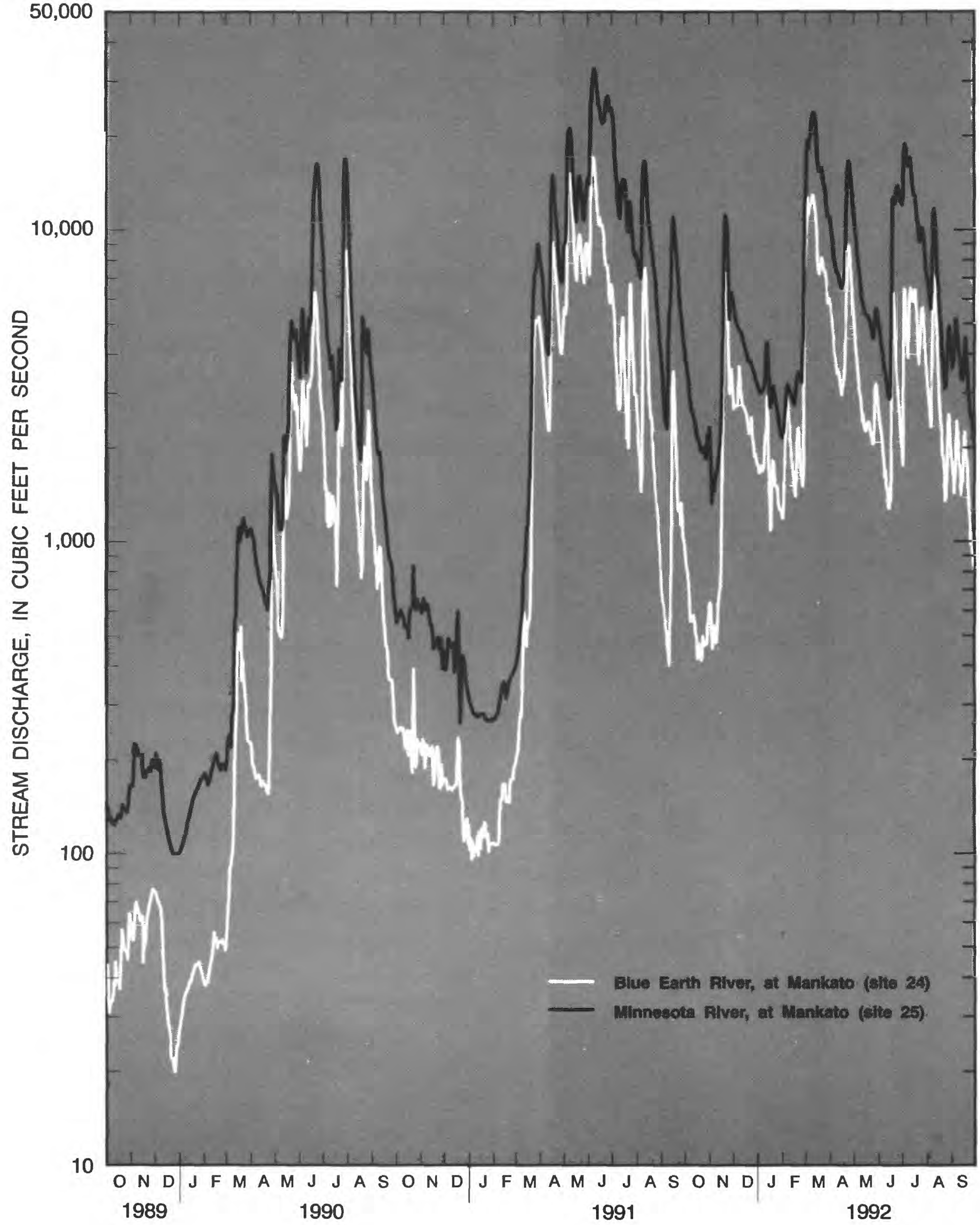


Figure 17.--Daily-mean stream discharge for the Blue Earth River at Mankato (site 24) and the Minnesota River at Mankato (site 25), October 1989-September 1992.

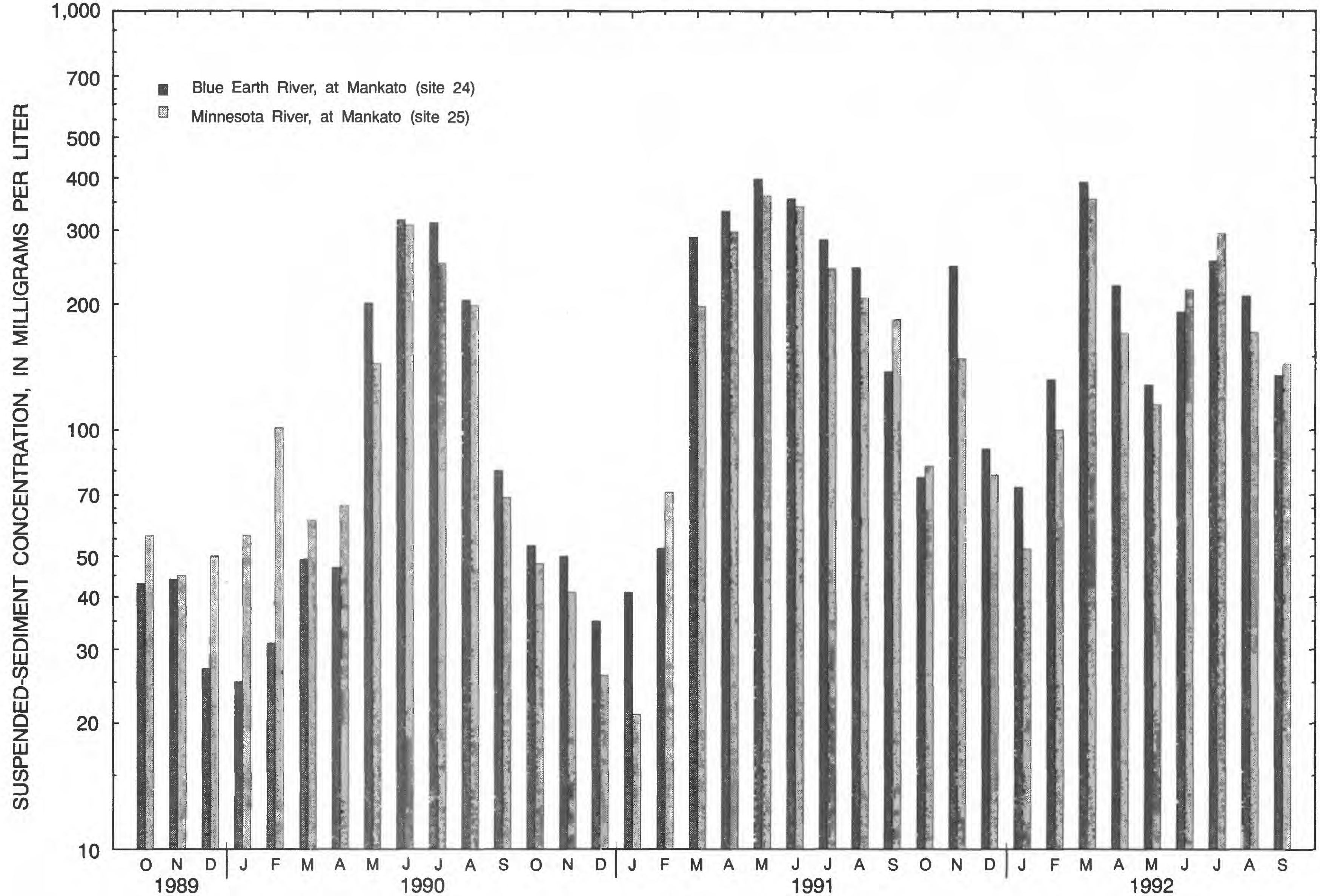


Figure 18.--Monthly-mean suspended-sediment concentration for the Blue Earth River at Mankato (site 24) and the Minnesota River at Mankato (site 25), October 1989-September 1992.

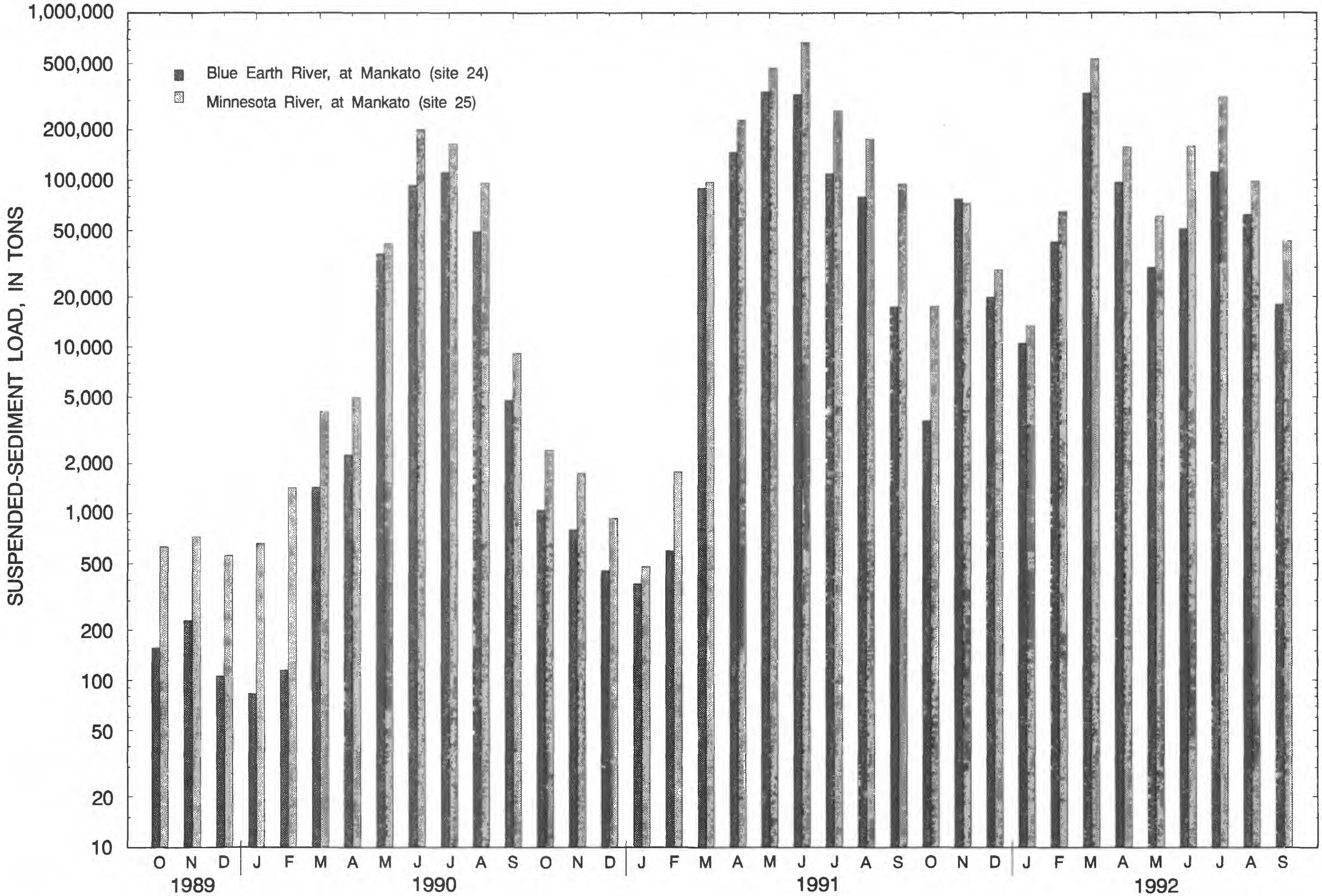


Figure 19.--Monthly suspended-sediment load for the Blue Earth River at Mankato (site 24) and the Minnesota River at Mankato (site 25), October 1989-September 1992.

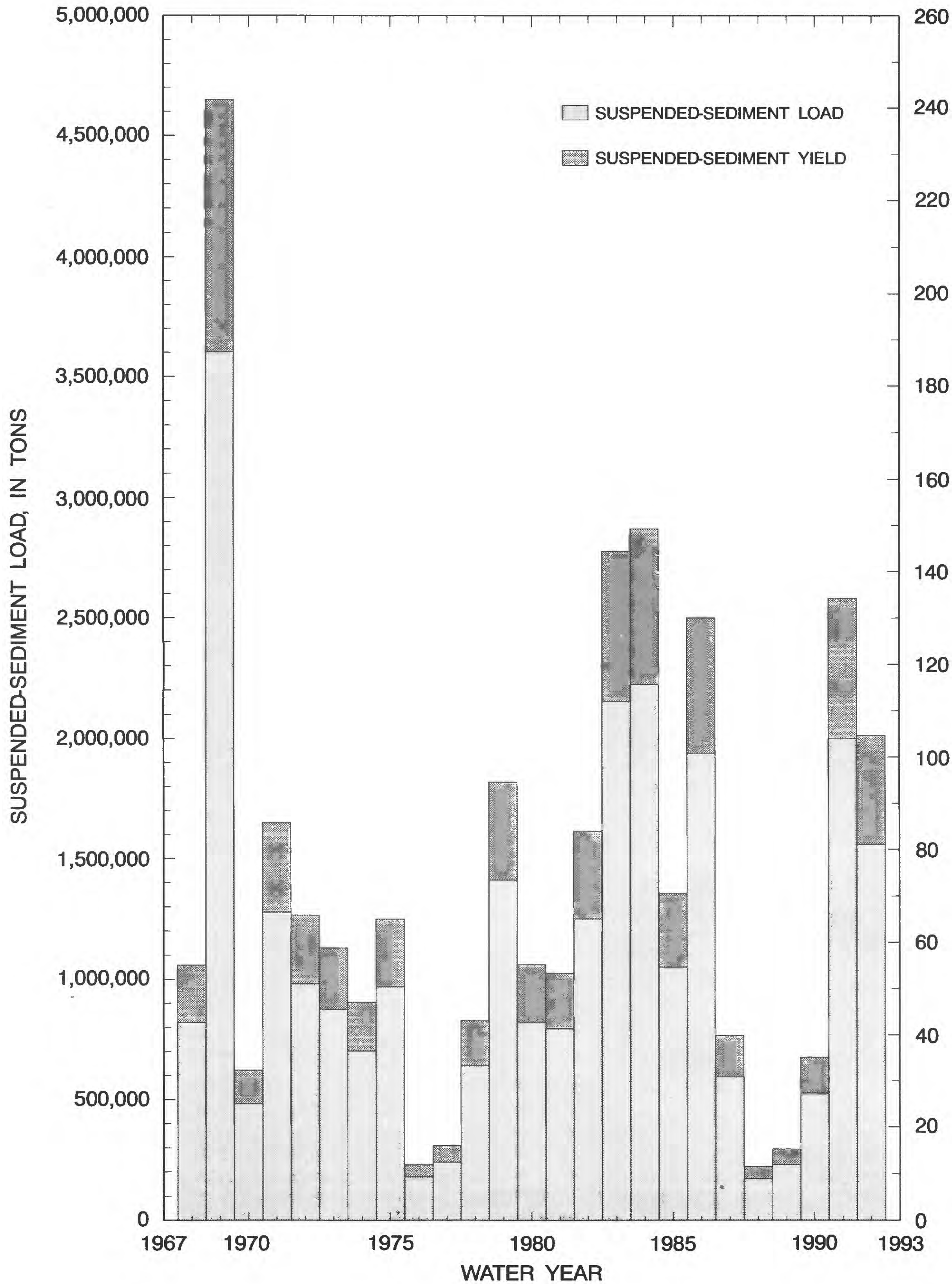


Figure 20.--Annual suspended-sediment load and yield for the Minnesota River at Mankato (site 25), 1968-92.

Source areas in the Minnesota River Basin upstream of the confluence of the Blue Earth River also made a significant contribution (45 percent) to the total suspended-sediment load at Mankato. Daily sediment records showed that, for brief periods at least, the sediment loading from these areas exceeded the loading from the Blue Earth River. Tornes (1986) estimated yields from two of the major basins, Redwood River and Cottonwood River. The yield estimates were based on relatively short-term daily-sediment records (2-10 years) that were extended to 14-year periods by use of daily flow records and suspended-sediment transport curves. Calculations using these methods estimated average annual suspended-sediment yields of 18 tons/mi^2 for the Redwood River Basin and 56 tons/mi^2 for the Cottonwood River Basin.

Data from long term (25 years) sediment records for the Minnesota River at Mankato (site 25) are shown in figure 20. The average annual sediment load for the Minnesota River at Mankato (site 25) is 1,490,000 tons. During the MRAP study, annual sediment loads in the Minnesota River at Mankato (site 25) ranged from below average (524,000 tons) during 1990, to about average (1,560,000 tons) during 1992, to above average (2,000,000 tons) during 1991. The year to year variability in annual sediment load is consistent with that seen in the 25 year period of record (fig. 20).

Upland and instream sediment sources

Concern has been expressed about effects of sediment contributed from erosion of river banks and beds. Bank erosion is highly visible along most of the Minnesota River mainstem and also along some reaches of the major tributaries. The concerns are: (1) what are the effects of erosion on suspended-sediment concentrations in the mainstem, (does bank and bed erosion cause high concentrations and turbidity in the mainstem), and (2) does sediment from the banks and beds contribute to the total load of sediment carried to the mouth of the Minnesota River, and subsequently, to the Mississippi River.

Gains in sediment load within stream reaches are attributable to bank and bed erosion, provided that no other sources, such as tributaries are delivering sediment at the time of sampling. Releases of relatively large amounts of water from Lac qui Parle Reservoir provided opportunities to measure the effects of bank and bed erosion. These releases took place during periods when flows from runoff in tributary streams had receded and the tributaries were delivering little sediment. Suspended-sediment samples were collected during two releases, one in August 1991 that filled the channel to about one-half bank full, and one in June 1992 that produced flows that were at or near bank-full levels. Bank and bed erosion was expected to be high at the time of sampling because the river had crested and was receding slowly. Under these conditions, saturated stream banks could slump and collapse.

The suspended-sediment data collected during the two reservoir releases are shown in figure 7, and in table 6. The August 1991 sampling was conducted at 12 sites located along the mainstem from the outlet of Lac qui Parle (site 1) to Henderson (site 28). The results of the sampling show that the net gain in suspended-sediment load in the reach was 3,550 tons per day, which represents an average gain of 16 tons per day per mile (tons/d/mi) at the time of sampling. Table 6 shows that load accretions in the first four subreaches from Lac qui Parle (site 1) to Morton (site 12) were relatively constant, ranging from 8-16 tons/d/mi. Between Morton (site 12) and Fairfax (site 13) the gain decreased to less than 1 ton/d/mi and between Fairfax (site 13) and New Ulm (site 14) there was a net loss of 6 tons/d/mi. Downstream from New Ulm (site 14), the river gained sediment at rates that ranged from 13-87 tons/d/mi.

Not all of the gain can be attributed to bank and bed erosion because the tributaries, while not carrying sediment from runoff at the time, were, nonetheless, carrying some sediment to the mainstem. This is shown by the relatively high gains of 33 tons/d/mi and 87 tons/d/mi in the subreaches where the Cottonwood and Blue Earth Rivers enter the mainstem. The sediment contribution of the Blue Earth River can be determined because it has a daily sediment-discharge record. Subtracting the load from the Blue Earth River and recalculating the gain from Judson (site 17) to Mankato (site 25), results in a change from 87 tons/d/mi to 39 tons/d/mi. The sediment discharge from the Cottonwood River can be estimated from stream discharge records and the sediment transport curve developed by Tornes (1986). Subtracting the estimated sediment discharge contributed by the Cottonwood River results in a change from 33 tons/d/mi to 30 tons/d/mi for the subreach between New Ulm (site 14) and Courtland (site 16). Suspended-sediment discharge from tributary streams could be subtracted from other reaches also, but data are not available. This would lower the average rate for the entire reach.

The water sampling during June 1992 was conducted at only five mainstem sites located from the outlet of Lac qui Parle (site 1) to New Ulm (site 14) (tab. 6). Bank and bed erosion was expected to be higher than it was during the August 1991 sampling because stream discharge at Lac qui Parle (site 1) was significantly higher during June

1992 (4,670 ft^3/s) than it was during August 1991 (2,390 ft^3/s). Only one of the subreaches, however, showed a load gain that was higher than those calculated for the August 1991 sampling. This gain, 918 tons per day, was calculated for the reach between Montevideo (site 3) and Sacred Heart (site 6). The increase in load in this reach represents a gain of 28 tons/d/mi. The other subreaches showed either a slight gain (8 tons per day) or losses of sediment. The reach between Morton (site 12) and New Ulm (site 14) had a substantial sediment loss (539 tons per day), which is consistent with the loss of 140 tons per day in this reach during the August 1991 sampling. The net sediment gain for the reach from Lac qui Parle (site 1) to New Ulm (site 14) was 325 tons per day during June 1992 as compared to 838 tons per day during August 1991.

The load accretion from bank and bed erosion, while significant over the length of the Minnesota River, is substantially less than loads carried by similar stream discharges during runoff. For example, during the August 1991 sampling when tributaries were not contributing much sediment load to the river, the stream discharge at Mankato (site 25) was 7,410 ft^3/s and the sediment load was 3,080 tons per day. During runoff in April 1991 when tributaries were contributing a greater sediment load, a nearly identical stream discharge of 7,650 ft^3/s carried a load of 16,100 tons per day.

The low suspended-sediment concentrations (<200 mg/L) measured during the August 1991 and June 1992 samplings suggest that bank and bed erosion does not produce high (>500 mg/L) suspended-sediment concentrations in the mainstem, such as those that were frequently measured in the Minnesota River at Mankato (site 25) (fig. 11). Perhaps the most significant results from the August 1991 and June 1992 samplings are in the suspended-sediment concentration data. These data show that, despite significant gains in sediment load in portions of the mainstem (1,140 tons per day in one subreach), the suspended-sediment concentrations increased only moderately. In the August 1991 sampling (tab. 6), concentrations did not rise above 102 mg/L in the upper 137 miles of the study reach. Concentrations increased in the portion of the reach downstream from New Ulm (site 14), but remained less than 200 mg/L. In the June 1992 sampling, concentrations increased even less than they did during the August 1991 sampling and remained less than 100 mg/L throughout the study reach.

To address concern that bank and bed erosion could be the source of a substantial part of the tributary suspended-sediment loads, sampling sites were established along the Redwood River near Redwood Falls (sites 8 and 10). The study reach was established where bank erosion was visible and ongoing during the MRAP study. The study approach involved sampling at paired sites in the study reach. Sediment loads were measured at each site so that the gain in sediment load from bank and bed erosion between the paired sites could be calculated. There was one tributary stream within the study reach (site 9). The tributary stream also was sampled so that its contribution to the total load could be calculated and subtracted out.

Data from a four-day runoff in the Redwood River study reach are shown in table 7. The Redwood River near Seaforth (site 8) is 5.2 river miles upstream from the Redwood River near Redwood Falls (site 10). The gain in sediment between these sites during the four-day period was 3,896 tons after subtracting the contribution (172 tons) from the tributary stream, Judicial Ditch 5 (site 9). Most of the gain (2,643 tons) occurred during the first day of runoff. The load accretion in the study reach was 526 tons/mi on the first day of runoff, but declined to 42 tons/mi on the fourth day. Samples were collected for determination of suspended-sediment particle size at all three sampling sites during the first day of runoff. The results showed that about 10 percent of the sediment at the Redwood River near Seaforth (site 8) was sand sized. At the Redwood River near Redwood Falls (site 10), however, 25 percent of the sediment was sand sized. The sediment transported by Judicial Ditch 5 (site 9), in contrast, was comprised almost entirely of silt- and clay-sized particles and had less than one percent sand. Material also was collected from the banks at 10 locations along the study reach. The bank-material samples ranged from 36 to 77 percent sand, and averaged 57 percent sand. The presence of a higher proportion of sand in the sediment in transport at the Redwood River near Redwood Falls (site 10) suggests that the additional sediment in transport at that site could have been from bank erosion. Bed scour is another potential source for the sediment gained in this reach.

The rate of sediment-load accretion (526 tons/d/mi) calculated for the Redwood River during the first day of runoff is high compared to rates determined for the Minnesota River mainstem. This rate probably is much higher than normal for the Redwood River, however, because the stream discharge at the time of sampling was much higher than normal. The stream discharge at the runoff peak has been exceeded only four times in 67 years and was the highest flow recorded since 1969.

Nutrients

Nutrients are necessary for growth and maintenance of all life forms. However, nutrients can cause problems in aquatic systems when they are present in quantities that greatly exceed the amounts normally needed to sustain organisms living in the system. This process of nutrient

Table 6.--Suspended-sediment concentrations, loads, and yields for water-quality sampling sites in the Minnesota River Basin for rainfall runoff periods, August 20-23, 1991, and June 30, 1992

[mm/dd/yy, month, day, year; ft^3/s, cubic feet per second; mg/L, milligrams per liter; tons/d, tons per day; tons/d/mi, tons per day per mile]

Site number	Site name	USGS identification number	River mile	Date mm/dd/yy	Stream discharge ft^3/s	Suspended-sediment concentration mg/L	Suspended-sediment load tons/d	Suspended-sediment load increment tons/d	Suspended-sediment load increment per river mile tons/d/mi
				Sampling period August 20-23, 1991					
1	Minnesota River near Lac qui Parle, Minn.	5301000	288	082091	2390	39	252		
3	Minnesota River at Montevideo, Minn.	5311000	271	082091	3150	62	527	276	16
6	Minnesota River near Sacred Heart, Minn.	5314560	238	082091	3890	82	861	334	10
7	Minnesota River near Delhi, Minn.	5314740	219	082091	4060	100	1100	235	12
12	Minnesota River at Morton, Minn.	5316580	203	082191	4460	102	1230	132	8
13	Minnesota River near Fairfax, Minn.	5316685	176	082191	4590	100	1240	11	0.41
14	Minnesota River near New Ulm, Minn.	5316760	151	082191	5240	77	1090	-150	-6
16	Minnesota River at Courtland, Minn.	5317250	134	082291	5500	111	1650	559	33
17	Minnesota River at Judson, Minn.	5317500	120	082291	5540	130	1940	296	21
25	Minnesota River at Mankato, Minn.	5325050	107	082291	7410	154	3080	1140	87
26	Minnesota River at St. Peter, Minn.	5325200	91	082291	7950	162	3480	396	25
28	Minnesota River at Henderson, Minn.	5326450	67	082391	7940	177	3790	317	13
				Sampling period June 30, 1992					
1	Minnesota River near Lac qui Parle, Minn.	5301000	288	063092	4670	46	580		
3	Minnesota River at Montevideo, Minn.	5311000	271	063092	6620	29	518	-62	-4
6	Minnesota River near Sacred Heart, Minn.	5314560	238	063092	7190	74	1440	918	28
12	Minnesota River at Morton, Minn.	5316580	203	063092	8630	62	1440	8	.23
14	Minnesota River near New Ulm, Minn.	5316760	151	063092	9580	35	905	-539	-10

enrichment (eutrophication) can cause production of algae and other aquatic plants to exceed desirable levels. This study investigated two nutrients, phosphorus and nitrogen, which have been frequently identified as contributors to eutrophication when present in high quantities and which, in the case of two forms of nitrogen, un-ionized ammonia and nitrate, can be toxic.

Table 7.--Suspended-sediment loads and yields for water-quality sampling sites in the Redwood River Basin for runoff period of June 17-20, 1992
[Suspended-sediment load, in tons]

Date	Redwood River at Seaforth (site 8)	Judicial Ditch 5 near Redwood Falls (site 9)	Redwood River near Redwood Falls (site 10)
06/17/92	3210	97	5950
06/18/92	1380	49	2240
06/19/92	818	17	1070
06/20/92	444	9	664
Total[a]	5852	172	9920
Yield [b]	10	20	16

[a] Total load for runoff period.

[b] Yield in tons per square mile for runoff period.

Phosphorus

Water samples were analyzed for both dissolved and particulate forms of phosphorus. Dissolved orthophosphorus commonly is regarded as problematic because it is readily available for uptake by algae. Phosphorus in the particulate form also can be problematic because it can be transported as part of the suspended load, potentially affecting aquatic systems located farther downstream. The combined amounts of dissolved and particulate phosphorus are termed total phosphorus. Total phosphorus data for the mainstem sites are shown in figure 21.

Total phosphorus concentrations for water samples collected at mainstem sites ranged from 0.04 to 0.48 mg/L and the median value was 0.22 mg/L. The interquartile range was 0.15-0.29 mg/L. At times, much of the phosphorus in the mainstem water samples was in the form of dissolved orthophosphorus. The proportion of dissolved orthophosphorus in mainstem water samples varied widely, ranging from 3 to 89 percent, but dissolved orthophosphorus comprised at least 33 percent of the total phosphorus in 50 percent of the samples. Dissolved orthophosphorus concentrations ranged from 0.01 to 0.34 mg/L and the median concentration was 0.07 mg/L. The interquartile range for dissolved orthophosphorus was 0.04-0.13 mg/L. The presence of dissolved orthophosphorus at these levels suggests that the Minnesota River is enriched with phosphorus in amounts that exceed the growth requirements of the algae that were in the river at the time of sampling.

The data in figure 22 show total phosphorus concentrations by source regions in selected subreaches of the mainstem. Differences in the phosphorus concentrations between subreaches might suggest that they are receiving different levels of phosphorus loading. The data were evaluated to determine if there were statistically significant differences in total phosphorus concentrations between the four source regions of mainstem sites shown in figure 22. Statistical tests showed that there was no difference between Source Region II, III, and IV, but that Source Region I was significantly different ($p<0.05$) from Source Region II, III, and IV. The results show that total phosphorus concentrations are lower in the part of the Minnesota River (Source Region I) that receives loading from the Minnesota River headwater basin source region, which may indicate that there is less phosphorus loading from this region.

Total phosphorus concentrations in the samples from tributary streams had a median concentration of 0.21 mg/L and an interquartile range of 0.13 to 0.34 mg/L. Dissolved orthophosphorus concentrations in samples from tributary streams had a median concentration of 0.11 mg/L and an interquartile range of 0.03 to 0.15 mg/L. Dissolved orthophosphorus comprised at least 42 percent of the total phosphorus in 50 percent of the samples. Phosphorus concentrations in tributaries increased during runoff periods. This response is shown by the total phosphorus and stream discharge data for the Blue Earth River (fig. 23). Total phosphorus concentrations often reached peak values during the rising portion of the stream discharge hydrograph. This is particularly evident in the data shown for March of 1990, 1991, and 1992 (fig. 23). The median total phosphorus concentration in Blue Earth River samples was 0.16 mg/L. During runoff, total phosphorus concentrations were about two times greater than the median value and about five times greater than concentrations in samples collected during low flow (fig. 23).

The other major tributaries were not sampled as frequently as the Blue Earth River, but efforts were directed to collecting samples over a wide range of stream discharge conditions from each stream. As indicated by

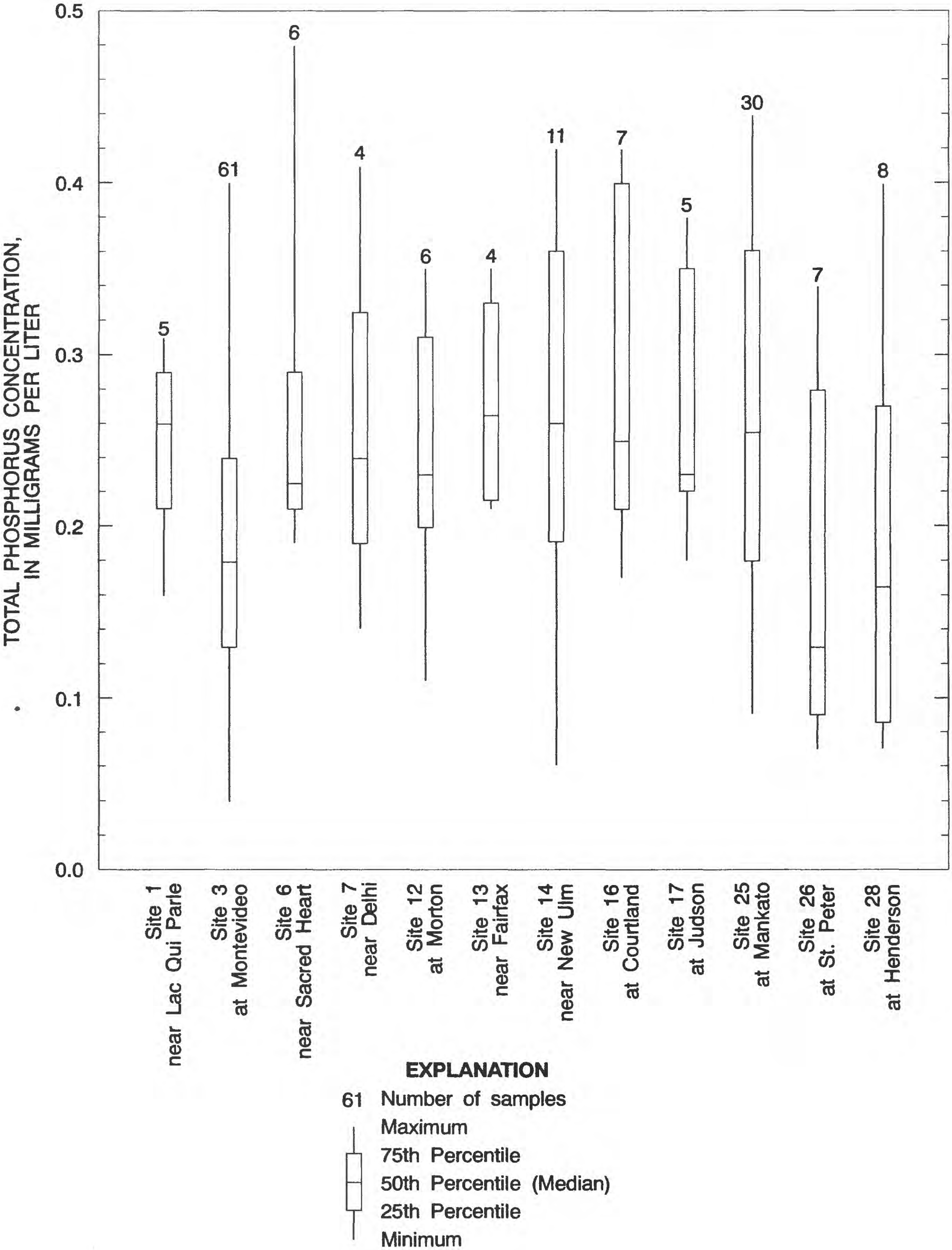


Figure 21.--Total phosphorus concentrations for Minnesota River sampling sites, August 1989-September 1992.

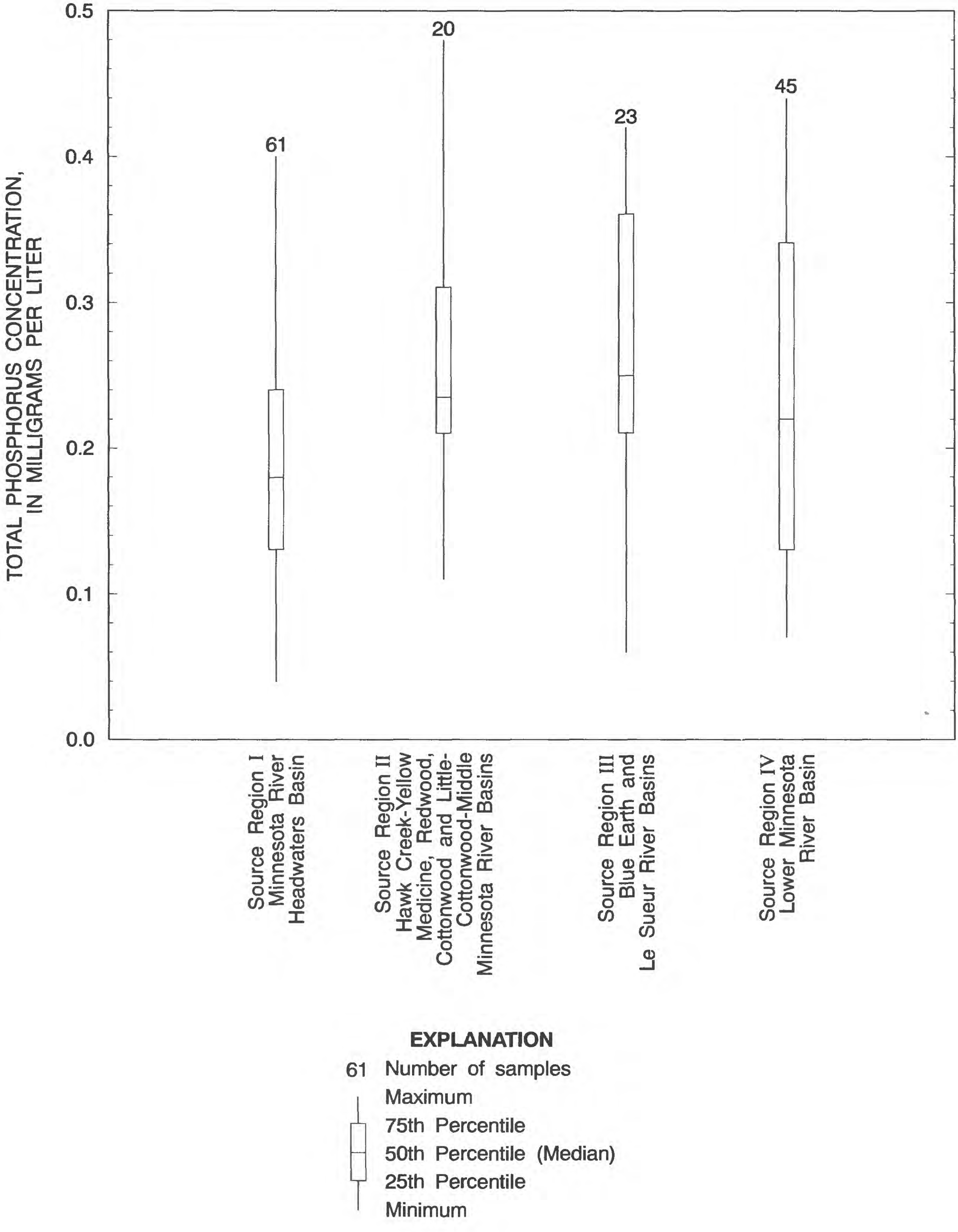


Figure 22.--Total phosphorus concentrations at Minnesota River Source Region stream monitoring sites, August 1989-September 1992.

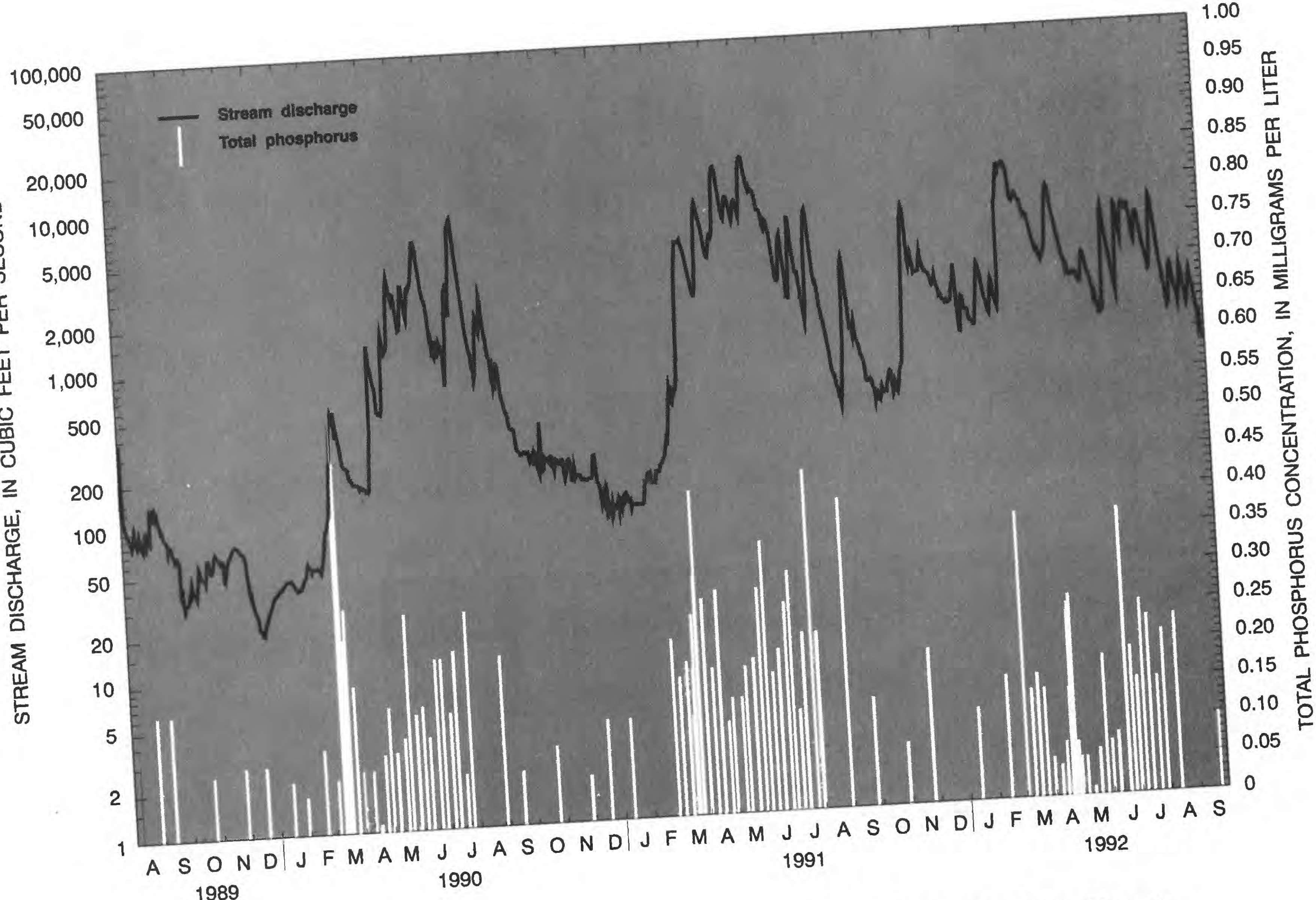


Figure 23.--Stream discharge and total phosphorus concentration and for the Blue Earth River at Mankato (site 24), August 1989-September 1992.

the total phosphorus data shown in figure 12, concentrations in all the tributaries fluctuated over a wide range of values. Generally these fluctuations correspond to increases in phosphorus concentrations during runoff, but some of the elevated concentrations occurred during non-runoff periods.

The data collected during this study show that the tributaries frequently transport phosphorus-enriched water to the mainstem. The phosphorus-enriched water is often delivered during periods of increased stream discharge which results in the transport of large amounts of phosphorus to the mainstem. Peak loading rates for days when the major tributaries were sampled ranged from 0.66 tons per day (tons/d) for High Island Creek (site 29) to 15 tons/d for the Blue Earth River. A quantitative determination of the annual phosphorus contribution from each of the major tributaries is beyond the scope of this report.

The phosphorus loading from each major tributary to the Minnesota River is most distinct in the reach immediately downstream of its confluence. Also, each major tributary will contribute to the total load of phosphorus transported to downstream locations on the Minnesota River and eventually to the Mississippi River. The effect of a tributary near its confluence with the mainstem depends on the flow rate in the mainstem at the time of runoff. A large volume of phosphorus-enriched water from a single tributary, for example, can significantly affect concentrations in the mainstem if the flow in the mainstem is low relative to the runoff volume of the tributary. The contribution of a single tributary to the total load in the Minnesota River, however, will depend not only on the flow rate and phosphorus concentration in that tributary during each runoff, but also on the number of runoff periods. Tributary streams located in the portions of the basin that have lower annual rainfall and runoff, therefore, can be expected to deliver a smaller portion of the Minnesota River's total annual phosphorus load. The effect of these streams is likely to be realized primarily in the vicinity of their confluence with the mainstem, with a lesser effect on the total load at the mouth of the mainstem. Streams draining the high rainfall and runoff areas of the basin, in contrast, are likely to have an effect on the mainstem at their point of confluence, and will contribute a relatively larger portion of the Minnesota River's annual phosphorus load.

Nitrogen

Water samples were collected and analyzed for nitrogen in four forms; nitrite, nitrate, ammonia, and organic nitrogen. Nitrate was the dominant form of nitrogen in nearly all samples, averaging 60 percent of the total nitrogen present. Nitrate in drinking water may cause methemoglobinemia (Blue Baby Syndrome) in young children and a maximum nitrate concentration of 10 mg/L has been adopted to protect public health (Minnesota Pollution Control Agency, 1990). Nitrate concentrations in the Minnesota River and its tributaries were less than 10 mg/L when the sites were sampled during low flow in August 1989. Flow during those samplings was sustained primarily by discharge from ground water (Magner and Alexander, 1993). When streamflow increased during the spring and summer of 1990, however, nitrate concentrations exceeded 10 mg/L in some parts of the Minnesota River Basin. This change is shown by the data for the Blue Earth River at Mankato (site 24) (fig. 24). As shown in figure 24, concentrations rose substantially during runoff and frequently exceeded 10 mg/L. Nitrate concentrations tended to decline during late fall and winter months when stream discharge declined (fig. 24). A notable exception occurred during fall 1991 when snowmelt raised stream discharge substantially. Nitrate concentrations increased from 5.2 mg/L on October 31, 1991 to 16 mg/L on November 25, 1991.

Increased nitrate concentrations during periods of increasing stream discharge was common to all sites sampled. The effect was less pronounced, however, in Source Region I as shown by the data from the Minnesota River at Montevideo (site 3) (fig. 25). Nitrate concentrations were elevated during runoff at the Minnesota River at Montevideo (site 3) but did not exceed 3 mg/L. Data from tributaries entering the Minnesota River from Source Region II, between Granite Falls and New Ulm, indicated that peak nitrate concentrations increased from west to east in the basin (fig. 12). Peak nitrate concentrations in water samples from Source Region II were higher than those in Source Region I, but generally did not exceed 10 mg/L except for one sample from Hawk Creek (site 5) which had a nitrate concentration of 11 mg/L, and two samples from the Cottonwood River near New Ulm (site 15) that had concentrations of 15 mg/L (May 1991) and 13 mg/L (April 1992).

Nitrate concentrations in samples from Source Region III, comprised of the Blue Earth River and its tributaries, frequently exceeded 10 mg/L, reaching 20 mg/L in the Watonwan River (site 22), 26 mg/L in the Le Sueur River (site 23), and 25 mg/L in the Blue Earth River (site 24). Similarly, nitrate concentrations in samples from the Lower Minnesota River, Source Region IV, also exceeded 10 mg/L, reaching 28 mg/L in the Rush River (site 27) and 15 mg/L in High Island Creek (site 29).

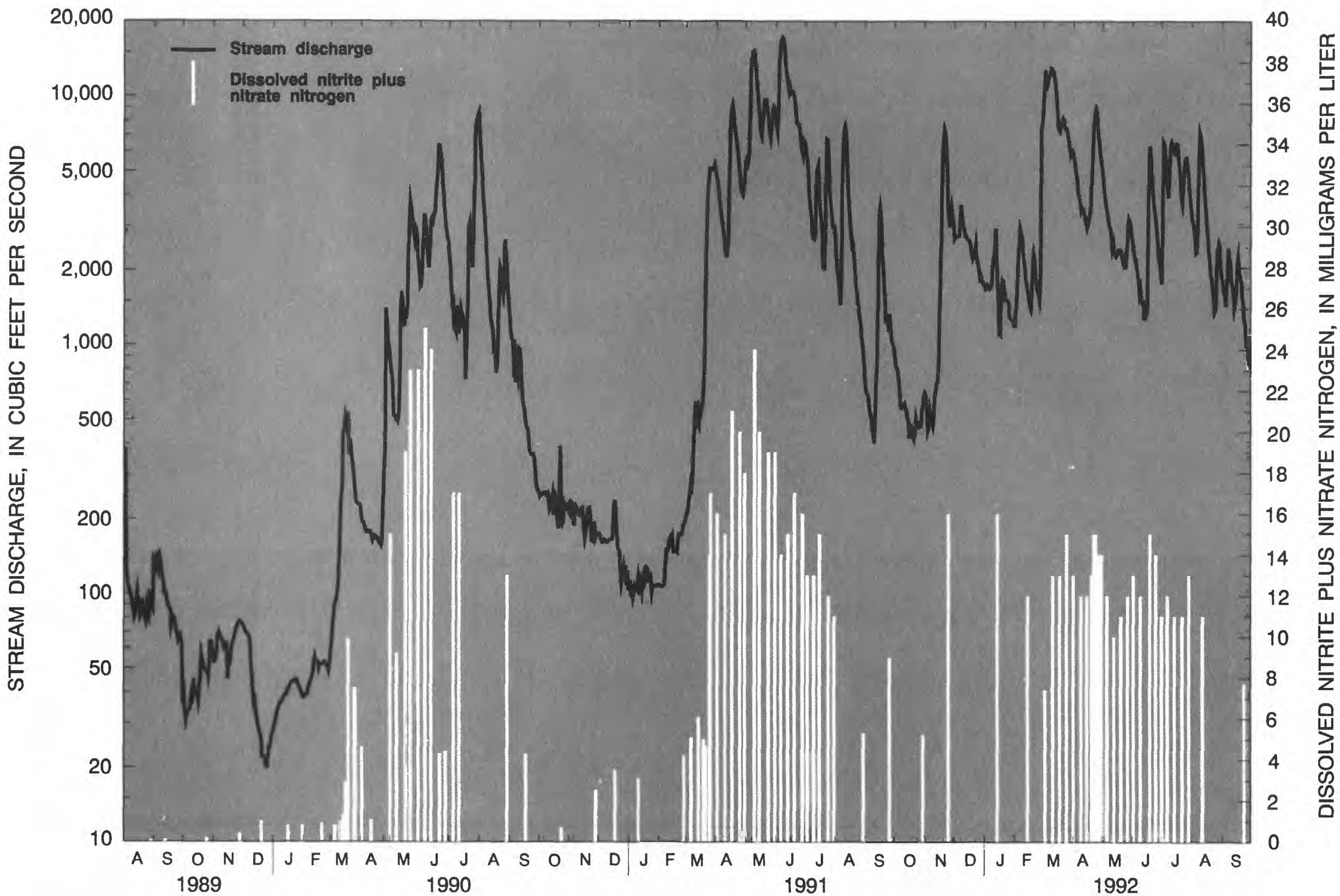


Figure 24.--Stream discharge and dissolved nitrite plus nitrate nitrogen concentration for the Blue Earth River at Mankato (site 24), August 1989-September 1992.

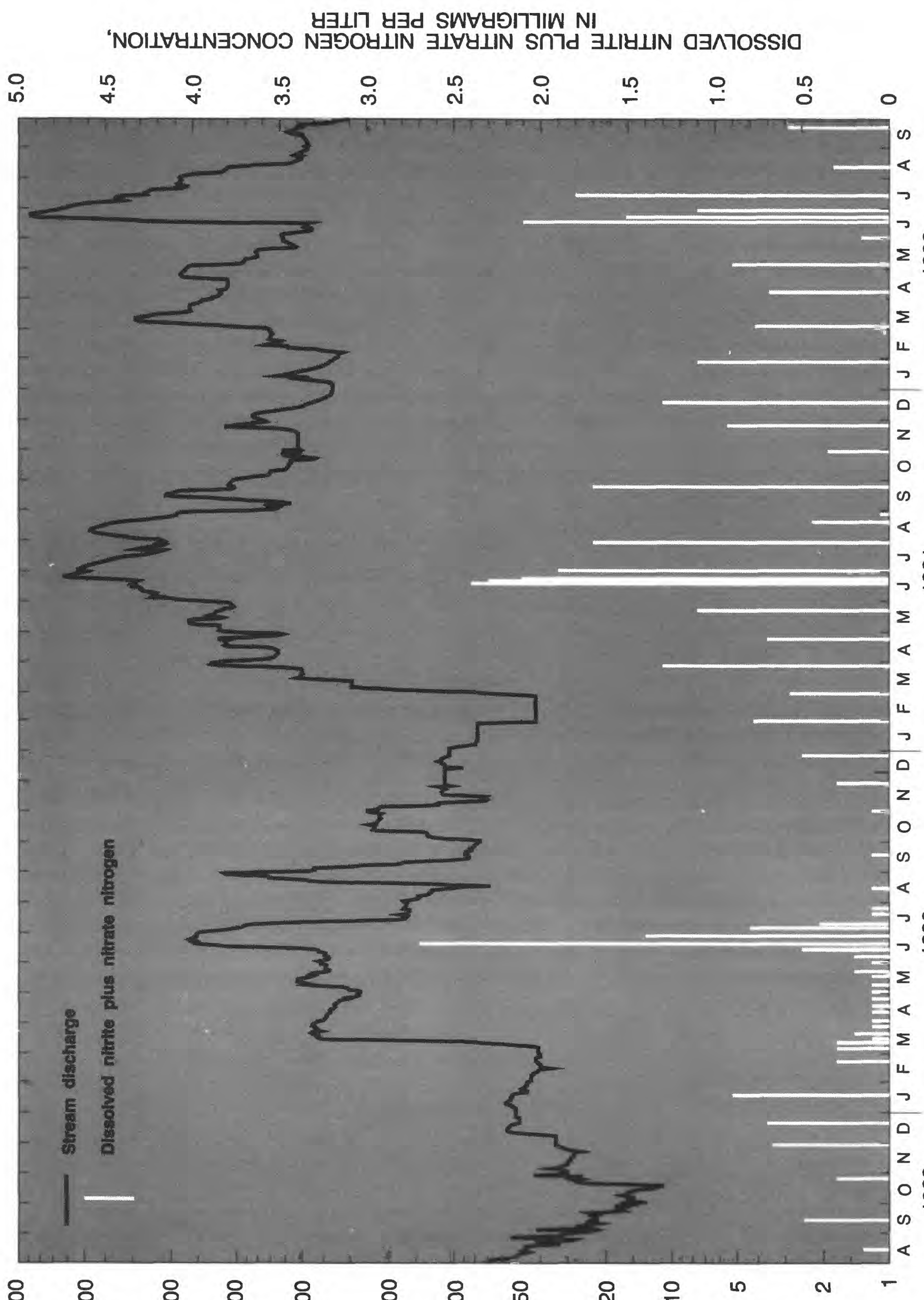


Figure 25.--Stream discharge and dissolved nitrite plus nitrate nitrogen concentration for the Minnesota River at Montevideo (site 3), August 1989-September 1992.

The west to east increase in nitrate concentration correlates with the west to east increase in rainfall and runoff. This relation, along with the increases in nitrate concentration that accompany increases in stream discharge, indicate that the movement of nitrate is closely tied to the movement of water. Examination of data from multiple samples collected during runoff periods showed that nitrate concentrations, unlike suspended-sediment and phosphorus concentrations, reach a maximum after the stream discharge has peaked. Stream discharge during this part of the runoff hydrograph is predominantly derived from subsurface drainage water delivered by ditches and tiles. This suggests that much of the nitrate is reaching the streams through a shallow subsurface pathway. Randall and others (1986) reported average nitrate concentrations that ranged from 16 to 172 mg/L in tiles draining shallow ground water at agricultural experiment stations located in the Minnesota River Basin.

Data collected during the first year of study indicated that nitrate loads in the Blue Earth River were high, exceeding 100 tons/d at times. These data suggested that the Blue Earth River (site 24) might be contributing a large proportion of the total nitrate load in the Minnesota River at Mankato (site 25). Both sites were sampled on a weekly basis from April 15-July 31, 1991, so that loads in both rivers could be estimated and compared. The Blue Earth River (site 24) contributed 47 percent of the stream discharge and 69 percent of the nitrate load in the Minnesota River at Mankato (site 25) during April 15-July 31, 1991.

Part of the nitrogen in transport in Minnesota River Basin streams is in the form of ammonia. Water samples collected for this study were routinely analyzed for ammonia because the un-ionized form of ammonia (NH_3) can be toxic to aquatic life. The percentage of un-ionized ammonia increases with increasing temperature and increasing pH. Total ammonia (NH_3 plus NH_4) was less than 0.1 mg/L in most of the water samples collected from April to November. Total ammonia concentrations less than 0.1 mg/L, in combination with the stream temperatures and pH measured during April through November, indicate that un-ionized ammonia levels would not pose a threat to aquatic life. During winter and the early part of the spring snowmelt, total ammonia concentrations are much higher, typically between 0.1-1.0 mg/L. The potential toxicity posed by these elevated winter and early-spring ammonia concentrations is reduced, however, because low (<5°C) stream temperatures during these periods reduce the amount of ammonia that is present in the un-ionized form. Evaluation of 382 analyses for total ammonia in water samples collected during this study showed that only two samples had un-ionized ammonia concentrations at or greater than the 0.04 mg/L standard established by the Minnesota Pollution Control Agency (1990). One of these water samples was collected less than 500 feet downstream from a known point source of ammonia. The other sample, collected from the Minnesota River at Mankato (site 25) during spring snowmelt, had a calculated un-ionized ammonia concentration of 0.04 mg/L.

Oxygen-Demanding Substances

Dissolved oxygen is required for the survival of the higher forms of aquatic life. The oxygen concentration in a surface-water body is a dynamic indicator of the balance between oxygen-consuming and oxygen-producing processes at the moment of sampling (Hem, 1985). The processes that consume oxygen are often biologically mediated, and typically involve bacterial processing of organic matter. This study investigated the oxygen-demand process by collecting water samples for the determination of biochemical oxygen demand (BOD) and chemical oxygen demand (COD). In addition, the amount of organic material was assessed by analyzing samples for organic carbon content in both dissolved and suspended forms. Water samples also were analyzed for fecal coliform and fecal *Streptococcus* bacteria, which are indicators of the presence of human and animal waste. Fecal wastes are oxygen-demanding substances.

BOD determinations are measurements of the amount of oxygen consumed in a specified time period. BOD concentrations vary with the amount of organic material and oxygen-consuming organisms present at the time of sampling. Monitoring of BOD that includes several seasons and various flow conditions can be useful for determining a characteristic BOD level for a stream. In this study, 152 BOD determinations were made from water samples collected at the mainstem sites. The mean BOD concentration in the mainstem was 5.3 mg/L and the median value was 4.6 mg/L (fig. 12). These values are similar to BOD concentrations determined from long-term monitoring of the Minnesota River at Shakopee (Minnesota Pollution Control Agency, 1985). Median BOD values at Shakopee from 1971-80 were 3.1 mg/L December-March, 5.2 mg/L April-May, 6.1 mg/L June-September, and 5.6 mg/L October-November.

These data indicate that a typical BOD concentration in the Minnesota River is about 5.0 mg/L. If 5.0 mg/L BOD is taken as an approximate norm, then 7.5 mg/L BOD would represent a 50 percent increase in oxygen demand. Using a level of 7.5 mg/L as an indicator of elevated BOD, the mainstem BOD data from this study were evaluated to determine if elevated BOD levels were associated with any particular time periods or river reaches. Sixteen percent of the mainstem BOD concentrations were greater than 7.5 mg/L. All of the values above 7.5 mg/L occurred during either early stages of the spring snowmelt or during August.

The elevated BOD values measured during August coincided with periods of elevated algal productivity. Algal productivity was high in the samples that had elevated BOD, as indicated by chlorophyll *a* concentrations that exceeded 50 µg/L. As algal cells die, the decomposition process causes oxygen demand. The relation of BOD to algal productivity was evaluated by use of both parametric (Pearson) and nonparametric (Spearman) correlations (tabs. 8-14).

Correlation coefficients measure the strength of association between two variables, but a correlation between two variables does not necessarily provide evidence of a causal relationship between the two variables. One variable may be caused by the other, but they may also be correlated because they both share the same cause (Helsel and Hirsch, 1992). Data from mainstem sites were evaluated as a whole (tab. 8), seasonally (tabs. 9, 12, 13, and 14), and by mainstem segment (tabs. 10 and 11). Correlation coefficients referred to in the following discussion are Spearman coefficients unless otherwise specified. An evaluation of data from all mainstem sites for all seasons (tab. 8) showed that there was a significant correlation between BOD and the amount of algal productivity at the time of sampling. The Spearman correlation, for example, showed a significant (correlation coefficient = 0.65, p = 0.0001) correlation between BOD and chlorophyll *a*. Algal productivity, however, generally does not reach elevated levels until late spring. The data were evaluated to determine if BOD and algal productivity were more highly correlated during the seasons when algal growth was elevated. The correlation between BOD and algal productivity increased (correlation coefficient = 0.77, p = 0.0001) when data from only late spring and summer (May-September 1989-92) were evaluated for all sites (tab. 9). The correlation between BOD and algal productivity was strongest for the data collected during May-September 1989-92 in the reach of the mainstem from Judson (site 17) to Henderson (site 28) (correlation coefficient= 0.91, p = 0.0001) (tab. 10). Algal growth and BOD were also highly correlated during May-September 1989-92 in the reach from Lac qui Parle (site 1) to Courtland (site 16) (correlation coefficient = 0.68, p = 0.0001) (tab. 11). BOD and chlorophyll *a* concentrations were not correlated (correlation coefficient = 0.28, p = 0.2370) in samples collected during February-March, a period of generally low algal productivity (tab. 12).

All of the elevated BOD values (>7.5 mg/L) associated with early-spring snowmelt occurred during 1990. The Minnesota River was at low flow during the winter of 1989-90 due to the drought of 1988-89. Stream discharge during March of 1990 was below normal because of little snow. Stagnant water had accumulated under ice in the small streams and drainage ditches during winter 1989-90. It was initially hypothesized that the elevated BOD was caused by the presence of dissolved organic matter and ammonia, both of which were above median values during January through March 1990. During January through March 1990, BOD was not correlated with ammonia or dissolved organic carbon (tab. 13), but was correlated with suspended organic carbon (correlation coefficient = 0.72, p = 0.0001). This correlation is consistent with analysis of data collected during all years of the study, which showed that BOD was most highly correlated with suspended organic carbon during October through April 1989-92 (tab. 14).

Suspended-organic carbon is a measure of the amount of particulate carbon that originated as plant or animal matter. It is a measure of the carbon in living cells such as algae and it also is a measure of the carbon in nonliving plant and animal matter such as crop residue, tree leaves, and algal cells that have died but remain in transport in a stream. Chlorophyll *a* is a measure of only that plant material which is living, primarily algal cells in aquatic systems. Analysis of the data showed that BOD was significantly correlated with suspended organic carbon whether the data were examined as a whole or examined by season. During May through September, when algal productivity is elevated, BOD was more strongly correlated with chlorophyll *a* than with suspended organic carbon (tab. 9). During October through April, when algal productivity was typically lower than it was during May through September, BOD was more strongly correlated with suspended-organic carbon (correlation coefficient = 0.70, p = 0.0001) (tab. 14) than it was with chlorophyll *a* (correlation coefficient = 0.49, p = 0.0003) (tab. 14). These correlations suggest that the primary oxygen-demanding material during May through September is instream-generated algae. Nonliving particulate organic matter exerts more of the oxygen demand during October through April.

The amount of oxygen-demanding substances also was investigated by sampling and analyzing for COD. The COD determination is a measure of all oxidizable material present in the water sample, whereas the BOD determination primarily measures oxygen consumed by biological processes during a five-day incubation at 20°C. An examination of the data showed that COD, unlike BOD, was not highly correlated with suspended-organic carbon or chlorophyll *a* (tabs. 8-14).

Table 8.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River sampling sites, 1989-92

Example: Correlation coefficient = 0.100000
Probability = 0.0
Number of samples = 164

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Pearson correlation coefficients								
Stream discharge	1.00000 0.0 164	0.61895 0.0001 149	0.55818 0.0001 152	0.24423 0.0024 152	0.01429 0.8604 154	0.06165 0.4490 153	-0.03870 0.6348 153	0.78733 0.0001 157	-0.21158 0.0080 156	-0.23051 0.0044 151	-0.37375 0.0001 152	-0.05770 0.4861 148	0.08889 0.2928 142	-0.22018 0.0072 148
Suspended sediment	0.61895 0.0001 149	1.00000 0.0 149	0.79683 0.0001 141	0.47857 0.0001 141	0.18155 0.0306 142	0.03029 0.7214 141	0.21350 0.0110 141	0.76237 0.0001 142	-0.18280 0.0300 141	-0.11059 0.1949 139	-0.29010 0.0005 140	0.03734 0.6649 137	0.30723 0.0004 131	-0.23001 0.0071 136
Total non-volatile suspended solids	0.55818 0.0001 152	0.79683 0.0001 141	1.00000 0.0 152	0.50076 0.0001 152	0.06234 0.4455 152	-0.07973 0.3288 152	0.16129 0.0471 152	0.65337 0.0001 152	-0.19058 0.0187 152	-0.05195 0.5292 149	-0.23362 0.0040 150	-0.00286 0.9727 146	0.33972 0.0001 140	-0.27315 0.0009 146
Total volatile suspended solids	0.24423 0.0024 152	0.47857 0.0001 141	0.50076 0.0001 152	1.00000 0.0 152	0.19071 0.0186 152	-0.15348 0.0591 152	0.40614 0.0001 152	0.25659 0.0014 152	-0.26322 0.0011 152	-0.15139 0.0653 149	0.01781 0.8288 150	0.28138 0.0006 146	0.25708 0.0022 140	-0.07956 0.3398 146
Total phosphorus	0.01429 0.8604 154	0.18155 0.0306 142	0.06234 0.4455 152	0.19071 0.0186 152	1.00000 0.0 154	0.67261 0.0001 153	0.70178 0.0001 153	-0.00198 0.9805 154	0.23890 0.0029 153	0.05592 0.4952 151	0.15808 0.0518 152	0.22683 0.0056 148	0.09112 0.2808 142	-0.05754 0.4873 148
Dissolved phosphorus	0.06165 0.4490 153	0.03029 0.7214 141	-0.07973 0.3288 152	-0.15348 0.0591 152	0.67261 0.0001 153	1.00000 0.0 153	-0.05514 0.4984 153	-0.02092 0.7974 153	0.54982 0.0001 153	-0.16163 0.0482 150	-0.18921 0.0200 151	0.07562 0.3626 147	-0.34208 0.0001 141	0.14934 0.0710 147
Suspended phosphorus	-0.03870 0.6348 153	0.21350 0.0110 141	0.16129 0.0471 152	0.40614 0.0001 152	0.70178 0.0001 153	-0.05514 0.4984 153	1.00000 0.0 153	0.01873 0.8183 153	-0.20697 0.0103 153	0.23953 0.0032 150	0.39790 0.0001 151	0.25750 0.0016 147	0.46098 0.0001 141	-0.22652 0.0058 147
Dissolved nitrite plus nitrate	0.78733 0.0001 157	0.76237 0.0001 142	0.65337 0.0001 152	0.25659 0.0014 152	-0.00198 0.9805 154	-0.02092 0.7974 153	0.01873 0.8183 153	1.00000 0.0 157	-0.15831 0.0484 156	-0.12035 0.1410 151	-0.35652 0.0001 152	-0.07350 0.3747 148	0.11892 0.1587 142	-0.26117 0.0013 148
Dissolved ammonia	-0.21158 0.0080 156	-0.18280 0.0300 141	-0.19058 0.0187 152	-0.26322 0.0011 152	0.23890 0.0029 153	0.54982 0.0001 153	-0.20697 0.0103 153	-0.15831 0.0484 156	1.00000 0.0 156	-0.18671 0.0222 150	-0.15510 0.0572 151	-0.07450 0.3698 147	-0.49767 0.0001 141	0.25433 0.0019 147
Chlorophyll *a*	-0.23051 0.0044 151	-0.11059 0.1949 139	-0.05195 0.5292 149	-0.15139 0.0653 149	0.05592 0.4952 151	-0.16163 0.0482 150	0.23953 0.0032 150	-0.12035 0.1410 151	-0.18671 0.0222 150	1.00000 0.0 151	0.42537 0.0001 149	-0.04388 0.6003 145	0.44932 0.0001 139	-0.28433 0.0005 145
Biochemical oxygen demand (BOD)	-0.37375 0.0001 152	-0.29010 0.0005 140	-0.23362 0.0040 150	0.01781 0.8288 150	0.15808 0.0518 152	-0.18921 0.0200 151	0.39790 0.0001 151	-0.35652 0.0001 152	-0.15510 0.0572 151	0.42537 0.0001 149	1.00000 0.0 152	0.21171 0.0103 146	0.47299 0.0001 140	-0.00291 0.9722 146
Chemical oxygen demand (COD)	-0.05770 0.4861 148	0.03734 0.6649 137	-0.00286 0.9727 146	0.28138 0.0006 146	0.22683 0.0056 148	0.07562 0.3626 147	0.25750 0.0016 147	-0.07350 0.3747 148	-0.07450 0.3698 147	-0.04388 0.6003 145	0.21171 0.0103 146	1.00000 0.0 148	0.05247 0.5367 141	0.21200 0.0099 147
Suspended oxygen demand (SOC)	0.08889 0.2928 142	0.30723 0.0004 131	0.33972 0.0001 140	0.25708 0.0022 140	0.09112 0.2808 142	-0.34208 0.0001 141	0.46098 0.0001 141	0.11892 0.1587 142	-0.49767 0.0001 141	0.44932 0.0001 139	0.47299 0.0001 140	0.05247 0.5367 141	1.00000 0.0 142	-0.35448 0.0001 142
Dissolved oxygen demand (DOC)	-0.22018 0.0072 148	-0.23001 0.0071 136	-0.27315 0.0009 146	-0.07956 0.3398 146	-0.05754 0.4873 148	0.14934 0.0710 147	-0.22652 0.0058 147	-0.26117 0.0013 148	0.25433 0.0019 147	-0.28433 0.0005 145	-0.00291 0.9722 146	0.21200 0.0099 147	-0.35448 0.0001 142	1.00000 0.0 148

Table 8.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River sampling sites, 1989-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 164	0.66267 0.0001 149	0.55448 0.0001 152	0.34727 0.0001 152	-0.16934 0.0358 154	-0.10590 0.1926 153	0.00625 0.9389 153	0.77059 0.0001 157	-0.32927 0.0001 156	-0.07880 0.3361 151	-0.34022 0.0001 152	-0.17874 0.0297 148	0.27854 0.0008 142	-0.37466 0.0001 148
Suspended sediment	0.66267 0.0001 149	1.00000 0.0 149	0.68030 0.0001 141	0.40294 0.0001 141	0.06757 0.4243 142	0.01652 0.8459 141	0.16555 0.0498 141	0.67281 0.0001 142	-0.19772 0.0188 141	0.00479 0.9554 139	-0.29028 0.0005 140	-0.06954 0.4194 137	0.37063 0.0001 131	-0.36554 0.0001 136
Total non-volatile suspended solids	0.55448 0.0001 152	0.68030 0.0001 141	1.00000 0.0 152	0.40668 0.0001 152	-0.07679 0.3471 152	-0.12301 0.1311 152	0.10395 0.2025 152	0.51987 0.0001 152	-0.15760 0.0525 152	0.11783 0.1524 149	-0.18484 0.0235 150	-0.06992 0.4017 146	0.44382 0.0001 140	-0.46461 0.0001 146
Total volatile suspended solids	0.34727 0.0001 152	0.40294 0.0001 141	0.40668 0.0001 152	1.00000 0.0 152	0.09636 0.2376 152	-0.14840 0.0681 152	0.33288 0.0001 152	0.22762 0.0048 152	-0.34001 0.0001 152	-0.12561 0.1269 149	-0.05529 0.5016 150	0.26728 0.0011 146	0.26824 0.0014 140	-0.23203 0.0048 146
Total phosphorus	-0.16934 0.0358 154	0.06757 0.4243 142	-0.07679 0.3471 152	0.09636 0.2376 152	1.00000 0.0 154	0.65576 0.0001 153	0.68310 0.0001 153	0.03850 0.6355 154	0.23458 0.0035 153	0.02051 0.8027 151	0.09543 0.2422 152	0.33535 0.0001 148	0.11981 0.1555 142	-0.01999 0.8095 148
Dissolved phosphorus	-0.10590 0.1926 153	0.01652 0.8459 141	-0.12301 0.1311 152	-0.14840 0.0681 152	0.65576 0.0001 153	1.00000 0.0 153	-0.02285 0.7792 153	0.15452 0.0565 153	0.46144 0.0001 153	-0.22690 0.0052 150	-0.29380 0.0003 151	0.10290 0.2149 147	-0.28106 0.0007 141	0.19372 0.0187 147
Suspended phosphorus	0.00625 0.9389 153	0.16555 0.0498 141	0.10395 0.2025 152	0.33288 0.0001 152	0.68310 0.0001 153	-0.02285 0.7792 153	1.00000 0.0 153	-0.01854 0.8201 153	-0.16217 0.0452 153	0.25077 0.0020 150	0.32215 0.0001 151	0.32567 0.0001 147	0.42701 0.0001 141	-0.25713 0.0017 147
Dissolved nitrite plus nitrate	0.77059 0.0001 157	0.67281 0.0001 142	0.51987 0.0001 152	0.22762 0.0048 152	0.03850 0.6355 154	0.15452 0.0565 153	-0.01854 0.8201 153	1.00000 0.0 157	-0.03833 0.6347 156	-0.06352 0.4384 151	-0.44050 0.0001 152	-0.27121 0.0009 148	0.15742 0.0613 142	-0.39001 0.0001 148
Dissolved ammonia	-0.32927 0.0001 156	-0.19772 0.0188 141	-0.15760 0.0525 152	-0.34001 0.0001 152	0.23458 0.0035 153	0.46144 0.0001 153	-0.16217 0.0452 153	-0.03833 0.6347 156	1.00000 0.0 156	-0.36318 0.0001 150	-0.30350 0.0002 151	-0.11214 0.1763 147	-0.43667 0.0001 141	0.26861 0.0010 147
Chlorophyll *a*	-0.07880 0.3361 151	0.00479 0.9554 139	0.11783 0.1524 149	-0.12561 0.1269 149	0.02051 0.8027 151	-0.22690 0.0052 150	0.25077 0.0020 150	-0.06352 0.4384 151	-0.36318 0.0001 150	1.00000 0.0 151	0.65035 0.0001 149	0.05079 0.5441 145	0.49217 0.0001 139	-0.24908 0.0025 145
Biochemical oxygen demand (BOD)	-0.34022 0.0001 152	-0.29028 0.0005 140	-0.18484 0.0235 150	-0.05529 0.5016 150	0.09543 0.2422 152	-0.29380 0.0003 151	0.32215 0.0001 151	-0.44050 0.0001 152	-0.30350 0.0002 151	0.65035 0.0001 149	1.00000 0.0 152	0.29977 0.0002 146	0.46097 0.0001 140	-0.07550 0.3651 146
Chemical oxygen demand (COD)	-0.17874 0.0297 148	-0.06954 0.4194 137	-0.06992 0.4017 146	0.26728 0.0011 146	0.33535 0.0001 148	0.10290 0.2149 147	0.32567 0.0001 147	-0.27121 0.0009 148	-0.11214 0.1763 147	0.05079 0.5441 145	0.29977 0.0002 146	1.00000 0.0 148	0.15571 0.0652 141	0.30279 0.0002 147
Suspended oxygen demand (SOC)	0.27854 0.0008 142	0.37063 0.0001 131	0.44382 0.0001 140	0.26824 0.0014 140	0.11981 0.1555 142	-0.28106 0.0007 141	0.42701 0.0001 141	0.15742 0.0613 142	-0.43667 0.0001 141	0.49217 0.0001 139	0.46097 0.0001 140	0.15571 0.0652 141	1.00000 0.0 142	-0.47809 0.0001 142
Dissolved oxygen demand (DOC)	-0.37466 0.0001 148	-0.36554 0.0001 136	-0.46461 0.0001 146	-0.23203 0.0048 146	-0.01999 0.8095 148	0.19372 0.0187 147	-0.25713 0.0017 147	-0.39001 0.0001 148	0.26861 0.0010 147	-0.24908 0.0025 145	-0.07550 0.3651 146	0.30279 0.0002 147	-0.47809 0.0001 142	1.00000 0.0 148

Table 9.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River sampling sites, May-September 1989-92

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 108

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Pearson correlation coefficients								
Stream discharge	1.00000 0.0 108	0.58305 0.0001 105	0.47728 0.0001 101	0.26974 0.0064 101	0.13813 0.1683 101	0.27325 0.0057 101	-0.03913 0.6976 101	0.78132 0.0001 104	-0.11650 0.2389 104	-0.32602 0.0009 100	-0.50863 0.0001 100	0.00860 0.9337 96	-0.01581 0.8811 92	-0.14212 0.1672 96
Suspended sediment	0.58305 0.0001 105	1.00000 0.0 105	0.79208 0.0001 101	0.60101 0.0001 101	0.27801 0.0049 101	0.17146 0.0864 101	0.23016 0.0206 101	0.73690 0.0001 101	-0.04796 0.6339 101	-0.19174 0.0560 100	-0.38372 0.0001 100	0.18148 0.0768 96	0.30254 0.0034 92	-0.12389 0.2291 96
Total non-volatile suspended solids	0.47728 0.0001 101	0.79208 0.0001 101	1.00000 0.0 101	0.56264 0.0001 101	0.16406 0.1011 101	0.03334 0.7407 101	0.19120 0.0555 101	0.61710 0.0001 101	0.02989 0.7666 101	-0.08119 0.4220 100	-0.25656 0.0100 100	0.03347 0.7461 96	0.37047 0.0003 92	-0.24511 0.0161 96
Total volatile suspended solids	0.26974 0.0064 101	0.60101 0.0001 101	0.56264 0.0001 101	1.00000 0.0 101	0.34802 0.0004 101	0.05221 0.6041 101	0.42070 0.0001 101	0.33002 0.0008 101	-0.00927 0.9267 101	-0.25934 0.0092 100	-0.27253 0.0061 100	0.26494 0.0091 96	0.07840 0.4576 92	-0.14503 0.1586 96
Total phosphorus	0.13813 0.1683 101	0.27801 0.0049 101	0.16406 0.1011 101	0.34802 0.0004 101	1.00000 0.0 101	0.66193 0.0001 101	0.79102 0.0001 101	0.09522 0.3435 101	0.09869 0.3262 101	-0.29567 0.0028 100	-0.19374 0.0534 100	0.22920 0.0247 96	-0.00295 0.9777 92	-0.05070 0.6237 96
Dissolved phosphorus	0.27325 0.0057 101	0.17146 0.0864 101	0.03334 0.7407 101	0.05221 0.6041 101	0.66193 0.0001 101	1.00000 0.0 101	0.06501 0.5183 101	0.09826 0.3283 101	0.26416 0.0076 101	-0.46859 0.0001 100	-0.37226 0.0001 100	0.12643 0.2196 96	-0.26691 0.0101 92	0.11734 0.2549 96
Suspended phosphorus	-0.03913 0.6976 101	0.23016 0.0206 101	0.19120 0.0555 101	0.42070 0.0001 101	0.79102 0.0001 101	0.06501 0.5183 101	1.00000 0.0 101	0.04656 0.6438 101	-0.08423 0.4023 101	-0.00881 0.9307 100	0.04891 0.6289 100	0.20130 0.0492 96	0.21885 0.0361 92	-0.16663 0.1047 96
Dissolved nitrite plus nitrate	0.78132 0.0001 104	0.73690 0.0001 101	0.61710 0.0001 101	0.33002 0.0008 101	0.09522 0.3435 101	0.09826 0.3283 101	0.04656 0.6438 101	1.00000 0.0 104	-0.17734 0.0717 104	-0.15796 0.1165 100	-0.41862 0.0001 100	0.00439 0.9662 96	0.08703 0.4094 92	-0.19791 0.0533 96
Dissolved ammonia	-0.11650 0.2389 104	-0.04796 0.6339 101	0.02989 0.7666 101	-0.00927 0.9267 101	0.09869 0.3262 101	0.26416 0.0076 101	-0.08423 0.4023 101	-0.17734 0.0717 104	1.00000 0.0 104	-0.34924 0.0004 100	-0.30268 0.0022 100	-0.09937 0.3354 96	-0.36840 0.0003 92	0.10812 0.2944 96
Chlorophyll *a*	-0.32602 0.0009 100	-0.19174 0.0560 100	-0.08119 0.4220 100	-0.25934 0.0092 100	-0.29567 0.0028 100	-0.46859 0.0001 100	-0.00881 0.9307 100	-0.15796 0.1165 100	-0.34924 0.0004 100	1.00000 0.0 100	0.73589 0.0001 99	-0.11689 0.2593 95	0.51015 0.0001 91	-0.32024 0.0016 95
Biochemical oxygen demand (BOD)	-0.50863 0.0001 100	-0.38372 0.0001 100	-0.25656 0.0100 100	-0.27253 0.0061 100	-0.19374 0.0534 100	-0.37226 0.0001 100	0.04891 0.6289 100	-0.41862 0.0001 100	-0.30268 0.0022 100	0.73589 0.0001 99	1.00000 0.0 100	-0.03483 0.7376 95	0.44058 0.0001 91	-0.17675 0.0866 95
Chemical oxygen demand (COD)	0.00860 0.9337 96	0.18148 0.0768 96	0.03347 0.7461 96	0.26494 0.0091 96	0.22920 0.0247 96	0.12643 0.2196 96	0.20130 0.0492 96	0.00439 0.9662 96	-0.09937 0.3354 96	-0.11689 0.2593 95	-0.03483 0.7376 95	1.00000 0.0 96	-0.01845 0.8614 92	0.27715 0.0063 96
Suspended oxygen demand (SOC)	-0.01581 0.8811 92	0.30254 0.0034 92	0.37047 0.0003 92	0.07840 0.4576 92	-0.00295 0.9777 92	-0.26691 0.0101 92	0.21885 0.0361 92	0.08703 0.4094 92	-0.36840 0.0003 92	0.51015 0.0001 91	0.44058 0.0001 91	-0.01845 0.8614 92	1.00000 0.0 92	-0.41949 0.0001 92
Dissolved oxygen demand (DOC)	-0.14212 0.1672 96	-0.12389 0.2291 96	-0.24511 0.0161 96	-0.14503 0.1586 96	-0.05070 0.6237 96	0.11734 0.2549 96	-0.16663 0.1047 96	-0.19791 0.0533 96	0.10812 0.2944 96	-0.32024 0.0016 95	-0.17675 0.0866 95	0.27715 0.0063 96	-0.41949 0.0001 92	1.00000 0.0 96

Table 9.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River sampling sites, May-September 1989-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 108	0.55403 0.0001 105	0.37518 0.0001 101	0.33649 0.0006 101	-0.02790 0.7818 101	0.16213 0.1053 101	-0.09742 0.3325 101	0.86390 0.0001 104	-0.14993 0.1287 104	-0.27998 0.0048 100	-0.51317 0.0001 100	-0.16129 0.1164 96	0.04926 0.6410 92	-0.19693 0.0545 96
Suspended sediment	0.55403 0.0001 105	1.00000 0.0 105	0.67187 0.0001 101	0.51352 0.0001 101	0.08067 0.4226 101	0.12718 0.2050 101	0.06498 0.5186 101	0.72090 0.0001 101	-0.12147 0.2263 101	-0.13440 0.1825 100	-0.31876 0.0012 100	0.09834 0.3405 96	0.30923 0.0027 92	-0.23296 0.0224 96
Total non-volatile suspended solids	0.37518 0.0001 101	0.67187 0.0001 101	1.00000 0.0 101	0.42684 0.0001 101	-0.05723 0.5697 101	-0.06969 0.4886 101	0.00091 0.9928 101	0.53705 0.0001 101	0.02934 0.7708 101	0.01927 0.8491 100	-0.15808 0.1162 100	-0.03374 0.7442 96	0.42737 0.0001 92	-0.37042 0.0002 96
Total volatile suspended solids	0.33649 0.0006 101	0.51352 0.0001 101	0.42684 0.0001 101	1.00000 0.0 101	0.18155 0.0692 101	0.03433 0.7332 101	0.29290 0.0030 101	0.36313 0.0002 101	-0.14911 0.1367 101	-0.22617 0.0237 100	-0.25397 0.0108 100	0.22303 0.0289 96	0.02709 0.7977 92	-0.16412 0.1101 96
Total phosphorus	-0.02790 0.7818 101	0.08067 0.4226 101	-0.05723 0.5697 101	0.18155 0.0692 101	1.00000 0.0 101	0.67357 0.0001 101	0.74434 0.0001 101	0.01499 0.8817 101	0.20098 0.0439 101	-0.22750 0.0228 100	-0.15002 0.1363 100	0.31154 0.0020 96	0.00048 0.9964 92	-0.03707 0.7199 96
Dissolved phosphorus	0.16213 0.1053 101	0.12718 0.2050 101	-0.06969 0.4886 101	0.03433 0.7332 101	0.67357 0.0001 101	1.00000 0.0 101	0.06623 0.5105 101	0.15999 0.1100 101	0.31274 0.0015 101	-0.41294 0.0001 100	-0.41741 0.0001 100	0.19764 0.0536 96	-0.22221 0.0333 92	0.12277 0.2334 96
Suspended phosphorus	-0.09742 0.3325 101	0.06498 0.5186 101	0.00091 0.9928 101	0.29290 0.0030 101	0.74434 0.0001 101	0.06623 0.5105 101	1.00000 0.0 101	-0.05348 0.5953 101	-0.03958 0.6943 101	0.05052 0.6177 100	0.09916 0.3263 100	0.24859 0.0146 96	0.16521 0.1155 92	-0.13355 0.1946 96
Dissolved nitrite plus nitrate	0.86390 0.0001 104	0.72090 0.0001 101	0.53705 0.0001 101	0.36313 0.0002 101	0.01499 0.8817 101	0.15999 0.1100 101	-0.05348 0.5953 101	1.00000 0.0 104	-0.11385 0.2498 104	-0.15475 0.1242 100	-0.42646 0.0001 100	-0.19021 0.0634 96	0.15523 0.1395 92	-0.38311 0.0001 96
Dissolved ammonia	-0.14993 0.1287 104	-0.12147 0.2263 101	0.02934 0.7708 101	-0.14911 0.1367 101	0.20098 0.0439 101	0.31274 0.0015 101	-0.03958 0.6943 101	-0.11385 0.2498 104	1.00000 0.0 104	-0.45534 0.0001 100	-0.35457 0.0003 100	-0.02132 0.8367 96	-0.30527 0.0031 92	0.08695 0.3996 96
Chlorophyll *a*	-0.27998 0.0048 100	-0.13440 0.1825 100	0.01927 0.8491 100	-0.22617 0.0237 100	-0.22750 0.0228 100	-0.41294 0.0001 100	0.05052 0.6177 100	-0.15475 0.1242 100	-0.45534 0.0001 100	1.00000 0.0 100	0.77192 0.0001 99	-0.01659 0.8733 95	0.50592 0.0001 91	-0.16053 0.1202 95
Biochemical oxygen demand (BOD)	-0.51317 0.0001 100	-0.31876 0.0012 100	-0.15808 0.1162 100	-0.25397 0.0108 100	-0.15002 0.1363 100	-0.41741 0.0001 100	0.09916 0.3263 100	-0.42646 0.0001 100	-0.35457 0.0003 100	0.77192 0.0001 99	1.00000 0.0 100	0.00122 0.9906 95	0.42067 0.0001 91	-0.15181 0.1419 95
Chemical oxygen demand (COD)	-0.16129 0.1164 96	0.09834 0.3405 96	-0.03374 0.7442 96	0.22303 0.0289 96	0.31154 0.0020 96	0.19764 0.0536 96	0.24859 0.0146 96	-0.19021 0.0634 96	-0.02132 0.8367 96	-0.01659 0.8733 95	0.00122 0.9906 95	1.00000 0.0 96	0.06085 0.5645 92	0.41881 0.0001 96
Suspended oxygen demand (SOC)	0.04926 0.6410 92	0.30923 0.0027 92	0.42737 0.0001 92	0.02709 0.7977 92	0.00048 0.9964 92	-0.22221 0.0333 92	0.16521 0.1155 92	0.15523 0.1395 92	-0.30527 0.0031 92	0.50592 0.0001 91	0.42067 0.0001 91	0.06085 0.5645 92	1.00000 0.0 92	-0.38356 0.0002 92
Dissolved oxygen demand (DOC)	-0.19693 0.0545 96	-0.23296 0.0224 96	-0.37042 0.0002 96	-0.16412 0.1101 96	-0.03707 0.7199 96	0.12277 0.2334 96	-0.13355 0.1946 96	-0.38311 0.0001 96	0.08695 0.3996 96	-0.16053 0.1202 95	-0.15181 0.1419 95	0.41881 0.0001 96	-0.38356 0.0002 92	1.00000 0.0 96

Table 10.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites 17, 25, 26, and 28 (Judson, Minnesota to Henderson, Minnesota), May-September 1989-92

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 41

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
							Pearson correlation coefficients							
Stream discharge	1.00000 0.0 41	0.66550 0.0001 41	0.51684 0.0011 37	0.36750 0.0252 37	0.26623 0.1112 37	0.57359 0.0002 37	-0.05872 0.7299 37	0.69194 0.0001 37	0.21716 0.1967 37	-0.68762 0.0001 36	-0.77367 0.0001 37	0.10959 0.5185 37	-0.30547 0.0660 37	0.43771 0.0067 37
Suspended sediment	0.66550 0.0001 41	1.00000 0.0 41	0.83971 0.0001 37	0.65275 0.0001 37	0.23582 0.1600 37	0.37436 0.0224 37	0.05723 0.7365 37	0.80933 0.0001 37	0.17967 0.2873 37	-0.49865 0.0020 36	-0.61497 0.0001 37	0.21360 0.2043 37	0.05318 0.7546 37	0.53429 0.0007 37
Total non-volatile suspended solids	0.51684 0.0011 37	0.83971 0.0001 37	1.00000 0.0 37	0.56170 0.0003 37	0.09217 0.5874 37	0.14003 0.4085 37	0.02750 0.8716 37	0.68759 0.0001 37	0.25479 0.1280 37	-0.29668 0.0789 36	-0.44222 0.0061 37	-0.03920 0.8178 37	0.25481 0.1280 37	0.33379 0.0435 37
Total volatile suspended solids	0.36750 0.0252 37	0.65275 0.0001 37	0.56170 0.0003 37	1.00000 0.0 37	0.45260 0.0049 37	0.37498 0.0222 37	0.39047 0.0169 37	0.39020 0.0170 37	0.10289 0.5445 37	-0.55629 0.0004 36	-0.49816 0.0017 37	0.34619 0.0358 37	-0.06465 0.7038 37	0.43713 0.0068 37
Total phosphorus	0.26623 0.1112 37	0.23582 0.1600 37	0.09217 0.5874 37	0.45260 0.0049 37	1.00000 0.0 37	0.81004 0.0001 37	0.87779 0.0001 37	0.09721 0.5671 37	0.39068 0.0168 37	-0.60014 0.0001 36	-0.46477 0.0038 37	0.23946 0.1535 37	-0.33369 0.0436 37	0.25410 0.1291 37
Dissolved phosphorus	0.57359 0.0002 37	0.37436 0.0224 37	0.14003 0.4085 37	0.37498 0.0222 37	0.81004 0.0001 37	1.00000 0.0 37	0.43015 0.0079 37	0.26976 0.1064 37	0.39471 0.0156 37	-0.70341 0.0001 36	-0.56757 0.0002 37	0.25264 0.1314 37	-0.45593 0.0046 37	0.38707 0.0179 37
Suspended phosphorus	-0.05872 0.7299 37	0.05723 0.7365 37	0.02750 0.8716 37	0.39047 0.0169 37	0.87779 0.0001 37	0.43015 0.0079 37	1.00000 0.0 37	-0.07073 0.6774 37	0.27901 0.0945 37	-0.34446 0.0397 36	-0.25187 0.1326 37	0.16227 0.3373 37	-0.14127 0.4043 37	0.07498 0.6592 37
Dissolved nitrite plus nitrate	0.69194 0.0001 37	0.80933 0.0001 37	0.68759 0.0001 37	0.39020 0.0170 37	0.09721 0.5671 37	0.26976 0.1064 37	-0.07073 0.6774 37	1.00000 0.0 37	0.08193 0.6297 37	-0.55624 0.0004 36	-0.71193 0.0001 37	0.09658 0.5696 37	-0.26400 0.1144 37	0.58828 0.0001 37
Dissolved ammonia	0.21716 0.1967 37	0.17967 0.2873 37	0.25479 0.1280 37	0.10289 0.5445 37	0.39068 0.0168 37	0.39471 0.0156 37	0.27901 0.0945 37	0.08193 0.6297 37	1.00000 0.0 37	-0.28541 0.0915 36	-0.07846 0.6444 37	-0.20722 0.2185 37	0.02825 0.8682 37	-0.15911 0.3469 37
Chlorophyll *a*	-0.68762 0.0001 36	-0.49865 0.0020 36	-0.29668 0.0789 36	-0.55629 0.0004 36	-0.60014 0.0001 36	-0.70341 0.0001 36	-0.34446 0.0397 36	-0.55624 0.0004 36	-0.28541 0.0915 36	1.00000 0.0 36	0.91850 0.0001 36	-0.32906 0.0500 36	0.64940 0.0001 36	-0.62123 0.0001 36
Biochemical oxygen demand (BOD)	-0.77367 0.0001 37	-0.61497 0.0001 37	-0.44222 0.0061 37	-0.49816 0.0017 37	-0.46477 0.0038 37	-0.56757 0.0002 37	-0.25187 0.1326 37	-0.71193 0.0001 37	-0.07846 0.6444 37	0.91850 0.0001 36	1.00000 0.0 37	-0.24245 0.1482 37	0.59000 0.0001 37	-0.58913 0.0001 37
Chemical oxygen demand (COD)	0.10959 0.5185 37	0.21360 0.2043 37	-0.03920 0.8178 37	0.34619 0.0358 37	0.23946 0.1535 37	0.25264 0.1314 37	0.16227 0.3373 37	0.09658 0.5696 37	-0.20722 0.2185 37	-0.32906 0.0500 36	-0.24245 0.1482 37	1.00000 0.0 37	-0.21903 0.1927 37	0.42948 0.0080 37
Suspended oxygen demand (SOC)	-0.30547 0.0660 37	0.05318 0.7546 37	0.25481 0.1280 37	-0.06465 0.7038 37	-0.33369 0.0436 37	-0.45593 0.0046 37	-0.14127 0.4043 37	-0.26400 0.1144 37	0.02825 0.8682 37	0.64940 0.0001 36	0.59000 0.0001 37	-0.21903 0.1927 37	1.00000 0.0 37	-0.50478 0.0014 37
Dissolved oxygen demand (DOC)	0.43771 0.0067 37	0.53429 0.0007 37	0.33379 0.0435 37	0.43713 0.0068 37	0.25410 0.1291 37	0.38707 0.0179 37	0.07498 0.6592 37	0.58828 0.0001 37	-0.15911 0.3469 37	-0.62123 0.0001 36	-0.58913 0.0001 37	0.42948 0.0080 37	-0.50478 0.0014 37	1.00000 0.0 37

Table 10.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites 17, 25, 26, and 28 (Judson, Minnesota to Henderson, Minnesota), May-September 1989-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 41	0.69214 0.0001 41	0.39075 0.0168 37	0.45879 0.0043 37	0.23968 0.1531 37	0.51778 0.0010 37	-0.05686 0.7382 37	0.81539 0.0001 37	0.13842 0.4139 37	-0.72514 0.0001 36	-0.81235 0.0001 37	0.40860 0.0120 37	-0.38662 0.0181 37	0.52602 0.0008 37
Suspended sediment	0.69214 0.0001 41	1.00000 0.0 41	0.62253 0.0001 37	0.60281 0.0001 37	0.20702 0.2189 37	0.39565 0.0154 37	-0.05295 0.7556 37	0.83568 0.0001 37	0.10954 0.5187 37	-0.52664 0.0010 36	-0.65248 0.0001 37	0.58357 0.0001 37	-0.13488 0.4261 37	0.56554 0.0003 37
Total non-volatile suspended solids	0.39075 0.0168 37	0.62253 0.0001 37	1.00000 0.0 37	0.47287 0.0031 37	-0.05429 0.7496 37	0.02552 0.8808 37	-0.11554 0.4959 37	0.48885 0.0021 37	0.25465 0.1283 37	-0.17543 0.3061 36	-0.37156 0.0236 37	0.01988 0.9070 37	0.25443 0.1286 37	0.02250 0.8949 37
Total volatile suspended solids	0.45879 0.0043 37	0.60281 0.0001 37	0.47287 0.0031 37	1.00000 0.0 37	0.40939 0.0119 37	0.35288 0.0322 37	0.27228 0.1030 37	0.37788 0.0211 37	-0.03510 0.8366 37	-0.49266 0.0023 36	-0.49459 0.0019 37	0.57027 0.0002 37	-0.16022 0.3435 37	0.46418 0.0038 37
Total phosphorus	0.23968 0.1531 37	0.20702 0.2189 37	-0.05429 0.7496 37	0.40939 0.0119 37	1.00000 0.0 37	0.80914 0.0001 37	0.86537 0.0001 37	0.21073 0.2106 37	0.33987 0.0396 37	-0.59257 0.0001 36	-0.45688 0.0045 37	0.50654 0.0014 37	-0.33055 0.0457 37	0.31928 0.0541 37
Dissolved phosphorus	0.51778 0.0010 37	0.39565 0.0154 37	0.02552 0.8808 37	0.35288 0.0322 37	0.80914 0.0001 37	1.00000 0.0 37	0.43763 0.0068 37	0.44037 0.0064 37	0.35514 0.0310 37	-0.65886 0.0001 36	-0.54154 0.0005 37	0.49467 0.0019 37	-0.41586 0.0105 37	0.41379 0.0109 37
Suspended phosphorus	-0.05686 0.7382 37	-0.05295 0.7556 37	-0.11554 0.4959 37	0.27228 0.1030 37	0.86537 0.0001 37	0.43763 0.0068 37	1.00000 0.0 37	-0.06425 0.7056 37	0.26051 0.1194 37	-0.33606 0.0451 36	-0.22375 0.1831 37	0.27032 0.1056 37	-0.18038 0.2854 37	0.11111 0.5127 37
Dissolved nitrite plus nitrate	0.81539 0.0001 37	0.83568 0.0001 37	0.48885 0.0021 37	0.37788 0.0211 37	0.21073 0.2106 37	0.44037 0.0064 37	-0.06425 0.7056 37	1.00000 0.0 37	0.20249 0.2294 37	-0.61651 0.0001 36	-0.74872 0.0001 37	0.49276 0.0019 37	-0.28153 0.0914 37	0.57022 0.0002 37
Dissolved ammonia	0.13842 0.4139 37	0.10954 0.5187 37	0.25465 0.1283 37	-0.03510 0.8366 37	0.33987 0.0396 37	0.35514 0.0310 37	0.26051 0.1194 37	0.20249 0.2294 37	1.00000 0.0 37	-0.35634 0.0329 36	-0.27997 0.0933 37	-0.09677 0.5688 37	-0.03055 0.8576 37	-0.14505 0.3917 37
Chlorophyll *a*	-0.72514 0.0001 36	-0.52664 0.0010 36	-0.17543 0.3061 36	-0.49266 0.0023 36	-0.59257 0.0001 36	-0.65886 0.0001 36	-0.33606 0.0451 36	-0.61651 0.0001 36	-0.35634 0.0329 36	1.00000 0.0 36	0.90801 0.0001 36	-0.48976 0.0024 36	0.62676 0.0001 36	-0.52867 0.0009 36
Biochemical oxygen demand (BOD)	-0.81235 0.0001 37	-0.65248 0.0001 37	-0.37156 0.0236 37	-0.49459 0.0019 37	-0.45688 0.0045 37	-0.54154 0.0005 37	-0.22375 0.1831 37	-0.74872 0.0001 37	-0.27997 0.0933 37	0.90801 0.0001 36	1.00000 0.0 37	-0.45235 0.0049 37	0.56069 0.0003 37	-0.52739 0.0008 37
Chemical oxygen demand (COD)	0.40860 0.0120 37	0.58357 0.0001 37	0.01988 0.9070 37	0.57027 0.0002 37	0.50654 0.0014 37	0.49467 0.0019 37	0.27032 0.1056 37	0.49276 0.0019 37	-0.09677 0.5688 37	-0.48976 0.0024 36	-0.45235 0.0049 37	1.00000 0.0 37	-0.23476 0.1619 37	0.73399 0.0001 37
Suspended oxygen demand (SOC)	-0.38662 0.0181 37	-0.13488 0.4261 37	0.25443 0.1286 37	-0.16022 0.3435 37	-0.33055 0.0457 37	-0.41586 0.0105 37	-0.18038 0.2854 37	-0.28153 0.0914 37	-0.03055 0.8576 37	0.62676 0.0001 36	0.56069 0.0003 37	-0.23476 0.1619 37	1.00000 0.0 37	-0.52125 0.0009 37
Dissolved oxygen demand (DOC)	0.52602 0.0008 37	0.56554 0.0003 37	0.02250 0.8949 37	0.46418 0.0038 37	0.31928 0.0541 37	0.41379 0.0109 37	0.11111 0.5127 37	0.57022 0.0002 37	-0.14505 0.3917 37	-0.52867 0.0009 36	-0.52739 0.0008 37	0.73399 0.0001 37	-0.52125 0.0009 37	1.00000 0.0 37

Table 11.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites 1, 3, 6, 7, 12-14, and 16 (Lac qui Parle to Courtland, Minnesota), May-September 1989-92

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 67

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
							Pearson correlation coefficients							
Stream discharge	1.00000 0.0 67	-0.00010 0.9994 64	0.00544 0.9660 64	0.01789 0.8884 64	-0.14780 0.2438 64	0.08933 0.4827 64	-0.24726 0.0489 64	0.68707 0.0001 67	-0.02780 0.8233 67	-0.26353 0.0354 64	-0.37853 0.0022 63	-0.27435 0.0355 59	-0.07075 0.6077 55	-0.05011 0.7062 59
Suspended sediment	-0.00010 0.9994 64	1.00000 0.0 64	0.64001 0.0001 64	0.56319 0.0001 64	0.37090 0.0026 64	0.09449 0.4577 64	0.35952 0.0035 64	0.42396 0.0005 64	0.08276 0.5156 64	-0.13635 0.2827 64	-0.21094 0.0970 63	0.30358 0.0194 59	0.38693 0.0035 55	-0.20588 0.1177 59
Total non-volatile suspended solids	0.00544 0.9660 64	0.64001 0.0001 64	1.00000 0.0 64	0.54825 0.0001 64	0.25559 0.0415 64	-0.00245 0.9847 64	0.30308 0.0149 64	0.21708 0.0849 64	0.15359 0.2256 64	-0.03818 0.7645 64	-0.08651 0.5002 63	0.30778 0.0177 59	0.37258 0.0051 55	-0.41971 0.0009 59
Total volatile suspended solids	0.01789 0.8884 64	0.56319 0.0001 64	0.54825 0.0001 64	1.00000 0.0 64	0.28698 0.0215 64	-0.10577 0.4055 64	0.42467 0.0005 64	0.27207 0.0296 64	0.04377 0.7313 64	-0.15406 0.2242 64	-0.14031 0.2727 63	0.28778 0.0271 59	0.08409 0.5416 55	-0.33621 0.0092 59
Total phosphorus	-0.14780 0.2438 64	0.37090 0.0026 64	0.25559 0.0415 64	0.28698 0.0215 64	1.00000 0.0 64	0.54850 0.0001 64	0.72878 0.0001 64	0.19657 0.1195 64	0.04628 0.7165 64	0.02746 0.8294 64	0.03432 0.7894 63	0.23064 0.0788 59	0.28328 0.0361 55	-0.38182 0.0028 59
Dissolved phosphorus	0.08933 0.4827 64	0.09449 0.4577 64	-0.00245 0.9847 64	-0.10577 0.4055 64	0.54850 0.0001 64	1.00000 0.0 64	-0.17282 0.1721 64	0.20334 0.1071 64	0.24619 0.0499 64	-0.25982 0.0381 64	-0.25934 0.0401 63	-0.07094 0.5934 59	-0.11829 0.3897 55	-0.14386 0.2770 59
Suspended phosphorus	-0.24726 0.0489 64	0.35952 0.0035 64	0.30308 0.0149 64	0.42467 0.0005 64	0.72878 0.0001 64	-0.17282 0.1721 64	1.00000 0.0 64	0.06503 0.6097 64	-0.14710 0.2461 64	0.24512 0.0509 64	0.25837 0.0409 63	0.33145 0.0103 59	0.43048 0.0010 55	-0.32523 0.0120 59
Dissolved nitrite plus nitrate	0.68707 0.0001 67	0.42396 0.0005 64	0.21708 0.0849 64	0.27207 0.0296 64	0.19657 0.1195 64	0.20334 0.1071 64	0.06503 0.6097 64	1.00000 0.0 67	0.05017 0.6868 67	-0.28476 0.0226 64	-0.44174 0.0003 63	-0.11160 0.4001 59	0.18012 0.1882 55	-0.21482 0.1023 59
Dissolved ammonia	-0.02780 0.8233 67	0.08276 0.5156 64	0.15359 0.2256 64	0.04377 0.7313 64	0.04628 0.7165 64	0.24619 0.0499 64	-0.14710 0.2461 64	0.05017 0.6868 67	1.00000 0.0 67	-0.38564 0.0016 64	-0.42859 0.0005 63	-0.17015 0.1976 59	-0.41013 0.0019 55	-0.07370 0.5790 59
Chlorophyll *a*	-0.26353 0.0354 64	-0.13635 0.2827 64	-0.03818 0.7645 64	-0.15406 0.2242 64	0.02746 0.8294 64	-0.25982 0.0381 64	0.24512 0.0509 64	-0.28476 0.0226 64	-0.38564 0.0016 64	1.00000 0.0 64	0.69174 0.0001 63	0.34889 0.0068 59	0.37472 0.0048 55	0.07194 0.5882 59
Biochemical oxygen demand (BOD)	-0.37853 0.0022 63	-0.21094 0.0970 63	-0.08651 0.5002 63	-0.14031 0.2727 63	0.03432 0.7894 63	-0.25934 0.0401 63	0.25837 0.0409 63	-0.44174 0.0003 63	-0.42859 0.0005 63	0.69174 0.0001 63	1.00000 0.0 63	0.26407 0.0452 58	0.41121 0.0020 54	-0.07003 0.6014 58
Chemical oxygen demand (COD)	-0.27435 0.0355 59	0.30358 0.0194 59	0.30778 0.0177 59	0.28778 0.0271 59	0.23064 0.0788 59	-0.07094 0.5934 59	0.33145 0.0103 59	-0.11160 0.4001 59	-0.17015 0.1976 59	0.34889 0.0068 59	0.26407 0.0452 58	1.00000 0.0 59	0.30980 0.0214 55	0.12197 0.3574 59
Suspended oxygen demand (SOC)	-0.07075 0.6077 55	0.38693 0.0035 55	0.37258 0.0051 55	0.08409 0.5416 55	0.28328 0.0361 55	-0.11829 0.3897 55	0.43048 0.0010 55	0.18012 0.1882 55	-0.41013 0.0019 55	0.37472 0.0048 55	0.41121 0.0020 54	0.30980 0.0214 55	1.00000 0.0 55	-0.25265 0.0627 55
Dissolved oxygen demand (DOC)	-0.05011 0.7062 59	-0.20588 0.1177 59	-0.41971 0.0009 59	-0.33621 0.0092 59	-0.38182 0.0028 59	-0.14386 0.2770 59	-0.32523 0.0120 59	-0.21482 0.1023 59	-0.07370 0.5790 59	0.07194 0.5882 59	-0.07003 0.6014 58	0.12197 0.3574 59	-0.25265 0.0627 55	1.00000 0.0 59

Table 11.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites 1, 3, 6, 7, 12-14, and 16 (Lac qui Parle to Courtland, Minnesota), May-September 1989-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 67	0.33861 0.0062 64	0.07905 0.5346 64	0.17006 0.1791 64	-0.04947 0.6979 64	0.16042 0.2054 64	-0.10392 0.4138 64	0.79733 0.0001 67	-0.07779 0.5315 67	-0.23772 0.0586 64	-0.43822 0.0003 63	-0.15108 0.2534 59	0.09475 0.4914 55	0.04583 0.7303 59
Suspended sediment	0.33861 0.0062 64	1.00000 0.0 64	0.55131 0.0001 64	0.34976 0.0046 64	0.11655 0.3591 64	0.09888 0.4369 64	0.13794 0.2771 64	0.44796 0.0002 64	-0.07534 0.5541 64	-0.04828 0.7048 64	-0.20947 0.0994 63	0.13594 0.3046 59	0.42324 0.0013 55	-0.09820 0.4593 59
Total non-volatile suspended solids	0.07905 0.5346 64	0.55131 0.0001 64	1.00000 0.0 64	0.25695 0.0404 64	0.00226 0.9859 64	-0.06770 0.5951 64	0.09159 0.4716 64	0.19518 0.1222 64	0.11219 0.3774 64	0.07024 0.5813 64	-0.05008 0.6967 63	0.23216 0.0768 59	0.42597 0.0012 55	-0.20995 0.1105 59
Total volatile suspended solids	0.17006 0.1791 64 .	0.34976 0.0046 64	0.25695 0.0404 64	1.00000 0.0 64	0.06183 0.6274 64	-0.15785 0.2129 64	0.31767 0.0105 64	0.16054 0.2051 64	-0.14035 0.2686 64	-0.10806 0.3953 64	-0.11874 0.3540 63	0.13769 0.2984 59	0.05003 0.7168 55	-0.21314 0.1051 59
Total phosphorus	-0.04947 0.6979 64	0.11655 0.3591 64	0.00226 0.9859 64	0.06183 0.6274 64	1.00000 0.0 64	0.55431 0.0001 64	0.63552 0.0001 64	0.16400 0.1953 64	0.11563 0.3629 64	0.10100 0.4271 64	0.15343 0.2299 63	0.23565 0.0724 59	0.30676 0.0227 55	-0.28552 0.0284 59
Dissolved phosphorus	0.16042 0.2054 64	0.09888 0.4369 64	-0.06770 0.5951 64	-0.15785 0.2129 64	0.55431 0.0001 64	1.00000 0.0 64	-0.21210 0.0925 64	0.33058 0.0076 64	0.29649 0.0174 64	-0.21302 0.0910 64	-0.30177 0.0162 63	-0.04793 0.7185 59	-0.06200 0.6530 55	-0.01999 0.8806 59
Suspended phosphorus	-0.10392 0.4138 64	0.13794 0.2771 64	0.09159 0.4716 64	0.31767 0.0105 64	0.63552 0.0001 64	-0.21210 0.0925 64	1.00000 0.0 64	-0.02428 0.8490 64	-0.17198 0.1742 64	0.31849 0.0103 64	0.34893 0.0051 63	0.35362 0.0060 59	0.41271 0.0017 55	-0.28416 0.0292 59
Dissolved nitrite plus nitrate	0.79733 0.0001 67	0.44796 0.0002 64	0.19518 0.1222 64	0.16054 0.2051 64	0.16400 0.1953 64	0.33058 0.0076 64	-0.02428 0.8490 64	1.00000 0.0 67	0.06646 0.5931 67	-0.25064 0.0458 64	-0.47830 0.0001 63	-0.18268 0.1661 59	0.16110 0.2400 55	-0.24417 0.0624 59
Dissolved ammonia	-0.07779 0.5315 67	-0.07534 0.5541 64	0.11219 0.3774 64	-0.14035 0.2686 64	0.11563 0.3629 64	0.29649 0.0174 64	-0.17198 0.1742 64	0.06646 0.5931 67	1.00000 0.0 67	-0.54480 0.0001 64	-0.46136 0.0001 63	-0.07788 0.5577 59	-0.40987 0.0019 55	0.02295 0.8630 59
Chlorophyll *a*	-0.23772 0.0586 64	-0.04828 0.7048 64	0.07024 0.5813 64	-0.10806 0.3953 64	0.10100 0.4271 64	-0.21302 0.0910 64	0.31849 0.0103 64	-0.25064 0.0458 64	-0.54480 0.0001 64	1.00000 0.0 64	0.68384 0.0001 63	0.40124 0.0016 59	0.43811 0.0008 55	0.09961 0.4529 59
Biochemical oxygen demand (BOD)	-0.43822 0.0003 63	-0.20947 0.0994 63	-0.05008 0.6967 63	-0.11874 0.3540 63	0.15343 0.2299 63	-0.30177 0.0162 63	0.34893 0.0051 63	-0.47830 0.0001 63	-0.46136 0.0001 63	0.68384 0.0001 63	1.00000 0.0 63	0.26089 0.0479 58	0.35681 0.0081 54	-0.06314 0.6377 58
Chemical oxygen demand (COD)	-0.15108 0.2534 59	0.13594 0.3046 59	0.23216 0.0768 59	0.13769 0.2984 59	0.23565 0.0724 59	-0.04793 0.7185 59	0.35362 0.0060 59	-0.18268 0.1661 59	-0.07788 0.5577 59	0.40124 0.0016 59	0.26089 0.0479 58	1.00000 0.0 59	0.32687 0.0149 55	0.16536 0.2107 59
Suspended oxygen demand (SOC)	0.09475 0.4914 55	0.42324 0.0013 55	0.42597 0.0012 55	0.05003 0.7168 55	0.30676 0.0227 55	-0.06200 0.6530 55	0.41271 0.0017 55	0.16110 0.2400 55	-0.40987 0.0019 55	0.43811 0.0008 55	0.35681 0.0081 54	0.32687 0.0149 55	1.00000 0.0 55	-0.21326 0.1180 55
Dissolved oxygen demand (DOC)	0.04583 0.7303 59	-0.09820 0.4593 59	-0.20995 0.1105 59	-0.21314 0.1051 59	-0.28552 0.0284 59	-0.01999 0.8806 59	-0.28416 0.0292 59	-0.24417 0.0624 59	0.02295 0.8630 59	0.09961 0.4529 59	-0.06314 0.6377 58	0.16536 0.2107 59	-0.21326 0.1180 55	1.00000 0.0 59

Table 12.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, February-March 1990-92

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 24

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Pearson correlation coefficients								
Stream discharge	1.00000 0.0 24	0.46876 0.0278 22	0.44886 0.0361 22	-0.02959 0.8960 22	0.03302 0.8840 22	0.06011 0.7904 22	-0.01396 0.9508 22	0.54885 0.0082 22	0.19237 0.3911 22	0.01202 0.9599 20	0.32250 0.1539 21	0.08182 0.7174 22	0.09548 0.6725 22	-0.07097 0.7537 22
Suspended sediment	0.46876 0.0278 22	1.00000 0.0 22	0.25660 0.2748 20	0.06280 0.7925 20	0.04858 0.8388 20	-0.18696 0.4300 20	0.22898 0.3315 20	-0.05807 0.8079 20	-0.01028 0.9657 20	-0.07129 0.7786 18	-0.03548 0.8854 19	-0.33826 0.1446 20	0.14388 0.5451 20	-0.19854 0.4014 20
Total non-volatile suspended solids	0.44886 0.0361 22	0.25660 0.2748 20	1.00000 0.0 22	0.30028 0.1745 22	0.28498 0.1986 22	0.01078 0.9620 22	0.33353 0.1293 22	0.20448 0.3613 22	0.26714 0.2294 22	-0.07087 0.7665 20	0.13396 0.5626 21	0.08702 0.7002 22	0.22460 0.3150 22	-0.25793 0.2465 22
Total volatile suspended solids	-0.02959 0.8960 22	0.06280 0.7925 20	0.30028 0.1745 22	1.00000 0.0 22	0.16644 0.4591 22	-0.26742 0.2289 22	0.43946 0.0407 22	-0.20424 0.3619 22	-0.34223 0.1190 22	-0.06293 0.7921 20	0.39707 0.0747 21	0.25972 0.2431 22	0.51062 0.0152 22	0.12347 0.5841 22
Total phosphorus	0.03302 0.8840 22	0.04858 0.8388 20	0.28498 0.1986 22	0.16644 0.4591 22	1.00000 0.0 22	0.58021 0.0046 22	0.68557 0.0004 22	0.34985 0.1105 22	0.39085 0.0721 22	0.40900 0.0734 20	0.20563 0.3712 21	-0.02082 0.9267 22	0.27437 0.2166 22	-0.13424 0.5515 22
Dissolved phosphorus	0.06011 0.7904 22	-0.18696 0.4300 20	0.01078 0.9620 22	-0.26742 0.2289 22	0.58021 0.0046 22	1.00000 0.0 22	-0.19516 0.3841 22	0.39761 0.0669 22	0.56814 0.0058 22	0.15229 0.5216 20	-0.20547 0.3716 21	-0.20699 0.3554 22	-0.28305 0.2018 22	0.09755 0.6658 22
Suspended phosphorus	-0.01396 0.9508 22	0.22898 0.3315 20	0.33353 0.1293 22	0.43946 0.0407 22	0.68557 0.0004 22	-0.19516 0.3841 22	1.00000 0.0 22	0.06589 0.7708 22	-0.03717 0.8696 22	0.38056 0.0979 20	0.43045 0.0514 21	0.15994 0.4771 22	0.58339 0.0044 22	-0.24884 0.2641 22
Dissolved nitrite plus nitrate	0.54885 0.0082 22	-0.05807 0.8079 20	0.20448 0.3613 22	-0.20424 0.3619 22	0.34985 0.1105 22	0.39761 0.0669 22	0.06589 0.7708 22	1.00000 0.0 22	0.68744 0.0004 22	0.44283 0.0505 20	0.09201 0.6916 21	-0.28762 0.1943 22	-0.07394 0.7437 22	-0.30814 0.1630 22
Dissolved ammonia	0.19237 0.3911 22	-0.01028 0.9657 20	0.26714 0.2294 22	-0.34223 0.1190 22	0.39085 0.0721 22	0.56814 0.0058 22	-0.03717 0.8696 22	0.68744 0.0004 22	1.00000 0.0 22	0.32556 0.1613 20	-0.26093 0.2533 21	-0.44853 0.0363 22	-0.31149 0.1582 22	-0.21453 0.3377 22
Chlorophyll *a*	0.01202 0.9599 20	-0.07129 0.7786 18	-0.07087 0.7665 20	-0.06293 0.7921 20	0.40900 0.0734 20	0.15229 0.5216 20	0.38056 0.0979 20	0.44283 0.0505 20	0.32556 0.1613 20	1.00000 0.0 20	0.17024 0.4859 19	-0.09221 0.6990 20	0.37846 0.0999 20	-0.69584 0.0007 20
Biochemical oxygen demand (BOD)	0.32250 0.1539 21	-0.03548 0.8854 19	0.13396 0.5626 21	0.39707 0.0747 21	0.20563 0.3712 21	-0.20547 0.3716 21	0.43045 0.0514 21	0.09201 0.6916 21	-0.26093 0.2533 21	0.17024 0.4859 19	1.00000 0.0 21	0.63428 0.0020 21	0.69781 0.0004 21	-0.01292 0.9557 21
Chemical oxygen demand (COD)	0.08182 0.7174 22	-0.33826 0.1446 20	0.08702 0.7002 22	0.25972 0.2431 22	-0.02082 0.9267 22	-0.20699 0.3554 22	0.15994 0.4771 22	-0.28762 0.1943 22	-0.44853 0.0363 22	-0.09221 0.6990 20	0.63428 0.0020 21	1.00000 0.0 22	0.32299 0.1426 22	0.23452 0.2935 22
Suspended oxygen demand (SOC)	0.09548 0.6725 22	0.14388 0.5451 20	0.22460 0.3150 22	0.51062 0.0152 22	0.27437 0.2166 22	-0.28305 0.2018 22	0.58339 0.0044 22	-0.07394 0.7437 22	-0.31149 0.1582 22	0.37846 0.0999 20	0.69781 0.0004 21	0.32299 0.1426 22	1.00000 0.0 22	-0.28988 0.1907 22
Dissolved oxygen demand (DOC)	-0.07097 0.7537 22	-0.19854 0.4014 20	-0.25793 0.2465 22	0.12347 0.5841 22	-0.13424 0.5515 22	0.09755 0.6658 22	-0.24884 0.2641 22	-0.30814 0.1630 22	-0.21453 0.3377 22	-0.69584 0.0007 20	-0.01292 0.9557 21	0.23452 0.2935 22	-0.28988 0.1907 22	1.00000 0.0 22

Table 12.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, February-March 1990-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
							Spearman correlation coefficients							
Stream discharge	1.00000 0.0 24	0.49972 0.0179 22	0.51883 0.0134 22	-0.03682 0.8708 22	0.08644 0.7021 22	0.00793 0.9721 22	0.05210 0.8179 22	0.42893 0.0464 22	0.05277 0.8156 22	0.26702 0.2551 20	0.32076 0.1563 21	0.06126 0.7865 22	0.19463 0.3854 22	-0.10694 0.6357 22
Suspended sediment	0.49972 0.0179 22	1.00000 0.0 22	0.45480 0.0439 20	-0.02792 0.9070 20	0.11813 0.6199 20	-0.13575 0.5682 20	0.26330 0.2620 20	0.15498 0.5141 20	0.07943 0.7392 20	0.01446 0.9546 18	-0.05536 0.8219 19	-0.40046 0.0802 20	0.23738 0.3136 20	-0.34018 0.1422 20
Total non-volatile suspended solids	0.51883 0.0134 22	0.45480 0.0439 20	1.00000 0.0 22	0.27620 0.2134 22	0.21669 0.3327 22	0.08449 0.7085 22	0.36961 0.0905 22	0.46564 0.0290 22	0.28307 0.2018 22	0.21775 0.3564 20	0.18975 0.4100 21	0.13466 0.5502 22	0.46880 0.0277 22	-0.42147 0.0507 22
Total volatile suspended solids	-0.03682 0.8708 22	-0.02792 0.9070 20	0.27620 0.2134 22	1.00000 0.0 22	0.06177 0.7848 22	-0.16529 0.4623 22	0.43766 0.0416 22	-0.13979 0.5349 22	-0.47951 0.0239 22	-0.00189 0.9937 20	0.46164 0.0352 21	0.38350 0.0781 22	0.52753 0.0116 22	-0.22768 0.3082 22
Total phosphorus	0.08644 0.7021 22	0.11813 0.6199 20	0.21669 0.3327 22	0.06177 0.7848 22	1.00000 0.0 22	0.62238 0.0020 22	0.58130 0.0045 22	0.34059 0.1209 22	0.31536 0.1528 22	0.44846 0.0473 20	0.23918 0.2964 21	0.05363 0.8126 22	0.18936 0.3987 22	-0.25527 0.2516 22
Dissolved phosphorus	0.00793 0.9721 22	-0.13575 0.5682 20	0.08449 0.7085 22	-0.16529 0.4623 22	0.62238 0.0020 22	1.00000 0.0 22	-0.11925 0.5971 22	0.34537 0.1154 22	0.63499 0.0015 22	0.02264 0.9245 20	-0.13955 0.5463 21	-0.08419 0.7095 22	-0.22213 0.3204 22	0.11124 0.6221 22
Suspended phosphorus	0.05210 0.8179 22	0.26330 0.2620 20	0.36961 0.0905 22	0.43766 0.0416 22	0.58130 0.0045 22	-0.11925 0.5971 22	1.00000 0.0 22	0.24772 0.2663 22	-0.10697 0.6356 22	0.31257 0.1797 20	0.42284 0.0562 21	0.15444 0.4926 22	0.51801 0.0135 22	-0.36167 0.0981 22
Dissolved nitrite plus nitrate	0.42893 0.0464 22	0.15498 0.5141 20	0.46564 0.0290 22	-0.13979 0.5349 22	0.34059 0.1209 22	0.34537 0.1154 22	0.24772 0.2663 22	1.00000 0.0 22	0.47978 0.0238 22	0.37777 0.1006 20	0.02404 0.9176 21	-0.23982 0.2824 22	0.05208 0.8180 22	-0.37457 0.0859 22
Dissolved ammonia	0.05277 0.8156 22	0.07943 0.7392 20	0.28307 0.2018 22	-0.47951 0.0239 22	0.31536 0.1528 22	0.63499 0.0015 22	-0.10697 0.6356 22	0.47978 0.0238 22	1.00000 0.0 22	0.03474 0.8844 20	-0.40170 0.0711 21	-0.41351 0.0558 22	-0.38801 0.0744 22	-0.09203 0.6838 22
Chlorophyll *a*	0.26702 0.2551 20	0.01446 0.9546 18	0.21775 0.3564 20	-0.00189 0.9937 20	0.44846 0.0473 20	0.02264 0.9245 20	0.31257 0.1797 20	0.37777 0.1006 20	0.03474 0.8844 20	1.00000 0.0 20	0.28496 0.2370 19	-0.09245 0.6983 20	0.35857 0.1206 20	-0.68062 0.0010 20
Biochemical oxygen demand (BOD)	0.32076 0.1563 21	-0.05536 0.8219 19	0.18975 0.4100 21	0.46164 0.0352 21	0.23918 0.2964 21	-0.13955 0.5463 21	0.42284 0.0562 21	0.02404 0.9176 21	-0.40170 0.0711 21	0.28496 0.2370 19	1.00000 0.0 21	0.53663 0.0121 21	0.64635 0.0015 21	-0.18672 0.4177 21
Chemical oxygen demand (COD)	0.06126 0.7865 22	-0.40046 0.0802 20	0.13466 0.5502 22	0.38350 0.0781 22	0.05363 0.8126 22	-0.08419 0.7095 22	0.15444 0.4926 22	-0.23982 0.2824 22	-0.41351 0.0558 22	-0.09245 0.6983 20	0.53663 0.0121 21	1.00000 0.0 22	0.31600 0.1520 22	0.21257 0.3422 22
Suspended oxygen demand (SOC)	0.19463 0.3854 22	0.23738 0.3136 20	0.46880 0.0277 22	0.52753 0.0116 22	0.18936 0.3987 22	-0.22213 0.3204 22	0.51801 0.0135 22	0.05208 0.8180 22	-0.38801 0.0744 22	0.35857 0.1206 20	0.64635 0.0015 21	0.31600 0.1520 22	1.00000 0.0 22	-0.40582 0.0609 22
Dissolved oxygen demand (DOC)	-0.10694 0.6357 22	-0.34018 0.1422 20	-0.42147 0.0507 22	-0.22768 0.3082 22	-0.25527 0.2516 22	0.11124 0.6221 22	-0.36167 0.0981 22	-0.37457 0.0859 22	-0.09203 0.6838 22	-0.68062 0.0010 20	-0.18672 0.4177 21	0.21257 0.3422 22	-0.40582 0.0609 22	1.00000 0.0 22

Table 13.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, January-March 1990

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 28

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Pearson correlation coefficients								
Stream discharge	1.00000 0.0 28	0.32855 0.1831 18	0.37049 0.0571 27	0.20899 0.2955 27	0.03221 0.8708 28	-0.15933 0.4180 28	0.21329 0.2758 28	0.23503 0.2286 28	-0.16802 0.3927 28	0.05661 0.7836 26	0.77012 0.0001 27	0.14588 0.4678 27	0.42270 0.0280 27	-0.30664 0.1125 28
Suspended sediment	0.32855 0.1831 18	1.00000 0.0 18	0.31123 0.2087 18	0.18970 0.4509 18	0.10930 0.6660 18	-0.28536 0.2510 18	0.38729 0.1123 18	-0.10468 0.6793 18	-0.19686 0.4337 18	0.12186 0.6530 16	0.31626 0.2162 17	-0.28858 0.2455 18	0.38982 0.1098 18	-0.29092 0.2415 18
Total non-volatile suspended solids	0.37049 0.0571 27	0.31123 0.2087 18	1.00000 0.0 27	0.33847 0.0842 27	0.23828 0.2313 27	-0.03969 0.8442 27	0.31649 0.1078 27	0.11134 0.5803 27	0.15097 0.4522 27	-0.00655 0.9752 25	0.18061 0.3773 26	-0.02183 0.9157 26	0.25963 0.2002 26	-0.29381 0.1369 27
Total volatile suspended solids	0.20899 0.2955 27	0.18970 0.4509 18	0.33847 0.0842 27	1.00000 0.0 27	0.03166 0.8754 27	-0.38468 0.0476 27	0.45739 0.0164 27	-0.27493 0.1652 27	-0.38073 0.0501 27	-0.03522 0.8673 25	0.40931 0.0379 26	0.16112 0.4317 26	0.49820 0.0096 26	0.05140 0.7990 27
Total phosphorus	0.03221 0.8708 28	0.10930 0.6660 18	0.23828 0.2313 27	0.03166 0.8754 27	1.00000 0.0 28	0.60725 0.0006 28	0.47655 0.0104 28	0.46987 0.0116 28	0.31952 0.0974 28	0.25240 0.2135 26	-0.05546 0.7835 27	-0.09616 0.6333 27	0.05367 0.7903 27	-0.06790 0.7314 28
Dissolved phosphorus	-0.15933 0.4180 28	-0.28536 0.2510 18	-0.03969 0.8442 27	-0.38468 0.0476 27	0.60725 0.0006 28	1.00000 0.0 28	-0.40911 0.0306 28	0.55321 0.0023 28	0.69304 0.0001 28	-0.14137 0.4909 26	-0.54513 0.0033 27	-0.13808 0.4922 27	-0.55704 0.0025 27	0.27868 0.1510 28
Suspended phosphorus	0.21329 0.2758 28	0.38729 0.1123 18	0.31649 0.1078 27	0.45739 0.0164 27	0.47655 0.0104 28	-0.40911 0.0306 28	1.00000 0.0 28	-0.07250 0.7139 28	-0.39991 0.0350 28	0.47808 0.0135 26	0.53682 0.0039 27	0.04199 0.8353 27	0.68175 0.0001 27	-0.38635 0.0423 28
Dissolved nitrite plus nitrate	0.23503 0.2286 28	-0.10468 0.6793 18	0.11134 0.5803 27	-0.27493 0.1652 27	0.46987 0.0116 28	0.55321 0.0023 28	-0.07250 0.7139 28	1.00000 0.0 28	0.67080 0.0001 28	0.19187 0.3477 26	-0.13614 0.4983 27	-0.36526 0.0610 27	-0.22093 0.2681 27	-0.18134 0.3557 28
Dissolved ammonia	-0.16802 0.3927 28	-0.19686 0.4337 18	0.15097 0.4522 27	-0.38073 0.0501 27	0.31952 0.0974 28	0.69304 0.0001 28	-0.39991 0.0350 28	0.67080 0.0001 28	1.00000 0.0 28	-0.27137 0.1799 26	-0.57802 0.0016 27	-0.25929 0.1915 27	-0.64766 0.0003 27	0.15706 0.4248 28
Chlorophyll *a*	0.05661 0.7836 26	0.12186 0.6530 16	-0.00655 0.9752 25	-0.03522 0.8673 25	0.25240 0.2135 26	-0.14137 0.4909 26	0.47808 0.0135 26	0.19187 0.3477 26	-0.27137 0.1799 26	1.00000 0.0 26	0.12973 0.5365 25	-0.16698 0.4250 25	0.51375 0.0086 25	-0.56607 0.0026 26
Biochemical oxygen demand (BOD)	0.77012 0.0001 27	0.31626 0.2162 17	0.18061 0.3773 26	0.40931 0.0379 26	-0.05546 0.7835 27	-0.54513 0.0033 27	0.53682 0.0039 27	-0.13614 0.4983 27	-0.57802 0.0016 27	0.12973 0.5365 25	1.00000 0.0 27	0.38801 0.0502 26	0.72112 0.0001 26	-0.24366 0.2207 27
Chemical oxygen demand (COD)	0.14588 0.4678 27	-0.28858 0.2455 18	-0.02183 0.9157 26	0.16112 0.4317 26	-0.09616 0.6333 27	-0.13808 0.4922 27	0.04199 0.8353 27	-0.36526 0.0610 27	-0.25929 0.1915 27	-0.16698 0.4250 25	0.38801 0.0502 26	1.00000 0.0 27	0.14353 0.4842 26	0.23649 0.2350 27
Suspended oxygen demand (SOC)	0.42270 0.0280 27	0.38982 0.1098 18	0.25963 0.2002 26	0.49820 0.0096 26	0.05367 0.7903 27	-0.55704 0.0025 27	0.68175 0.0001 27	-0.22093 0.2681 27	-0.64766 0.0003 27	0.51375 0.0086 25	0.72112 0.0001 26	0.14353 0.4842 26	1.00000 0.0 27	-0.40274 0.0373 27
Dissolved oxygen demand (DOC)	-0.30664 0.1125 28	-0.29092 0.2415 18	-0.29381 0.1369 27	0.05140 0.7990 27	-0.06790 0.7314 28	0.27868 0.1510 28	-0.38635 0.0423 28	-0.18134 0.3557 28	0.15706 0.4248 28	-0.56607 0.0026 26	-0.24366 0.2207 27	0.23649 0.2350 27	-0.40274 0.0373 27	1.00000 0.0 28

Table 13.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, January-March 1990--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 28	0.53485 0.0222 18	0.26681 0.1785 27	0.14362 0.4748 27	0.16765 0.3938 28	-0.25812 0.1848 28	0.34733 0.0702 28	-0.06883 0.7278 28	-0.37581 0.0487 28	0.49726 0.0098 26	0.85640 0.0001 27	0.13062 0.5161 27	0.54913 0.0030 27	-0.51656 0.0049 28
Suspended sediment	0.53485 0.0222 18	1.00000 0.0 18	0.48568 0.0410 18	0.08493 0.7376 18	0.26860 0.2812 18	-0.25750 0.3023 18	0.47980 0.0439 18	-0.02003 0.9371 18	-0.25274 0.3116 18	0.38411 0.1419 16	0.39558 0.1160 17	-0.40395 0.0964 18	0.60766 0.0075 18	-0.52878 0.0241 18
Total non-volatile suspended solids	0.26681 0.1785 27	0.48568 0.0410 18	1.00000 0.0 27	0.28260 0.1532 27	0.27169 0.1704 27	0.05648 0.7796 27	0.26027 0.1898 27	0.33018 0.0926 27	0.14871 0.4591 27	0.28172 0.1725 25	0.14914 0.4671 26	-0.02230 0.9139 26	0.37916 0.0561 26	-0.46388 0.0148 27
Total volatile suspended solids	0.14362 0.4748 27	0.08493 0.7376 18	0.28260 0.1532 27	1.00000 0.0 27	-0.06475 0.7483 27	-0.38162 0.0495 27	0.42180 0.0284 27	-0.20166 0.3131 27	-0.45148 0.0181 27	0.05538 0.7926 25	0.38501 0.0521 26	0.26308 0.1941 26	0.50952 0.0078 26	-0.24515 0.2178 27
Total phosphorus	0.16765 0.3938 28	0.26860 0.2812 18	0.27169 0.1704 27	-0.06475 0.7483 27	1.00000 0.0 28	0.62908 0.0003 28	0.39726 0.0363 28	0.46329 0.0130 28	0.30222 0.1180 28	0.24927 0.2194 26	0.01743 0.9312 27	-0.01074 0.9576 27	-0.03201 0.8741 27	-0.11296 0.5671 28
Dissolved phosphorus	-0.25812 0.1848 28	-0.25750 0.3023 18	0.05648 0.7796 27	-0.38162 0.0495 27	0.62908 0.0003 28	1.00000 0.0 28	-0.34235 0.0745 28	0.54985 0.0024 28	0.75453 0.0001 28	-0.23346 0.2510 26	-0.51829 0.0056 27	-0.14336 0.4756 27	-0.56370 0.0022 27	0.33085 0.0855 28
Suspended phosphorus	0.34733 0.0702 28	0.47980 0.0439 18	0.26027 0.1898 27	0.42180 0.0284 27	0.39726 0.0363 28	-0.34235 0.0745 28	1.00000 0.0 28	-0.00980 0.9605 28	-0.37842 0.0471 28	0.50206 0.0090 26	0.56073 0.0023 27	0.10556 0.6003 27	0.61844 0.0006 27	-0.50536 0.0061 28
Dissolved nitrite plus nitrate	-0.06883 0.7278 28	-0.02003 0.9371 18	0.33018 0.0926 27	-0.20166 0.3131 27	0.46329 0.0130 28	0.54985 0.0024 28	-0.00980 0.9605 28	1.00000 0.0 28	0.60064 0.0007 28	0.10450 0.6114 26	-0.25884 0.1923 27	-0.36841 0.0586 27	-0.21627 0.2786 27	-0.11243 0.5690 28
Dissolved ammonia	-0.37581 0.0487 28	-0.25274 0.3116 18	0.14871 0.4591 27	-0.45148 0.0181 27	0.30222 0.1180 28	0.75453 0.0001 28	-0.37842 0.0471 28	0.60064 0.0007 28	1.00000 0.0 28	-0.32117 0.1096 26	-0.61072 0.0007 27	-0.33799 0.0846 27	-0.64381 0.0003 27	0.25465 0.1910 28
Chlorophyll *a*	0.49726 0.0098 26	0.38411 0.1419 16	0.28172 0.1725 25	0.05538 0.7926 25	0.24927 0.2194 26	-0.23346 0.2510 26	0.50206 0.0090 26	0.10450 0.6114 26	-0.32117 0.1096 26	1.00000 0.0 26	0.37033 0.0684 25	-0.14470 0.4901 25	0.54861 0.0045 25	-0.67198 0.0002 26
Biochemical oxygen demand (BOD)	0.85640 0.0001 27	0.39558 0.1160 17	0.14914 0.4671 26	0.38501 0.0521 26	0.01743 0.9312 27	-0.51829 0.0056 27	0.56073 0.0023 27	-0.25884 0.1923 27	-0.61072 0.0007 27	0.37033 0.0684 25	1.00000 0.0 27	0.39873 0.0436 26	0.72110 0.0001 26	-0.44321 0.0206 27
Chemical oxygen demand (COD)	0.13062 0.5161 27	-0.40395 0.0964 18	-0.02230 0.9139 26	0.26308 0.1941 26	-0.01074 0.9576 27	-0.14336 0.4756 27	0.10556 0.6003 27	-0.36841 0.0586 27	-0.33799 0.0846 27	-0.14470 0.4901 25	0.39873 0.0436 26	1.00000 0.0 27	0.19973 0.3280 26	0.09929 0.6222 27
Suspended oxygen demand (SOC)	0.54913 0.0030 27	0.60766 0.0075 18	0.37916 0.0561 26	0.50952 0.0078 26	-0.03201 0.8741 27	-0.56370 0.0022 27	0.61844 0.0006 27	-0.21627 0.2786 27	-0.64381 0.0003 27	0.54861 0.0045 25	0.72110 0.0001 26	0.19973 0.3280 26	1.00000 0.0 27	-0.49050 0.0094 27
Dissolved oxygen demand (DOC)	-0.51656 0.0049 28	-0.52878 0.0241 18	-0.46388 0.0148 27	-0.24515 0.2178 27	-0.11296 0.5671 28	0.33085 0.0855 28	-0.50536 0.0061 28	-0.11243 0.5690 28	0.25465 0.1910 28	-0.67198 0.0002 26	-0.44321 0.0206 27	0.09929 0.6222 27	-0.49050 0.0094 27	1.00000 0.0 28

Table 14.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, October-April 1989-92

Example: Correlation coefficient = 1.00000
Probability = 0.0
Number of samples = 56

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
	Pearson correlation coefficients													
Stream discharge	1.00000 0.0 56	0.70742 0.0001 44	0.81569 0.0001 51	0.15886 0.2655 51	-0.14260 0.3084 53	-0.21945 0.1180 52	0.04785 0.7362 52	0.96906 0.0001 53	-0.20191 0.1512 52	-0.11946 0.4038 51	-0.20378 0.1473 52	-0.08896 0.5306 52	0.16402 0.2550 50	-0.22964 0.1015 52
Suspended sediment	0.70742 0.0001 44	1.00000 0.0 44	0.81113 0.0001 40	0.19293 0.2330 40	0.03251 0.8401 41	-0.20267 0.2098 40	0.22433 0.1640 40	0.80135 0.0001 41	-0.18659 0.2490 40	-0.03824 0.8172 39	-0.13966 0.3901 40	-0.13691 0.3933 41	0.25553 0.1164 39	-0.24630 0.1255 40
Total non-volatile suspended solids	0.81569 0.0001 51	0.81113 0.0001 40	1.00000 0.0 51	0.38059 0.0059 51	0.03073 0.8305 51	-0.16695 0.2416 51	0.22376 0.1145 51	0.74156 0.0001 51	-0.14914 0.2962 51	-0.04791 0.7437 49	-0.07307 0.6140 50	0.07683 0.5959 50	0.23529 0.1074 48	-0.18120 0.2079 50
Total volatile suspended solids	0.15886 0.2655 51	0.19293 0.2330 40	0.38059 0.0059 51	1.00000 0.0 51	0.00705 0.9608 51	-0.36402 0.0086 51	0.40707 0.0030 51	0.07944 0.5795 51	-0.44860 0.0010 51	-0.00042 0.9977 49	0.31057 0.0282 50	0.39907 0.0041 50	0.45056 0.0013 48	0.01860 0.8980 50
Total phosphorus	-0.14260 0.3084 53	0.03251 0.8401 41	0.03073 0.8305 51	0.00705 0.9608 51	1.00000 0.0 53	0.67929 0.0001 52	0.60083 0.0001 52	-0.07850 0.5764 53	0.25556 0.0675 52	0.44342 0.0011 51	0.31310 0.0238 52	0.18517 0.1888 52	0.24171 0.0908 50	-0.16819 0.2333 52
Dissolved phosphorus	-0.21945 0.1180 52	-0.20267 0.2098 40	-0.16695 0.2416 51	-0.36402 0.0086 51	0.67929 0.0001 52	1.00000 0.0 52	-0.17850 0.2055 52	-0.10673 0.4514 52	0.67241 0.0001 52	0.08514 0.5566 50	-0.20696 0.1451 51	-0.03311 0.8176 51	-0.36183 0.0106 49	0.10405 0.4674 51
Suspended phosphorus	0.04785 0.7362 52	0.22433 0.1640 40	0.22376 0.1145 51	0.40707 0.0030 51	0.60083 0.0001 52	-0.17850 0.2055 52	1.00000 0.0 52	0.01114 0.9376 52	-0.38979 0.0043 52	0.53184 0.0001 50	0.64559 0.0001 51	0.40241 0.0034 51	0.72263 0.0001 49	-0.33937 0.0148 51
Dissolved nitrite plus nitrate	0.96906 0.0001 53	0.80135 0.0001 41	0.74156 0.0001 51	0.07944 0.5795 51	-0.07850 0.5764 53	-0.10673 0.4514 52	0.01114 0.9376 52	1.00000 0.0 53	-0.08781 0.5359 52	-0.08017 0.5760 51	-0.29381 0.0345 52	-0.14024 0.3214 52	0.07771 0.5917 50	-0.26177 0.0608 52
Dissolved ammonia	-0.20191 0.1512 52	-0.18659 0.2490 40	-0.14914 0.2962 51	-0.44860 0.0010 51	0.25556 0.0675 52	0.67241 0.0001 52	-0.38979 0.0043 52	-0.08781 0.5359 52	1.00000 0.0 52	-0.21060 0.1421 50	-0.41705 0.0023 51	-0.31030 0.0267 51	-0.54704 0.0001 49	0.12456 0.3838 51
Chlorophyll *a*	-0.11946 0.4038 51	-0.03824 0.8172 39	-0.04791 0.7437 49	-0.00042 0.9977 49	0.44342 0.0011 51	0.08514 0.5566 50	0.53184 0.0001 50	-0.08017 0.5760 51	-0.21060 0.1421 50	1.00000 0.0 51	0.29903 0.0349 50	0.06032 0.6773 50	0.40931 0.0039 48	-0.28803 0.0425 50
Biochemical oxygen demand (BOD)	-0.20378 0.1473 52	-0.13966 0.3901 40	-0.07307 0.6140 50	0.31057 0.0282 50	0.31310 0.0238 52	-0.20696 0.1451 51	0.64559 0.0001 51	-0.29381 0.0345 52	-0.41705 0.0023 51	0.29903 0.0349 50	1.00000 0.0 52	0.35859 0.0098 51	0.68356 0.0001 49	-0.11519 0.4209 51
Chemical oxygen demand (COD)	-0.08896 0.5306 52	-0.13691 0.3933 41	0.07683 0.5959 50	0.39907 0.0041 50	0.18517 0.1888 52	-0.03311 0.8176 51	0.40241 0.0034 51	-0.14024 0.3214 52	-0.31030 0.0267 51	0.06032 0.6773 50	0.35859 0.0098 51	1.00000 0.0 52	0.22714 0.1165 49	0.07409 0.6054 51
Suspended oxygen demand (SOC)	0.16402 0.2550 50	0.25553 0.1164 39	0.23529 0.1074 48	0.45056 0.0013 48	0.24171 0.0908 50	-0.36183 0.0106 49	0.72263 0.0001 49	0.07771 0.5917 50	-0.54704 0.0001 49	0.40931 0.0039 48	0.68356 0.0001 49	0.22714 0.1165 49	1.00000 0.0 50	-0.23902 0.0946 50
Dissolved oxygen demand (DOC)	-0.22964 0.1015 52	-0.24630 0.1255 40	-0.18120 0.2079 50	0.01860 0.8980 50	-0.16819 0.2333 52	0.10405 0.4674 51	-0.33937 0.0148 51	-0.26177 0.0608 52	0.12456 0.3838 51	-0.28803 0.0425 50	-0.11519 0.4209 51	0.07409 0.6054 51	-0.23902 0.0946 50	1.00000 0.0 52

Table 14.--Correlation coefficients for stream discharge and water-quality data collected at Minnesota River water-quality sampling sites, October-April 1989-92--Continued

	Stream discharge	Suspended sediment	Total non-volatile suspended solids	Total volatile suspended solids	Total phosphorus	Dissolved phosphorus	Suspended phosphorus	Dissolved nitrite plus nitrate	Dissolved ammonia	Chlorophyll *a*	Biochemical oxygen demand (BOD)	Chemical oxygen demand (COD)	Suspended oxygen content (SOC)	Dissolved oxygen content (DOC)
						Spearman correlation coefficients								
Stream discharge	1.00000 0.0 56	0.65715 0.0001 44	0.48479 0.0003 51	0.21592 0.1281 51	-0.24000 0.0835 53	-0.52617 0.0001 52	0.22176 0.1141 52	0.16765 0.2302 53	-0.48171 0.0003 52	0.17967 0.2071 51	0.27421 0.0492 52	-0.03166 0.8237 52	0.48349 0.0004 50	-0.42876 0.0015 52
Suspended sediment	0.65715 0.0001 44	1.00000 0.0 44	0.54141 0.0003 40	0.15707 0.3331 40	0.13102 0.4142 41	-0.29313 0.0664 40	0.42352 0.0065 40	0.39475 0.0106 41	-0.20804 0.1977 40	0.14220 0.3878 39	0.01183 0.9422 40	-0.20690 0.1943 41	0.43792 0.0053 39	-0.36823 0.0194 40
Total non-volatile suspended solids	0.48479 0.0003 51	0.54141 0.0003 40	1.00000 0.0 51	0.44968 0.0009 51	0.06969 0.6270 51	-0.20300 0.1531 51	0.33518 0.0162 51	0.33621 0.0159 51	-0.24219 0.0868 51	0.27175 0.0589 49	0.08950 0.5365 50	0.14952 0.3000 50	0.45767 0.0011 48	-0.39423 0.0046 50
Total volatile suspended solids	0.21592 0.1281 51	0.15707 0.3331 40	0.44968 0.0009 51	1.00000 0.0 51	-0.01493 0.9172 51	-0.42644 0.0018 51	0.37367 0.0069 51	-0.14373 0.3143 51	-0.57493 0.0001 51	-0.01895 0.8972 49	0.28896 0.0418 50	0.43035 0.0018 50	0.50576 0.0002 48	-0.26169 0.0664 50
Total phosphorus	-0.24000 0.0835 53	0.13102 0.4142 41	0.06969 0.6270 51	-0.01493 0.9172 51	1.00000 0.0 53	0.66020 0.0001 52	0.59746 0.0001 52	0.25492 0.0655 53	0.23093 0.0995 52	0.39645 0.0040 51	0.35494 0.0098 52	0.30430 0.0283 52	0.21838 0.1276 50	-0.05620 0.6923 52
Dissolved phosphorus	-0.52617 0.0001 52	-0.29313 0.0664 40	-0.20300 0.1531 51	-0.42644 0.0018 51	0.66020 0.0001 52	1.00000 0.0 52	-0.11923 0.3999 52	0.29613 0.0330 52	0.72200 0.0001 52	0.08305 0.5664 50	-0.15215 0.2865 51	-0.04024 0.7792 51	-0.41565 0.0030 49	0.29068 0.0385 51
Suspended phosphorus	0.22176 0.1141 52	0.42352 0.0065 40	0.33518 0.0162 51	0.37367 0.0069 51	0.59746 0.0001 52	-0.11923 0.3999 52	1.00000 0.0 52	0.02958 0.8351 52	-0.40421 0.0030 52	0.53375 0.0001 50	0.63015 0.0001 51	0.41912 0.0022 51	0.73542 0.0001 49	-0.39691 0.0039 51
Dissolved nitrite plus nitrate	0.16765 0.2302 53	0.39475 0.0106 41	0.33621 0.0159 51	-0.14373 0.3143 51	0.25492 0.0655 53	0.29613 0.0330 52	0.02958 0.8351 52	1.00000 0.0 53	0.41547 0.0022 52	0.05433 0.7049 51	-0.33232 0.0161 52	-0.40019 0.0033 52	-0.06110 0.6734 50	-0.16002 0.2571 52
Dissolved ammonia	-0.48171 0.0003 52	-0.20804 0.1977 40	-0.24219 0.0868 51	-0.57493 0.0001 51	0.23093 0.0995 52	0.72200 0.0001 52	-0.40421 0.0030 52	0.41547 0.0022 52	1.00000 0.0 52	-0.23798 0.0961 50	-0.49036 0.0003 51	-0.43577 0.0014 51	-0.64321 0.0001 49	0.31164 0.0260 51
Chlorophyll *a*	0.17967 0.2071 51	0.14220 0.3878 39	0.27175 0.0589 49	-0.01895 0.8972 49	0.39645 0.0040 51	0.08305 0.5664 50	0.53375 0.0001 50	0.05433 0.7049 51	-0.23798 0.0961 50	1.00000 0.0 51	0.49462 0.0003 50	0.18015 0.2106 50	0.52544 0.0001 48	-0.32582 0.0209 50
Biochemical oxygen demand (BOD)	0.27421 0.0492 52	0.01183 0.9422 40	0.08950 0.5365 50	0.28896 0.0418 50	0.35494 0.0098 52	-0.15215 0.2865 51	0.63015 0.0001 51	-0.33232 0.0161 52	-0.49036 0.0003 51	0.49462 0.0003 50	1.00000 0.0 52	0.62821 0.0001 51	0.70199 0.0001 49	-0.16449 0.2487 51
Chemical oxygen demand (COD)	-0.03166 0.8237 52	-0.20690 0.1943 41	0.14952 0.3000 50	0.43035 0.0018 50	0.30430 0.0283 52	-0.04024 0.7792 51	0.41912 0.0022 51	-0.40019 0.0033 52	-0.43577 0.0014 51	0.18015 0.2106 50	0.62821 0.0001 51	1.00000 0.0 52	0.40843 0.0036 49	0.07649 0.5937 51
Suspended oxygen demand (SOC)	0.48349 0.0004 50	0.43792 0.0053 39	0.45767 0.0011 48	0.50576 0.0002 48	0.21838 0.1276 50	-0.41565 0.0030 49	0.73542 0.0001 49	-0.06110 0.6734 50	-0.64321 0.0001 49	0.52544 0.0001 48	0.70199 0.0001 49	0.40843 0.0036 49	1.00000 0.0 50	-0.43081 0.0018 50
Dissolved oxygen demand (DOC)	-0.42876 0.0015 52	-0.36823 0.0194 40	-0.39423 0.0046 50	-0.26169 0.0664 50	-0.05620 0.6923 52	0.29068 0.0385 51	-0.39691 0.0039 51	-0.16002 0.2571 52	0.31164 0.0260 51	-0.32582 0.0209 50	-0.16449 0.2487 51	0.07649 0.5937 51	-0.43081 0.0018 50	1.00000 0.0 52

Fecal bacteria in water samples are an indicator of the presence of sewage and manure. Fecal bacteria were present in all water samples collected for determination of bacteria during this study (194 samples from 22 sites). Fecal coliform bacteria exceeded 200 colonies/100 ml in 38 percent of the water samples and fecal *Streptococcus* bacteria exceeded 200 colonies/100 ml in 48 percent of the water samples. Fecal coliform bacteria counts exceeded 1000 colonies/100 ml in 16 percent of the water samples. Fecal *Streptococcus* bacteria counts also exceeded 1000 colonies/100 ml in 16 percent of the water samples. These bacteria analyses, while not a quantitative measure of oxygen demand, indicate that a potential for oxygen demand from these sources is present throughout much of the Minnesota River Basin.

Relation of suspended sediment to nutrients and oxygen-demanding substances

Suspended-sediment, nutrient, BOD, organic carbon, and chlorophyll *a* data were evaluated by computing correlation coefficients (tabs. 8-14). A relation between sediment and nutrients might be expected, especially for phosphorus, because a portion of the phosphorus in a stream is sorbed to sediment particles. Correlation coefficients were computed using data from all sites and all seasons to determine the association between suspended sediment and suspended phosphorus (total phosphorus - dissolved phosphorus) (tab. 8). The results showed that these constituents were only weakly correlated (correlation coefficient= 0.17, p=0.0498). A somewhat stronger association (correlation coefficient= 0.43, p= 0.0001) was indicated by the results of correlating suspended phosphorus with suspended-organic carbon. Suspended phosphorus also was associated with volatile suspended solids (correlation coefficient= 0.33, p= 0.0001), but virtually no association (correlation coefficient=0.10, p= 0.2025) was indicated with non-volatile suspended (total suspended solids - volatile suspended solids) solids (tab. 8). Suspended organic carbon and volatile-suspended solids are both measures of the part of the suspended sediment that is comprised of organic matter. The Pearson correlation of suspended phosphorus with suspended-organic carbon (correlation coefficient= 0.46, p= 0.0001) indicates that only 21 percent of the variation in suspended-phosphorus concentrations can be explained by the variation in suspended-organic carbon concentrations (tab. 8).

Suspended sediment was positively correlated with nitrate (correlation coefficient=0.67, p= 0.0001) (tab. 8). A causal association between these constituents is unlikely, because nitrate does not sorb to sediment. The association between the two may exist because both suspended sediment and nitrate are positively correlated with stream discharge.

A positive correlation might be expected between suspended sediment and BOD because some of the material transported in the suspended-sediment load is likely to consist of oxygen-demanding substances. Suspended sediment is a measure of inorganic, as well as organic material. The organic fraction of the sediment, as measured by suspended-organic carbon, was positively correlated with BOD. The inorganic fraction of the sediment (total suspended solids - volatile suspended solids) was negatively correlated with BOD (correlation coefficient= -0.18, p= 0.0235) (tab. 8).

No association between suspended sediment and algal productivity was indicated when data from all sites during all seasons were correlated (tab. 8). When only data from the lower part of the mainstem (sites 17, 25, 26, and 28 during May-September 1989-92) were correlated (tab. 10), algal productivity, as measured by chlorophyll *a* concentrations, was found to be negatively correlated with suspended sediment (correlation coefficient=- 0.52, p= 0.001). Algal productivity was negatively correlated with stream discharge in the lower part of the mainstem (correlation coefficient= -0.72, p=0.0001), while suspended sediment was positively correlated with stream discharge in this reach (correlation coefficient= 0.69, p= 0.0001). Chlorophyll *a* concentrations in the mainstem probably decline during periods of increasing stream discharge because water in the mainstem is diluted by runoff water that contains relatively little chlorophyll *a*. Algal growth, furthermore, may be inhibited during runoff because of a lack of sunlight penetration caused by increased turbidity from elevated suspended-sediment concentrations.

Transport of Sediment, Nutrients, and Oxygen-Demanding Substances

The concentration and form of chemical constituents and compounds from non-point sources can be modified by physical, chemical, and biological processes while they are in transport. These processes can affect the river environment. Examples of these processes include dilution, deposition and resuspension of particulate matter, uptake of nutrients by algae, and decomposition of organic matter.

The transport of non-point source constituents in channels is determined by discharge characteristics of the stream. Stream velocity will determine rate of movement and the residence time of a constituent within a stream reach. The duration of the residence time may determine the extent of transformation the constituent will undergo within a reach, although other factors, such as the amount of micro-organisms present and their activity levels, also have a bearing on the fate of the constituent. The form of the constituent, whether particulate or soluble, is an important determinant of the fate of the constituent and the type of processing and degree of transformation that the constituent will undergo. Stream velocity is variable along stream reaches because of variable channel morphology, primarily changes in width, depth, and slope.

Transport of Particulates

Transport of particulate matter in streams is affected by the quantity of material placed in transport, the size of the particles, and stream velocity. Particles are supported in suspension by vertical components of current in turbulent flow and the magnitude of these currents is largely a function of the horizontal (stream) velocity, bed roughness, and the distance above the streambed (Guy, 1970). Coarse-grained particles require greater turbulence to remain suspended than do fine-grained particles. Particles are commonly grouped into three general categories on the basis of their diameter. These are (1) sand (0.062-2.0 mm, (2) silt (0.004-0.062 mm), and (3) clay (< 0.004 mm). Particles that are smaller than 0.062 mm are commonly collectively referred to as "fines". Fine sediment particles are easily carried in suspension by fluid forces in natural streams and hence have a tendency to move out of the drainage basin with the water in which they are suspended (Guy, 1970). This characteristic of fines is relevant to transport of particulates in the Minnesota River Basin because much of the suspended sediment in the Minnesota River and its tributaries is made up of fine particles.

Particle size of suspended sediment was determined for 42 water samples. The proportion of fines in these samples ranged from 34 to 100 percent, with a median value of 86 percent. Additional particle-size analyses were performed on 13 of the samples to determine the percentage of material in the medium- and fine-clay fraction (<0.002 mm). The proportion of clay-sized material in these samples ranged from 22 to 51 percent with a median value of 35 percent.

The presence of a high proportion of fines in the suspended material suggests that a substantial part of the sediment loads originating throughout the basin will eventually be transported to the mouth of the Minnesota River. Some of the suspended sediment, however, is deposited within the mainstem channel. Sampling sites were visited repetitively during this study, some on a weekly basis. Visual appraisals of sediment deposition were made in the vicinity of the sampling sites. A general sense of the depositional patterns was determined by these visits. Newly-deposited sediment was frequently observed following the recession of runoff. These deposits ranged in thickness from 6 to 12 inches and were located along the streambanks, extending downward from the high-water mark of the most recent event to the waters edge and continuing to a point about 3 to 5 feet into the stream. In subsequent visits to these sites, these deposits would sometimes be found to be diminished in depth and extent or even missing. This was observed when moderate rises in stage had occurred between sampling visits and the deposits had been inundated. This process was most noticeable at site 3 near Montevideo, where rises in stage subsequent to the depositional periods were caused by release of relatively sediment-free water from Lac qui Parle Reservoir. These releases, unlike the sediment-laden runoff flows that preceded them, deposited no sediment during their recession. This suggests that sediment deposited along the streambanks during recessions of runoff can be resuspended during subsequent runoff periods.

The smallest tributaries, termed first-order streams, originate in the most upstream portions of small watersheds. The first-order streams derive their flow primarily from seepage from shallow ground water. First-order streams also collect overland surface runoff during heavy rains and snowmelt. The larger tributaries receive this flow from the small tributaries and also receive ground-water discharge from the larger, deeper regional aquifers. The time required to move water through the smallest tributaries is often brief, usually less than one day, allowing little time for processing to take place. The small tributaries, therefore, can be thought of as conduits that carry non-point constituents to larger tributaries and the mainstem of the Minnesota River where the bulk of the processing takes place. This is especially true during high runoff when velocities are higher. At low flow some processing can be expected even in small streams, particularly with regard to nutrient uptake, which can be very rapid if algae are present in sufficient numbers and other conditions such as sunlight and temperature are optimum for algal growth.

Settling of particulate matter can also occur and will be dependent on stream velocity. Stream velocity is primarily determined by stream slope. Slope is highly variable within first-order streams in the basin, ranging from values of about 2-8 ft/mi in the till plains to 15-30 ft/mi in the Coteau des Prairies (fig. 5). Data collection was focused primarily at the mouths of the major tributaries and on the Minnesota River mainstem with only limited data collection in the small streams.

Data collected during runoff periods in the Blue Earth River indicated that most of the suspended sediment delivered to the Blue Earth River by the Watonwan and Le Sueur Rivers remained in transport and was delivered to the Minnesota River at the mouth of the Blue Earth. Data from these runoff periods also indicated that some of the sediment (less than 10 percent) was lost from transport during the recessional stages. Deposits of fine sediment were observed along banks at tributary sites following the recession of runoff. Much of the deposited fine-particle sediment is resuspended during subsequent rises in river stage, resulting in only temporary storage of these sediments within the tributary channels. Most of the fine-particle sediment placed into the major tributaries, therefore, will eventually be carried to the Minnesota River. Portions of some of the major tributaries, however, contain low-gradient reaches or small dams where low stream velocities may lead to deposition and longer-term storage of sediment.

Most of the changes in concentration and loads of non-point-source constituents in the mainstem can be attributed to loading from the tributaries. Concentrations and loads within the mainstem can, however, also be modified by variations in stream morphology along the course of the mainstem. Changes in stream velocity related to changes in slope, width, and depth may affect commonly-occurring stream processes. Some examples include accelerated stream bank and bed erosion in high velocity reaches, increased deposition of fine-grained sediments in low-velocity reaches, and a potential for release of solutes from accumulated sediment in depositional areas.

The slope of the mainstem channel between Lac qui Parle (site 1) and Henderson (site 28) averages about 0.9 ft/mi. Variation in river slope is shown by the water-surface elevation graph in figure 26. Much of the river, from Courtland (site 16) to Henderson (site 28), has a generally uniform slope that conforms to the average for the entire study reach. In the reach between Granite Falls and Courtland, however, there are three distinct departures from the average slope. Downstream of Granite Falls between sites 6 and 7, there is a 15-mile reach where the slope steepens to about 2.0 ft/mi, including a five-mile subreach where the slope is about 3.5 ft/mi. Channel slope flattens appreciably to about 0.3 ft/mi within a 45-mile reach that begins 10 miles upstream from site 13 near Fairfax and extends to the confluence of the Minnesota River with the Cottonwood River near New Ulm (site 15). Immediately downstream from the confluence with the Cottonwood River, slope steepens once again to about 1.7 ft/mi along a seven-mile reach that extends to Courtland where the river resumes its average slope of about 0.9 ft/mi.

These changes in slope are accompanied by changes in average stream velocity. Lower stream velocities were especially noticeable during low flow at site 14 in the gently sloping reach upstream from New Ulm. Average stream velocity at this site during the winter 1990 sampling, for example, was only 0.16 ft/s as compared to velocities that exceeded 1.0 ft/s at sites that were located in adjacent reaches. The losses of sediment load in this reach during some of the samplings may be a result of the decrease in stream velocity.

Evidence for release of dissolved phosphorus from sediments in this reach is seen in the data from the August 1989 sampling. The concentration of dissolved orthophosphorus increased from 0.02 mg/L to 0.24 mg/L, and the load of dissolved orthophosphorus increased about 0.005 to 0.05 tons/d (fig. 27) between sites 13 and 14. The phosphorus added in this reach, however, could have come from sources other than channel sediments.

Transport of Solutes

Dissolved constituents (solutes), unlike particulate matter, are not subject to processes of settling, deposition, and resuspension. Constituents are termed conservative if they are transported in a river system without chemical change or loss of mass. Many solutes, however, are subject to chemical transformation as well as uptake and release by biological organisms. In this study, it was important to determine the fate of dissolved forms of nitrogen, phosphorus, and organic carbon once they were placed in transport. Nitrate in high concentrations for example, if transported conservatively, could pose a threat to water users throughout the river system. Conversely, nitrate transported nonconservatively could arrive downstream in the form of relatively harmless

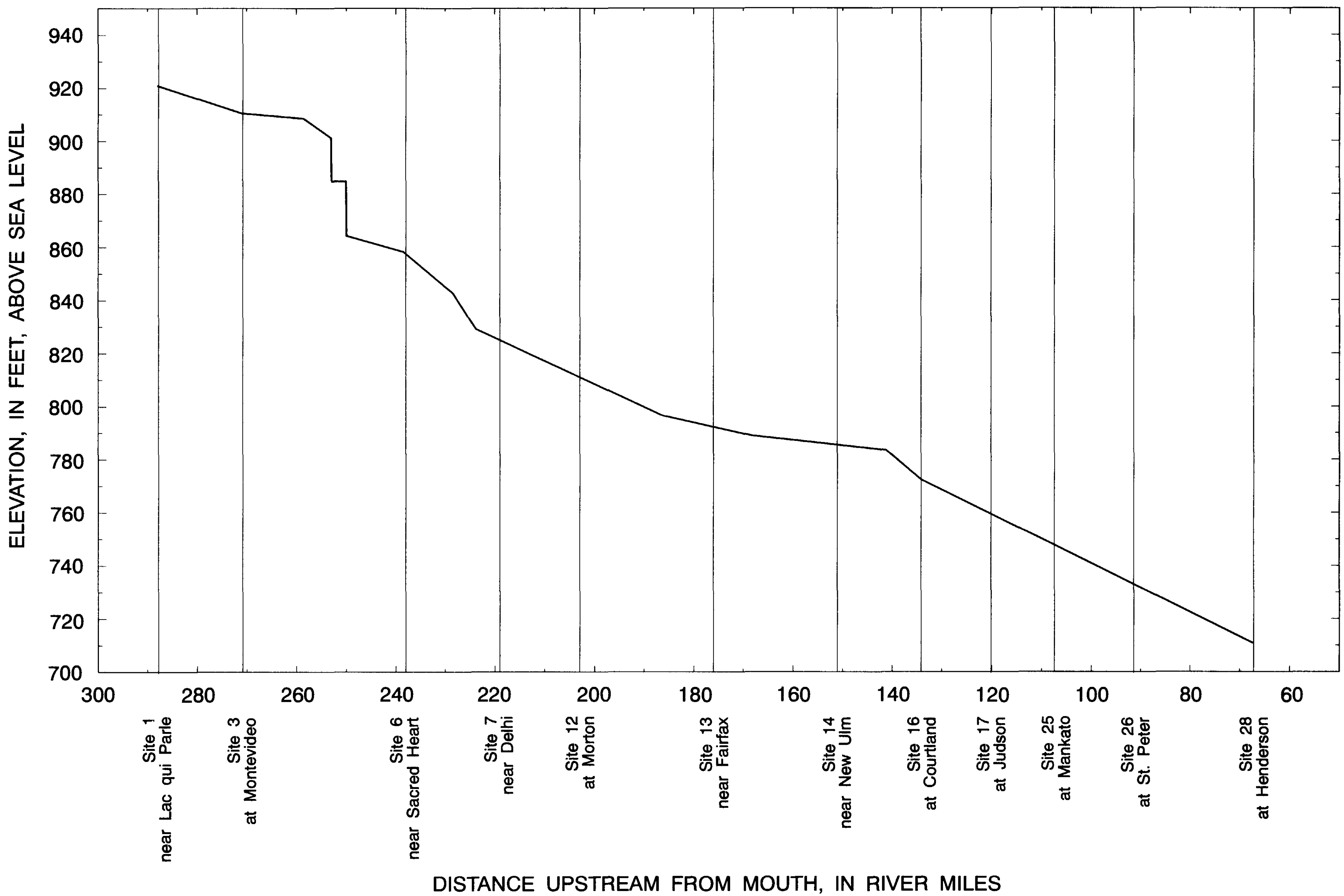


Figure 26.--Water-surface elevation, by river mile, for Minnesota River water-quality sampling sites, August 1989-August 1991.

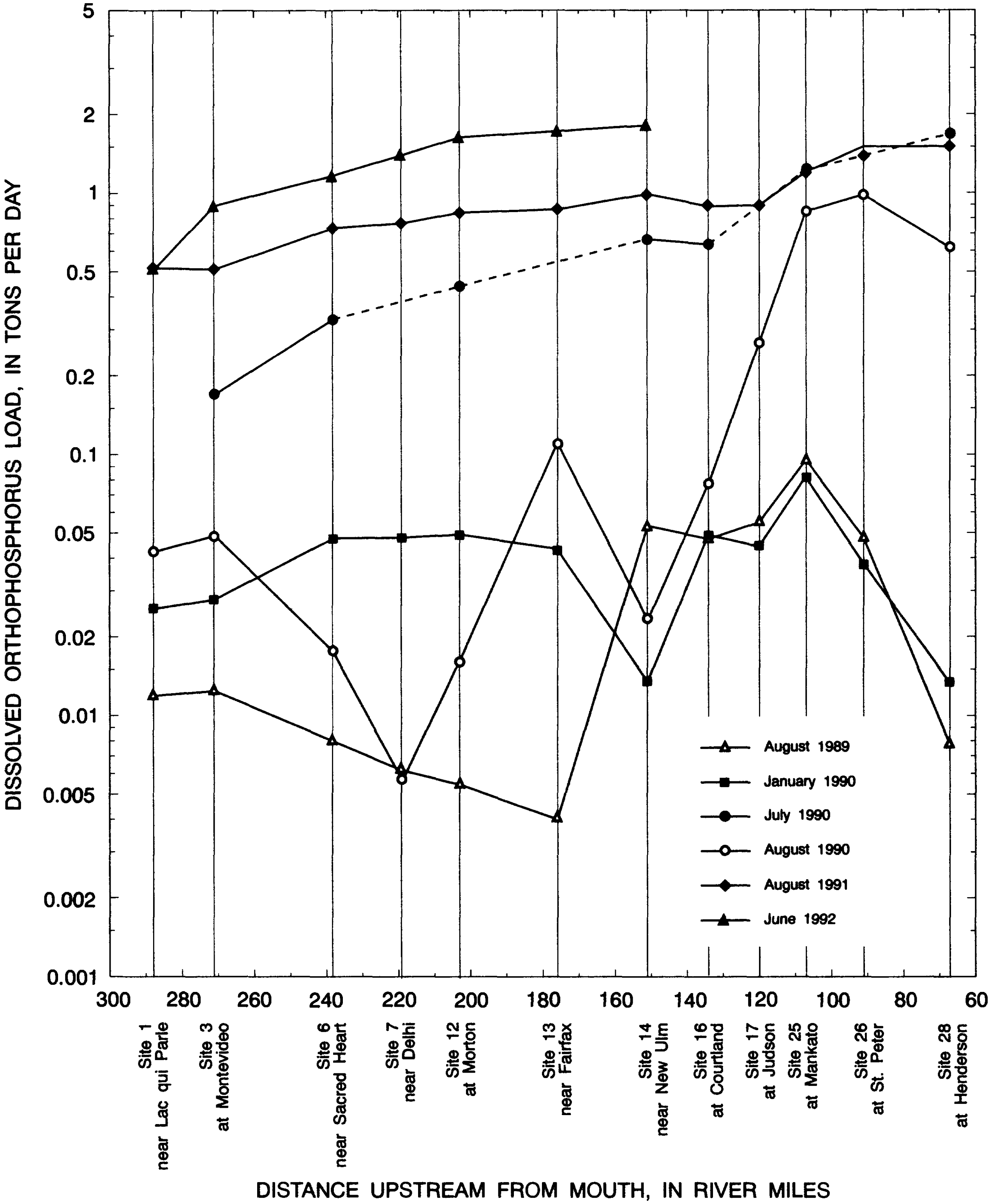


Figure 27.--Dissolved orthophosphorus loads at the time of sampling, by river mile, for Minnesota River water-quality sampling sites, August 1989-June 1992.

organic nitrogen after being converted by microorganisms. Data for dissolved forms of three non-point source constituents, nitrate, orthophosphorus, and organic carbon, were evaluated. The data were selected from the synoptic samplings conducted within the mainstem. Loads were computed for each site and changes in load were calculated for portions of the mainstem (subreaches) located between sites. Losses in load were considered to be an indication of nonconservative transport brought about by chemical or biological processing.

Dissolved-organic carbon appeared to be the most conservative of the three constituents evaluated. Data for five synoptic samplings are shown in figure 28. Some subreaches showed load losses that ranged from 0.4 to 14 percent, but overall it appears that there is little net loss of dissolved organic matter within the mainstem. The organic carbon may have undergone chemical or biological transformation during transport, but this could not be determined because the analytical method does not differentiate between the various forms of organic carbon in the Minnesota River. The indicated losses of load may have arisen from the variability associated with detecting differences in stream discharge over short stream segments combined with sampling and analytical variability. Only two losses exceeding 10 percent were indicated, both during January 1990, when accurate measurement of stream discharge was complicated by ice cover.

The effects of the input of, as well as the uptake and utilization of, orthophosphorus are evident in the shape of the graphs shown in figure 27. These processes are most evident in the graphs for samplings during August 1989 and January 1990, when the river was at low flow. Net gains or losses were calculated for mainstem subreach segments. Inputs from the major tributaries were measured during the August 1989, January 1990, and August 1990 samplings and these values were included in the calculations. Taking into account the inputs from the major tributaries, the calculations indicated a net loss of orthophosphorus over the course of the mainstem between Lac qui Parle (site 1) and Henderson (site 28) during the August 1989 and January 1990 samplings. These results suggest that mainstem instream processes, presumably algal uptake, were sufficient to utilize all orthophosphorus inputs. High rates of algal productivity are indicated by high chlorophyll *a* concentrations that exceeded 50 μg/L in some reaches during both August 1989 and January 1990. High rates of orthophosphorus utilization were also indicated by the results from August 1990, but interpretation of these data is complicated by runoff that occurred in watersheds downstream of site 7 near Delhi, Minnesota while sampling was in progress.

At high flows, as shown by data for July 1990, August 1991, and June 1992 (fig. 27), four instances of load loss were indicated in individual subreaches, but the losses were small (<10 percent), and may be within the error of measurement associated with load determinations. The calculations for these periods indicate a net gain in orthophosphorus within the course of the mainstem between Lac qui Parle (site 1) and Henderson (site 28). These results suggest that inputs of orthophosphorus during these periods were in excess of the amounts that could be utilized by stream processes. This excess of unutilized orthophosphorus resulted in concentrations of orthophosphorus that ranged from 0.04 to 0.15 mg/L throughout the reach from Lac qui Parle (site 1) to Henderson (site 28) and orthophosphorus loads at Henderson (site 28) that ranged from 1.0 to 1.5 tons/d.

Gains in nitrate load were found in all subreaches sampled at elevated flows (July 1990, August 1991, and June 1992, fig. 29). Nitrate loading rates were high during these samplings, as indicated by load gains of 100 to 400 percent in some subreaches. The amount of nitrate added in each subreach exceeded the amount taken up by algae and therefore any losses due to algal uptake could not be detected. Nitrate concentrations also increased in each successive subreach resulting in a gradual rise in nitrate concentration in a downstream direction.

When stream discharge was not elevated, as shown by the data for August 1989 and January 1990 in figure 29, losses as well as gains in nitrate load were indicated. Three of the indicated losses can be considered significant in that the loads were reduced 37 to 45 percent within individual subreaches. Reductions in nitrate concentrations accompanied the load losses. These data suggest that rates of nitrate utilization by algae were sufficiently high in some subreaches so as to reduce the amount of nitrate in transport. The amount of nitrate reaching the mainstem during these samplings was much lower than at other times during this study, however, because of low stream discharges that resulted from widespread drought and because of low nitrate concentrations (<0.1 to 1.9 mg/L) in the major tributaries.

The results of the synoptic samplings indicate that under normal- and high-flow conditions, such as those sampled during the mid and latter part of this study, the amount of nitrate placed in transport in the Minnesota River greatly exceeds the amount utilized by the

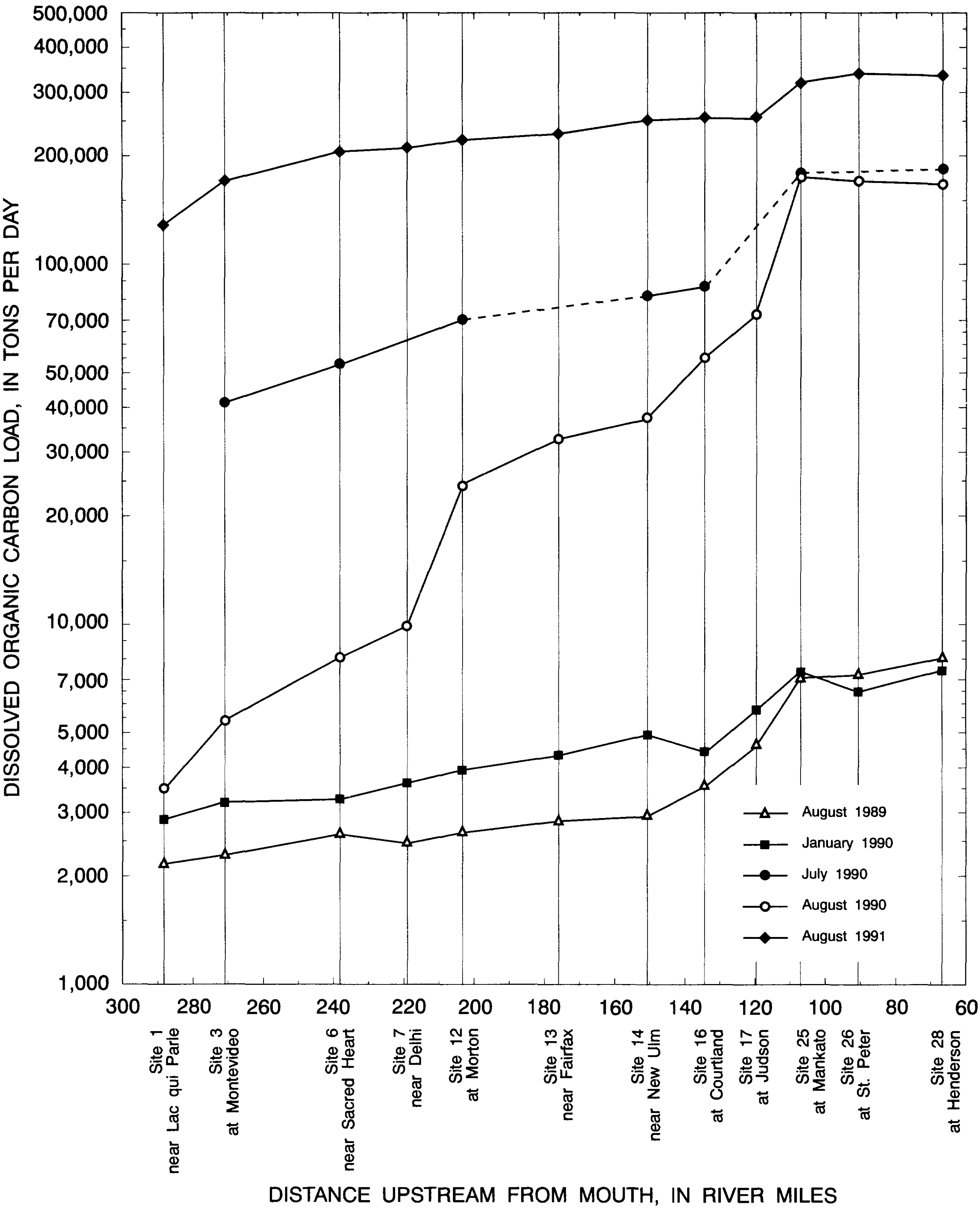


Figure 28.--Dissolved organic carbon load at time of sampling, by river mile, for Minnesota River water-quality sampling sites, August 1989-August 1991.

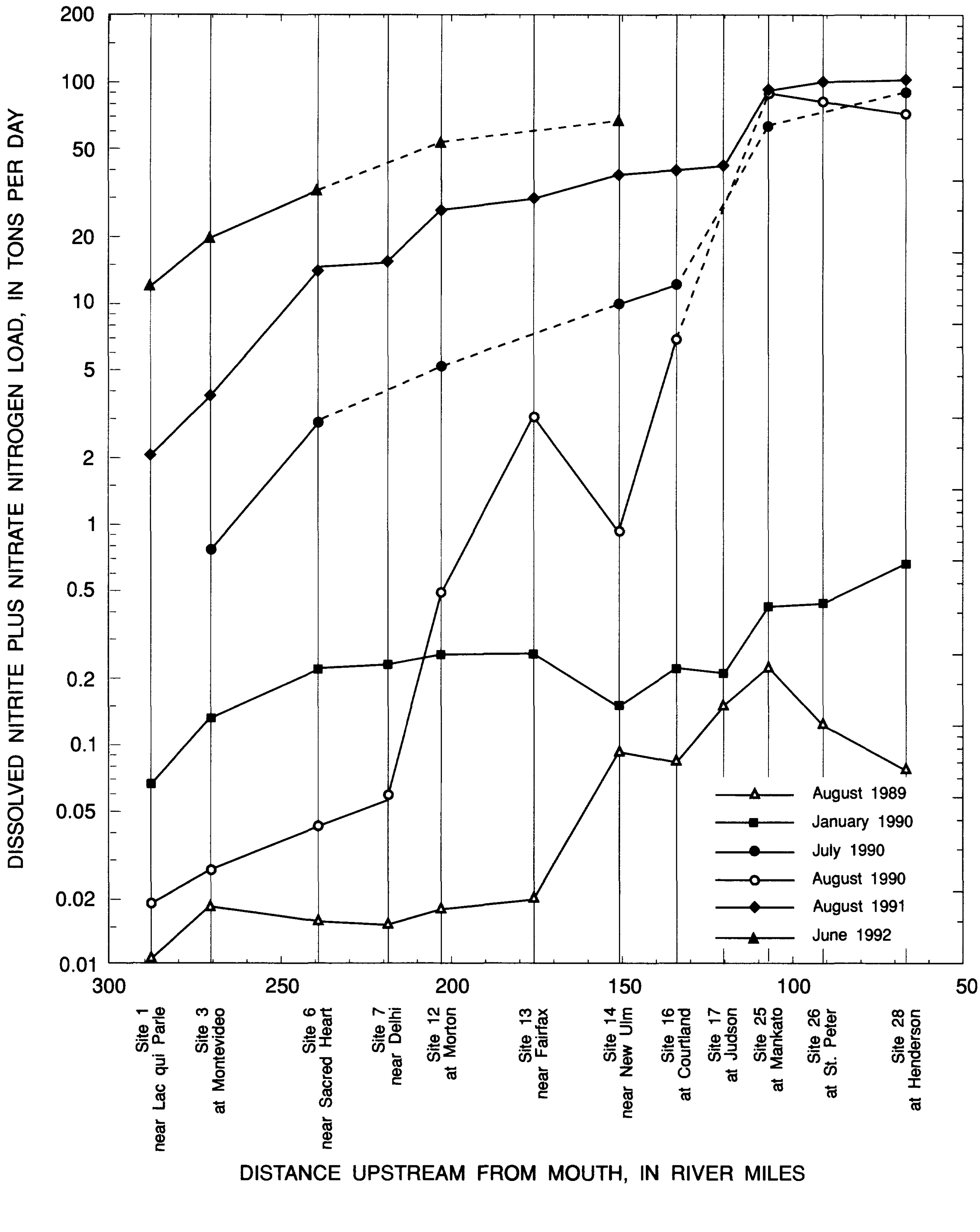


Figure 29.--Dissolved nitrite plus nitrate nitrogen load at time of sampling, by river mile, for Minnesota River water-quality sampling sites, August 1989-June 1992.

mainstem's biological systems. This results in the transport of virtually all nitrate inputs to downstream locations with modification of nitrate concentrations limited to the effects of dilution and longitudinal dispersion.

Summary

Water quality in the Minnesota River is affected by non-point source constituents, such as suspended sediment, nutrients, oxygen-demanding substances, and bacteria. Tributary watersheds are the source of most of these constituents, but oxygen demand often arises from biochemical processing of instream-generated organic matter produced when algal productivity is elevated.

Sediment concentrations and loads were elevated in all major tributaries during runoff, affecting water quality in the Minnesota River. Most of the annual sediment load in the lower reaches of the Minnesota River is delivered from tributary basins that have the highest annual rainfall and runoff. These basins are located in the eastern part of the Minnesota River Basin.

The Minnesota River is enriched with particulate, as well as soluble, forms of phosphorus throughout its reach from Lac qui Parle to Henderson. The bulk of this phosphorus is carried to the mainstem in tributary flow during runoff, but elevated loading of soluble phosphorus also was found during nonrunoff, particularly within low-velocity reaches. The source of this soluble phosphorus was not determined, but release from channel sediments is a possible explanation.

Watersheds located in the south-central and eastern part of the basin, particularly those watersheds that are tributary to the Blue Earth River, are the primary source of nitrate loading to the Minnesota River. The Blue Earth River delivered 69 percent of the total nitrate load in transport in the Minnesota River at Mankato during April through July 1991. Nitrate concentrations exceeded 10 mg/L in the Blue Earth River and its major tributaries and also in major tributaries in the Lower Minnesota River Basin.

A response to elevated nutrient loading was evidenced by high levels of algal productivity throughout the mainstem, especially during summer months.

BOD was most elevated during summer during nonrunoff conditions. Statistically-significant correlations were found between BOD and levels of algal productivity. The increase in BOD with increases in algal productivity suggest that part of the oxygen-demanding material may be from instream production of algae. BOD also was elevated during snowmelt, when algal productivity was low relative to summer periods. During snowmelt, BOD was most strongly correlated with suspended organic carbon.

About 86 percent of the particulate matter in transport is silt- and clay-sized material. Most of this fine-grained material is suspended and transported to downstream portions of the Minnesota River. Some of the particulate matter is deposited along the edges of channels during the recessions of runoff, but visual observations and the results of sampling suggest that this material is resuspended and transported during subsequent runoff.

During low-flow, utilization of nutrients by algae reduced concentrations and loads of nitrate and orthophosphorus in the Minnesota River. At normal and high flow loading rates for these constituents exceeded rates of utilization, resulting in increasing loads downstream in the Minnesota River mainstem.

Sampling on the mainstem during nonrunoff indicated that measurable amounts of sediment were placed in transport by bank and bed erosion. Incremental gains of suspended sediment from bank and bed erosion measured in selected subreaches ranged from 0.4 to 39 tons/d/mi. Some of this sediment was lost from transport, especially in lower-velocity reaches. The sediment placed in transport by the bank- and bed-erosion process was not sufficient to elevate suspended-sediment concentrations to high levels. Suspended-sediment concentrations were below 200 mg/L at the sampling sites and were lower than concentrations typically observed when tributaries deliver sediment to the mainstem during runoff. Results of limited study of bank and bed erosion in the Redwood River indicated that bank and bed erosion produced loads of 42-526 tons/d/mi for short periods during runoff.

References Cited

Adolphson, D.G., Ruhl, J.F., and Wolf, R.J., 1981, Designation of principal water supply aquifers in Minnesota: U.S. Geological Survey Open-File Report 81-51, 19 p.

Anderson, H.W., Jr., Farrell, D.F., Broussard, W.L., 1974a, Water resources of the Blue Earth River Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-525, scale 1:250,000, 3 plates.

_____ 1974b, Water resources of the Lower Minnesota River Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-526, scale 1:250,000, 3 plates.

Anderson, J.P., and Craig, W.J., 1984, Growing energy crops in Minnesota's wetlands—The land use perspective: Minneapolis, University of Minnesota Center for Urban and Regional Affairs, 95 p.

Britton, L.J., and Greeson, P.E., eds., 1989, Methods for collection and analysis of aquatic biological and microbiological samples: Techniques of Water Resources Investigations of the U.S. Geological Survey, Book 5, Chapter A4, 363 p.

Buchanan, T.J., and Somers; W.P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water Resources Investigations, Book 3, Chapter A8, 65 p.

Broussard, W.L., Anderson, H.W., Jr., and Farrell, D.F., 1973, Water resources of the Cottonwood River Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-466, scale 1:250,000, 3 plates.

Edwards, T.K., and Glysson, G.D., 1988, U.S. Geological Survey Open-File Report 86-531, 118 p., 13 p., *in* Field measurement of fluvial sediment: Techniques of Water Resources Investigations of the U.S. Geological Survey, Book 3, Chapter C2, 13 p. (in press).

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water Resources Investigations, Book 5, Chapter A1, 545 p.

Gunard, K.T., Hess, J.H., Zirbel, J.L., and Cornelius, C.E., 1990, Water Resources Data Minnesota Water Year 1989—Volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey, 335 p.

_____1991, Water Resources Data Minnesota Water Year 1990—Volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey, 351 p.

_____1992, Water Resources Data Minnesota Water Year 1991—Volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey, 271 p.

_____in press, Water Resources Data Minnesota Water Year 1992—Volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey.

Guy, H.P., 1969 Laboratory theory and methods for sediment analysis: U.S. Geological Survey Water Resources Techniques of Water Resources Investigations, Book 5, Chapter C1, 58 p.

_____1970, Fluvial sediment concepts: U.S. Geological Survey Techniques of Water Resources Investigations, Book 3, Chapter C1, 55 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Science Publishers, 522 p.

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Leach, James, and Magner, J.A., 1992, Wetland drainage impacts within the Minnesota River Basin: Currents 2, p. 3-10.

Magner, J.A., and Alexander, S.C., 1993, The Minnesota River Basin: A hydrogeologic overview, Minnesota Pollution Control Agency, 21 p.

Magner, J.A., Johnson, G.D., Larson, T.J., 1993, The Minnesota River Basin: Environmental impacts of basin-wide drainage, *in* Eckstein and Zaporozec eds., Industrial and agricultural impacts of the hydrologic environment, v. 5, p. 147-162.

Minnesota Department of Natural Resources, Division of Waters, State Climatology Office, 1993, Normal annual precipitation map: Minnesota Department of Natural Resources, March, 1 p.

Minnesota Pollution Control Agency, 1982, Minnesota River subbasin water quality, an assessment of non-point source pollution, St. Paul, Minnesota, 161 p.

_____1985, Lower Minnesota River wasteload allocation study, St. Paul, Minnesota, 190 p.

_____1990, Standards for the protection of the quality and purity of the waters of the state, St. Paul, Minnesota, Chapter 7050, 91 p.

Novitzki, R.P., Van Voast, W.A., and Jerabek, L.A., 1969, Water resources of the Yellow Medicine River Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-320, scale 1:250,000, 3 plates.

Quade, H.W., Boyum, K.W., Braaten, D.O., Gordon, Donald, Pierce, C.L., Silis, A.Z., Smith, D.R., and Thompson, B.C., 1980, The nature and effects of county drainage ditches in South Central Minnesota: Water Resources Research Center, University of Minnesota, Bulletin 105, 121 p.

Randall, G.W., Buzicky, G.C., and Nelson, W.W., 1986, Nitrate losses to the environment as affected by nitrogen management, *in* Proceedings of the Agricultural impacts on ground water—a conference, National Water Well Association, Dublin, Ohio, p. 561-573.

Southern Minnesota River Basin Commission, 1977, Minnesota River Basin Report: Southern Minnesota River Basin Commission, 120 p.

Strahler, A.N., 1950, Equilibrium theory of erosional slopes approached by frequency distribution analysis: American Journal of Science, v. 248, p. 673-696

Tornes, L.H., 1986, Suspended sediment in Minnesota streams: U.S. Geological Survey Water-Resources Investigations Report 85-4312, 33 p.

U.S. Geological Survey, 1976, Hydrologic Unit Map - 1974, State of Minnesota: U.S. Geological Survey Hydrologic Unit Map—1974, 1 pl.

_____1986, National Water Summary—Minnesota Surface-Water Resources: U.S. Geological Survey Water Supply Paper 2300, p. 285-295.

_____1992, National Water Conditions—Streamflow data during July: U.S. Geological Survey, 31 p.

Van Voast, W.A., Jerabek, L.A., Novitzki, R.P., 1970, Water resources of the Redwood River Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-345, scale 1:250,000, 3 plates.

Van Voast, W.A., Broussard, W.L., and Wheat, D.E., 1972, Water resources of the Hawk Creek Watershed: U.S. Geological Survey Hydrologic Investigations Atlas HA-391, scale 1:250,000, 3 plates.

Ward, J.R., and Harr, C.A., 1990, Methods for collection and processing of surface water and bed material samples for physical and chemical analysis: U.S. Geological Survey Open-File Report 90-140, 71 p.

Wershaw, R.L., Fishman, M.J., Grabbe, R.R., and Lowe, L.E., 1983, Methods for the determination of organic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 82-1004, 173 p.

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