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Suspended-Sediment Budget, Flow Distribution, and Lake Circulation for the Fox Chain of Lakes in Lake and McHenry Counties, Illinois, 1997–99

Water-Resources Investigations Report 00–4115

U.S. DEPARTMENT OF THE INTERIOR
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By David L. Schrader and Robert R. Holmes, Jr.

Water-Resources Investigations Report 00–4115

De Kalb, Illinois
2000

U.S. DEPARTMENT OF THE INTERIOR
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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per acre-foot (acre-ft/acre-ft)	1	cubic meter per cubic meter
	Velocity	
mile per hour (mi/h)	1.609	kilometer per hour
foot per year (ft/yr)	0.3048	meter per year
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per year [(ft^3/s)/yr]	0.02832	cubic meter per second per year
	Mass	
ton, short (2,000 lb)	0.9072	megagram
ton per day (ton/d)	0.9072	megagram per day
ton per year (ton/yr)	0.9072	megagram per year
ton per square mile per year [(ton/mi^2)/yr]	0.3503	metric ton per square kilometer per year
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter

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

Abbreviated water-quality units: Suspended-sediment concentrations are given in milligrams per liter (mg/L).

Suspended-Sediment Budget, Flow Distribution, and Lake Circulation for the Fox Chain of Lakes in Lake and McHenry Counties, Illinois, 1997–99

By David L. Schrader *and* Robert R. Holmes, Jr.

Abstract

The Fox Chain of Lakes is a glacial lake system in McHenry and Lake Counties in northern Illinois and southern Wisconsin. Sedimentation and nutrient overloading have occurred in the lake system since the first dam was built (1907) in McHenry to raise water levels in the lake system. Using data collected from December 1, 1997, to June 1, 1999, suspended-sediment budgets were constructed for the most upstream lake in the system, Grass Lake, and for the lakes downstream from Grass Lake. A total of 64,900 tons of suspended sediment entered Grass Lake during the study, whereas a total of 70,600 tons of suspended sediment exited the lake, indicating a net scour of 5,700 tons of sediment. A total of 44,100 tons of suspended sediment was measured exiting the Fox Chain of Lakes at Johnsburg, whereas 85,600 tons entered the system downstream from Grass Lake. These suspended-sediment loads indicate a net deposition of 41,500 tons downstream from Grass Lake, which represents a trapping efficiency of 48.5 percent. A large amount of recreational boating takes place on the Fox Chain of Lakes during summer months, and suspended-sediment load was observed to rise from 110 tons per day to 339 tons per day during the 1999 Memorial Day weekend (May 26 –31, 1999). Presumably, this rise was the result of the boating traffic because no other hydrologic event is known to have occurred that might have caused the rise. This study covers a relatively short period and may not represent the long-term processes of the Fox Chain of Lakes system, although the sediment transport was probably higher than an average year.

The bed sediments found on the bottom of the lakes are composed of mainly fine particles in the silt-clay range. The Grass Lake sediments were characterized as black peat with an organic content of between 9 and 18 percent, and the median particle size ranged from 0.000811 to 0.0013976 inches. Other bed material samples were collected at streamflow-gaging stations on the tributaries to the Fox Chain of Lakes. With the exception of Grass Lake Outlet at Lotus Woods, most of the bed sediments are sand size or larger. The bed material at the streamflow-gaging station at Grass Lake Outlet at Lotus Woods contains 31.5 percent silt- and clay-sized particles. The bed material at Nippersink Creek near Spring Grove also has higher silt content (10.7 percent) than the bed material found in the Fox River at Wilmot (2.1 percent) and Johnsburg (1.3 percent). Additionally, water velocities at 80 cross sections in the Fox Chain of Lakes were collected to provide sample circulation patterns during two separate 1-week periods, and discharge was measured at 18 locations in the lakes. These data were collected to be available for use in hydrodynamic models.

INTRODUCTION

The Fox Chain of Lakes is a glacial lake system in McHenry and Lake Counties in northern Illinois and southern Wisconsin. Catherine, Channel, Fox, Grass, Marie, Nippersink, and Pistakee Lakes compose the lake system (fig. 1). Other minor lakes connected to the Fox Chain of Lakes include Bluff, Lily, Long, Petite,

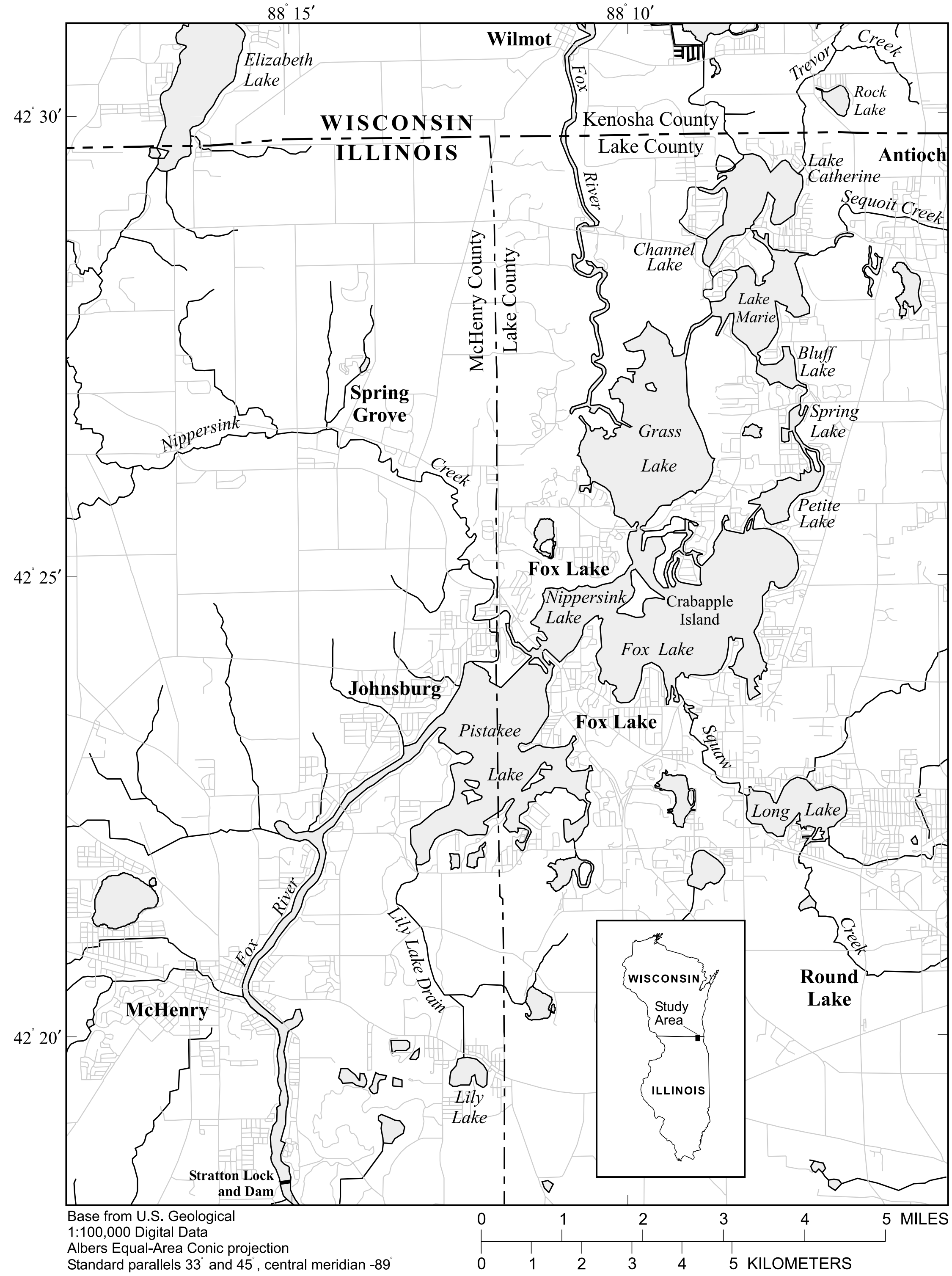

Figure 1. Location of Fox Chain of Lakes study area in northern Illinois and southern Wisconsin.

and Spring Lakes. Sedimentation and nutrient overloading have occurred in the lake system since the first dam was built in McHenry, Illinois in 1907 (Kothandaraman and others, 1977). The sediment catch for the lake system is considered to be Grass Lake, and its capacity for sediment storage may have been reached (Kothandaraman and others, 1977); consequently, sedimentation may have increased downstream in Fox Lake. In 1975–76, the U.S. Geological Survey (USGS) conducted a study of the sediment inflow to the Fox Chain of Lakes (Brabets, 1977). During the mid-1970's, the Illinois State Water Survey and the Illinois State Geological Survey completed a study of the Fox Chain of Lakes that included a description of the geology, sediment geochemistry and hydrology, and some rudimentary measurements of the circulation patterns in the lakes (Kothandaraman and others, 1977). In 1975–77 and 1997, extensive lake surveys were done to provide recommendations for lake management (Metcalf & Eddy, Inc., 1980; Smith Engineering Consultants, Inc., written commun., 1997).

From December 1997 to June 1999, the USGS, in cooperation with the Illinois Department of Natural Resources and the Fox Waterway Agency, conducted a study of the sedimentation problems in the Fox Chain of Lakes to investigate specifically the sediment-trapping capability of Grass Lake and to collect hydrodynamic data as a precursor to future studies. This report presents the results of this study.

Purpose and Scope

This report presents the suspended-sediment budget and flow distribution for the Fox Chain of Lakes, Ill., including the estimated amount of sediment trapped in Grass Lake and the lakes downstream from Grass Lake, during the study period. Circulation patterns in the Fox Chain of Lakes were determined for April 20–22, 1998, and July 27–31, 1998, and are presented in this report. Suspended-sediment samples were collected at the four streamflow-gaging stations that were installed and operated as part of this study. Instantaneous discharges were measured at 18 other locations, and water velocities were measured at many locations in the Fox Chain of Lakes. Bed-material samples were collected at seven locations.

Description of Study Area

The study area encompasses about 150 mi^2, from McHenry, Ill., in the south to Wilmot, Wis., in the north and from Spring Grove, Ill., in the west to Round Lake, Ill., in the east (fig. 1). Physiographically, the study area is in the Great Lakes section of the Central Lowlands Province and lies along the Valparaiso Moraine System (Fenneman, 1938). Shale and limestone are the predominant rocks underlying this area. The Fox Chain of Lakes has a surface area of more than 6,000 acres, with the larger lakes being Grass (1,760 acres), Fox (1,830 acres), and Pistakee (1,960 acres) (Brabets, 1977). The larger lakes tend to be shallow, about 5 ft deep, although Fox and Pistakee Lakes have sections greater than 20 ft deep. The smaller lakes (Bluff, Catherine, Channel, Marie, and Petite) generally are deeper than the larger lakes, with depths of more than 15 ft common and some sections greater than 30 ft deep. The lakes freeze over in winter, with ice often more than 1 ft thick (Metcalf & Eddy, Inc., 1980).

The Fox Chain of Lakes was formed by primarily the melting of large ice blocks during the retreat of the Wisconsinan stage glaciers. Assuming two minor sub-lobes of the glacier met along what is now the Lake-McHenry County line just west of the Chain of Lakes, a prominent escarpment was formed that separates the coarse-grained surficial till, sand, and gravel materials of McHenry County from the clayey till, silts, clays, and peats of the lake's basins and regions to the east in Lake County. The eastern sub-lobe melted, leaving a hummocky kame-and-kettle topography around the lakes (Kothandaraman and others, 1977).

The Stratton Dam in McHenry (constructed in 1907) controls the water levels in the lakes and creates backwater along the Fox River and the Chain of Lakes upstream to Wilmot. In November of each year, the gate settings at the dam are changed to lower the water levels by 1.5–2 ft, which creates additional storage to control spring flooding. The Fox Chain of Lakes is used extensively for recreational boating, with 27,000 boat usage stickers sold (I.R. Enriquez, Fox Waterway Agency, oral commun., 1999) and 23,000 boat lockages (F. Novak, Illinois Department of Natural Resources, oral commun., 1999) at the Stratton Dam in 1998.

The two main tributaries of the Fox Chain of Lakes are the Fox River, with a drainage area of 868 mi^2 at Wilmot, and Nippersink Creek, with a drainage area of 205 mi^2 at its mouth (Healy, 1979). The drainage basins generally are rural farmland with some urban areas. The soil associations in the study area are as follows (Paschke and Alexander, 1970; Ray and Wascher, 1965): Marsh-Fox-Boyer soil is found west of Channel, Fox, and Marie Lakes surrounding Grass, Nippersink, and Pistakee Lakes. This soil is moderately well drained, moderately deep, with rapid to moderate permeability, level to rolling topography, and generally results in a marshy landscape. This soil overlays sand and gravel. Nappane-Montgomery soil is found east of Catherine and Channel Lakes, southwest of Lake Marie, between Catherine and Channel Lakes and Lake Marie, west of Bluff and Spring Lakes, and northwest of Petite Lake. This soil is poorly drained, deep, poorly permeable, and has level to depressional topography. Morley-Morkham-Haughton soil is found east of Bluff, Fox, Petite, and Spring Lakes. The characteristics of this soil vary from moderately well drained, deep, and with moderately low permeability to very dark colored, very poorly drained, and organically rich. This soil is found in areas ranging from steep to depressional topography. Zurich-Grays-Wauconda soil is found south of Fox Lake. This soil is well drained to poorly drained, deep, with moderate permeability, and level to moderately steep topography.

Acknowledgments

The authors thank Frank Novak, Lockmaster at Stratton Lock and Dam in McHenry, Ill., and his staff for their assistance in installing station equipment and providing wind and survey data.

DATA COLLECTION AND METHODOLOGY

Water levels (also called stages or gage heights) were measured and water samples were collected and analyzed for suspended-sediment concentration at four USGS streamflow-gaging stations: Fox River at Wilmot, Wis., Grass Lake Outlet at Lotus Woods, Ill., Nippersink Creek near Spring Grove, Ill., and Fox River at Johnsburg, Ill. Water-velocity data were collected at the Wilmot, Lotus Woods, and Johnsburg stations to enable calculation of water discharges under the backwater conditions caused by the Stratton Lock and Dam. Discharge and sediment data were collected from Dec. 1, 1997, to June 1, 1999. Water-discharge data from USGS streamflow-gaging station Squaw Creek at Round Lake, Ill., also were used for determining discharge on the ungaged tributaries. Water levels recorded at Channel Lake near Antioch, Ill., Fox Lake near Lake Villa, Ill., Nippersink Lake at Fox Lake, Ill., and Fox River at McHenry, Ill., were used to detect and illustrate the effect of wind on the lakes. From July 16, 1998, to June 1, 1999, wind speed and direction were recorded at the Grass Lake Outlet station. Wind speed and direction also were recorded by the Illinois Department of Natural Resources at the Stratton Dam in McHenry, Ill. Rainfall data from the National Oceanic and Atmospheric Administration rain gage in Antioch, Illinois were used to describe the amount of rain that fell during certain periods. Additionally, water-velocity data were collected at 80 cross sections in the Fox Chain of Lakes to provide sample circulation patterns during two separate 1-week periods, and discharge was measured at 18 locations in the lakes (table 1 and fig. 2).

The USGS streamflow-gaging station on the Fox River at Wilmot, Wis., operated from 1939 to 1993, was renovated and an acoustic velocity meter (AVM) (Laenen, 1985) was installed. A new station was installed at the Grass Lake Outlet in Lotus Woods, Ill., consisting of a stage sensor and an AVM. An AVM was added to the stage-monitoring station on the Fox River in Johnsburg, Ill. The station on Nippersink Creek near Spring Grove, Ill., also was used because Nippersink Creek is the only major tributary to the Fox River in the study area. Water discharge on Nippersink Creek was computed on the basis of a standard stage-discharge rating (Rantz and others, 1982). Water discharges for the Wilmot, Lotus Woods, and Johnsburg stations were computed on the basis of an index-velocity rating (Rantz and others, 1982). Water discharges were estimated for periods of missing data. Long-term water discharge data were available for the Spring Grove (1966–99) and Wilmot (1939–99) stations.

Observers were hired locally to collect water samples at the Wilmot, Grass Lake Outlet, and Spring Grove stations. An automatic sampler was installed at the Johnsburg station because no observers were available to manually collect samples. Samples were collected manually using DH-76, DH-59, and DH-48 sediment samplers in accordance with USGS procedures (Edwards and Glysson, 1988). From December 1997 to June 1999, samples were collected twice a week and more often during periods of high flow (Johnson, 1997). These samples were analyzed to determine suspended-sediment concentrations that were then used to compute daily sediment loads (Porterfield, 1972). Most bed-material samples were collected using BMH-53 and BMH-60 samplers as

Table 1. Map index numbers and data collected at locations in the Fox Chain of Lakes, Ill.

[DCN, continuous water discharge; SED, suspended-sediment load; BM, bed material; Q, water-discharge measurement; SCN, continuous water stage]

Location	Map index number (see figure 2)	Data collected
Fox River at Wilmot	1	DCN,SED,BM
Fox River mouth in Grass Lake	2	Q
Trevor Creek at North Avenue	3	Q
Channel Lake East Outlet	4	Q
Channel Lake near Antioch (West Outlet)	5	Q,SCN
Sequoit Creek at mouth	6	Q
Lake Marie-Grass Lake channel	7	Q
Lake Marie-Bluff Lake channel	8	Q
Grass Lake East	9	BM
Grass Lake Center	10	BM
Grass Lake West	11	BM
Grass Lake Outlet at Lotus Woods	12	DCN,SED,BM
Nippersink Lake side channel	13	Q
Northwest of Crabapple Island	14	Q
Fox Lake West boat channel	15	Q
Petite Lake Outlet	16	Q
Southwest of Crabapple Island	17	Q
Squaw Creek near Round Lake	18	DCN
Nippersink Lake West Outlet	19	Q
Nippersink Lake East Outlet	20	Q
Nippersink Creek near mouth	21	Q
Nippersink Creek main Outlet	22	Q
Nippersink Creek minor Outlet	23	Q
Nippersink Creek near Spring Grove	24	DCN,SED,BM
Pistakee Lake Outlet to Fox River	25	Q
Fox River at Johnsburg	26	DCN,SED,BM
Fox Lake near Lake Villa	27	SCN
Nippersink Lake at Fox Lake	28	SCN
Fox River at McHenry	29	SCN

described by Edwards and Glysson (1988). In Grass Lake, 18 shallow core samples were collected; at least 11 of these samples were collected by pushing a clear cylindrical tube into the bed sediments and extracting the samples by hand.

In various parts of the lakes, water-velocity data were collected to determine water-circulation patterns. Velocity values were collected along 61 lines across 7 lakes and at 18 constrictions. Velocities were measured using an acoustic Doppler current profiler (ADCP) (Simpson and Oltmann, 1993). The ADCP was mounted on a boat and connected to a differential Global Positioning System (GPS) receiver to record the boat's location and velocity. The ADCP used four 600-megaHertz sonar beams to measure the water depth and the speed and direction of particles in the water. The ADCP recorded the water velocity at various depths, and these values were averaged after accounting for the boat's velocity.

SUSPENDED-SEDIMENT BUDGET

The sediments found in suspension within the Fox Chain of Lakes originate from the following sources: transport into the system by tributary inflow, resuspension from the bed by some forcing functions (for example, boat traffic or wind), or erosion from the lake's banks. The bed sediments found on the bottom of Grass Lake are composed of mainly fine particles in the silt-clay range. As part of the current study, three bed-material cores were collected in Grass Lake (locations 9–11, fig. 2). The bed materials at these sites were characterized as black peat with an organic content of between 9 and 18 percent. The median particle size

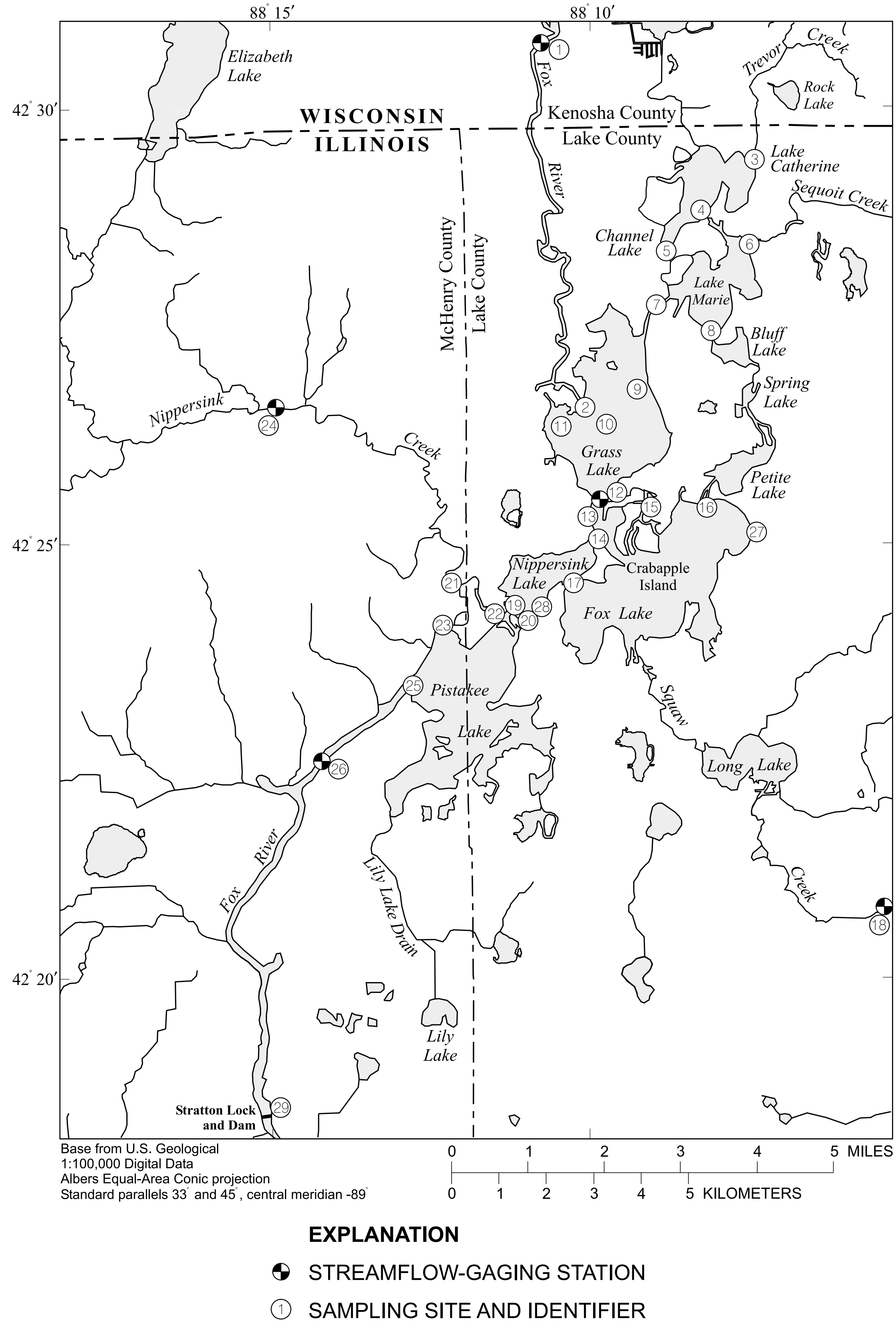

Figure 2. Locations of streamflow-gaging stations and sampling site locations in the study area in northern Illinois and southern Wisconsin.

(D_{50}) of these materials ranged from 0.000811 to 0.0013976 inches. These cores indicated that the sediments of Grass Lake have not appreciably changed since the study by Kothandaraman and others (1977). Other bed-material samples were collected with a BM-54 sampler at Fox River at Wilmot, Grass Lake Outlet at Lotus Woods, Nippersink Creek near Spring Grove, and Fox River at Johnsburg. The particle-size distribution of these samples, as well as those samples for the cores collected in Grass Lake, are summarized in table 2. The analyses of the samples collected at the streamflow-gaging stations did not separate silt- and clay-sized particles so that only the percentage smaller than sand is available; therefore, the silt and clay values for the streamflow-gaging stations are combined in table 2. With the exception of Grass Lake Outlet at Lotus Woods, most bed sediments at the gaging stations are sand-sized or larger. Silt-sized particles are easier than sand to resuspend; the reason bed sediments have a majority of sand-sized particles at the streamflow-gaging stations is that stream velocities and boat traffic are higher in these narrow locations compared to the middle parts of the lakes.

Table 2. Bed-material grain size at seven locations, Fox Chain of Lakes, Ill.

[--, not determined]

Sampling site	Map index number (see figure 2)	Percentage of gravel	Percentage of sand	Percentage of silt	Percentage of clay	Percentage of organic content
Fox River at Wilmot station	1	4.9	93.0	(combined	2.1)	--
Grass Lake Outlet at Lotus Woods station	12	3.2	65.4	(combined	31.5)	--
Nippersink Creek near Spring Grove station	24	6.9	82.5	(combined	10.7)	--
Fox River at Johnsburg station	26	13.8	84.9	(combined	1.3)	--
Grass Lake East	9	.0	20.8	66.0	13.2	18.0
Grass Lake Center	10	.0	22.0	67.4	10.6	9.0
Grass Lake West	11	.0	28.9	60.1	11.0	18.0

The suspended-sediment concentration in the water column is dependent on the supply of sediment, the flow rate, and the presence or absence of a forcing function that can resuspend sediments from the bottom. Increased water velocities and turbulence, whether caused by an increase in discharge or by boat traffic, fish, or wind, resuspend sediment from lakebeds (or streambeds). Sediment transport in lakes can be more complex than in streams, as Ward and Harr (1990) report:

> "In standing water bodies, wave and current action may transport sediment back and forth over the same area, in contrast to downstream transport in streams, for long periods with coarser sediments deposited near shorelines or inflowing streams and finer sediments deposited in deeper portions of the water body."

During the study period, the daily suspended-sediment concentration ranged from 1.7 mg/L at Fox River at Johnsburg to 868 mg/L at Fox River at Johnsburg. Limited size analyses of selected multivertical samples are shown in table 3.

Total water discharge, suspended-sediment load, and sediment trapped in Grass Lake for April, July, and October 1998 are shown in figure 3. Sediment transport is episodic, especially in lake systems. Sediment can be trapped during one period only to be released out of the lake later, depending on hydrologic conditions. In April 1998, 463 tons of suspended sediment were trapped in Grass Lake, compared with 775 tons scoured in July 1998. Daily suspended-sediment loads during February 1998 for the four stations are shown in figure 4. The suspended-sediment load at the Grass Lake Outlet remained high for a period after the load at Wilmot had decreased. The load at Johnsburg increases slightly but remains low (73 tons/d), so the sediment leaving Grass Lake during February 1998 appeared to be trapped in the lakes between Grass Lake and Johnsburg (fig. 1).

During the period from May 26, 1999, to May 31, 1999, water samples (containing suspended sediment) were collected at 6-hour intervals by the automatic sampler at the Fox River at Johnsburg station. This period included Memorial Day weekend, so an increased amount of boat traffic was expected on the Fox Chain of Lakes. During this period, the water discharge at this station averaged 1,850 ft^3/s and was slowly decreasing, varying from 2,570 ft^3/s to 1,270 ft^3/s, with daily averages decreasing from 2,120 ft^3/s on May 26 to 1,530 ft^3/s on May 31. Water discharges were higher during daylight and early evening hours, possibly because of an increased

Table 3. Laboratory analyses of suspended sediment (sand-fine split) in water samples from four streamflow-gaging stations, Fox Chain of Lakes, Ill.

[ft^3/s, cubic feet per second; mg/L, milligrams per liter]

Station	Date	Water discharge (ft^3/s)	Suspended-sediment concentration (mg/L)	Percentage of particles sand-sized or larger
Fox River at Wilmot	January 6, 1998	1,120	98	39
	March 5, 1998	738	27	44
	April 28, 1998	1,120	32	21
	June 18, 1998	332	82	4
	June 30, 1998	1,050	134	9
	January 26, 1999	1,640	13	63
	March 26, 1999	645	5	25
	May 17, 1999	1,090	12	59
Grass Lake Outlet at Lotus Woods	January 7, 1998	860	226	8
	March 5, 1998	900	45	25
	May 1, 1998	930	177	59
	June 17, 1998	490	278	19
	June 30, 1998	1,080	179	14
	March 26, 1999	660	146	26
	May 17, 1999	1,300	52	23
Nippersink Creek near Spring Grove	January 5, 1998	205	46	19
	March 19, 1998	286	58	56
	May 1, 1998	212	39	17
	June 19, 1998	190	158	7
	June 30, 1998	674	72	10
	January 25, 1999	755	143	22
	March 29, 1999	118	158	54
	May 19, 1999	589	43	66
Fox River at Johnsburg	December 23, 1997	584	9	55
	March 19, 1998	1,190	12	45
	April 27, 1998	2,320	20	48
	June 15, 1998	958	43	19
	June 30, 1998	1,940	89	22
	December 16, 1998	786	12	60
	January 27, 1999	1,880	6	7
	March 23, 1999	984	15	61
	April 29, 1999	3,800	11	24
	May 18, 1999	1,570	19	24

number of lockages at the Stratton Dam. The suspended-sediment load increased from 110 tons/d on May 25, 1999, to 339 tons/d on May 29, 1999, and remained more than 330 tons/d on May 30 and 31, 1999. A peak instantaneous load equivalent to 889 tons/d was measured on May 30, 1999. Wind speeds measured at the Grass Lake Outlet at Lotus Woods did not exceed 16 mi/h during May 26–31, 1999. The water discharges and suspended-sediment concentrations during this period are shown in figure 5. During a day, the suspended-sediment concentrations are highest in the evening and lowest in the morning. Boat traffic was not monitored but could be assumed to increase and peak during the daylight hours and decrease overnight. Similarly, the number of active boats could be assumed to increase between Wednesday (May 26, 1999) and Sunday (May 30, 1999) and the suspended-sediment concentrations in the samples collected at 7 p.m. each day progressively increase during that period. If the assumptions about the boat traffic are correct, these data indicate that boat traffic induces sediment resuspension in the shallow sections of the Fox Chain of Lakes. This conclusion is reinforced because the suspended-sediment loads at Grass Lake Outlet at Lotus Woods remained relatively constant until May 28, 1999, and then the loads increased 75 percent by May 30, 1999.

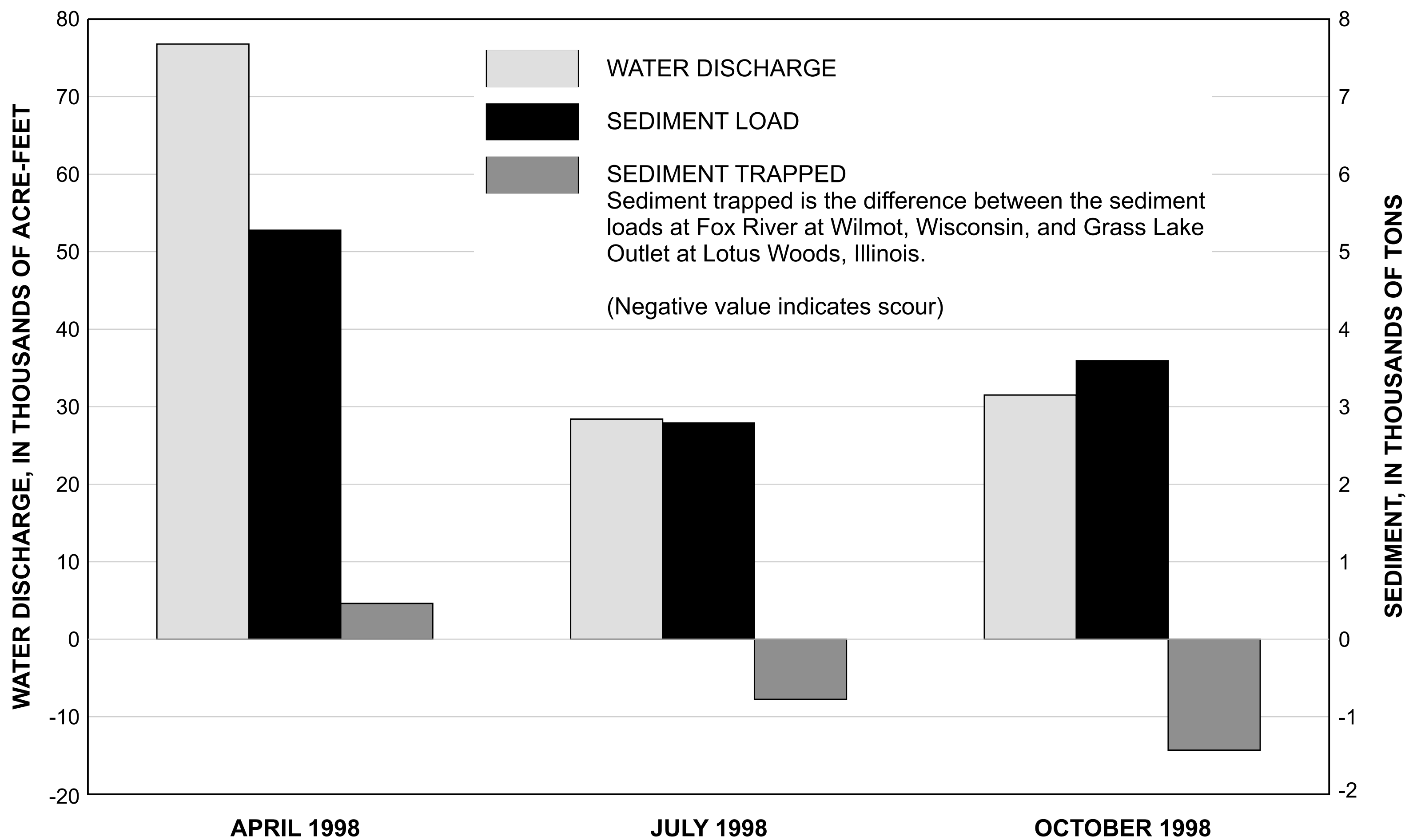

Figure 3. Monthly water discharge, suspended-sediment load, and sediment trapped for Grass Lake Outlet at Lotus Woods, Ill., April, July, and October 1998.

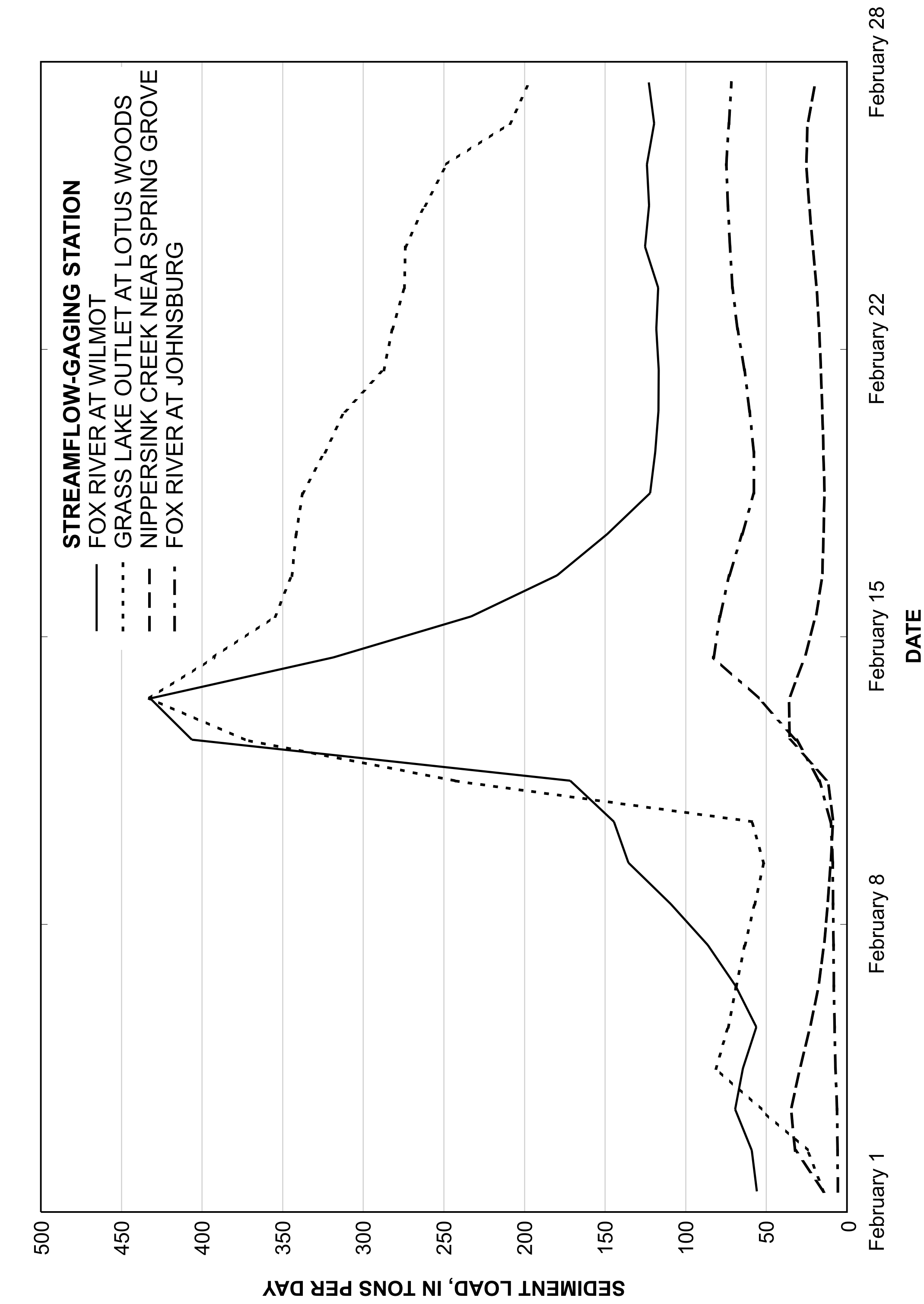

Figure 4. Daily suspended-sediment load at four streamflow-gaging stations, Fox Chain of Lakes, Ill., February 1998.

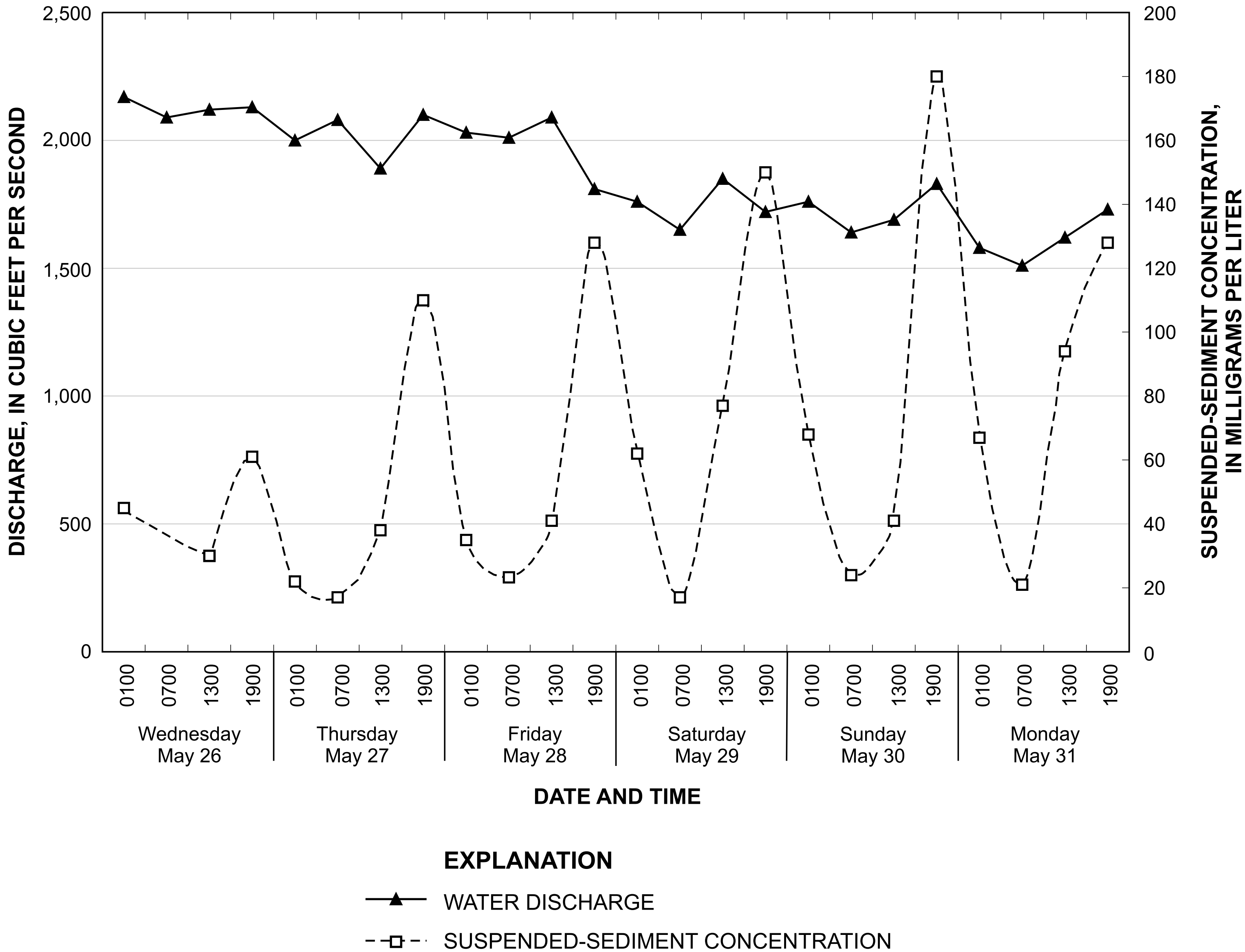

Figure 5. Water discharges and suspended-sediment concentrations for Fox River at Johnsburg, Ill., May 26–31, 1999.

The suspended-sediment loads from Dec. 1, 1997, to June 1, 1999, are summarized on table 4. Suspended-sediment loads for the ungaged portions of the drainage basin were estimated by averaging values for small tributaries to Channel Lake and Lake Catherine (R.T. Kay, U.S. Geological Survey, written commun., 1999). Monthly suspended-sediment loads for the four streamflow-gaging stations from Dec. 1, 1997, to June 1, 1999, are shown in figure 6. The suspended-sediment load in June and July 1998 at Grass Lake Outlet at Lotus Woods is greater than the sediment load at Fox River at Wilmot. Therefore, Grass Lake is releasing sediment during those months. Grass Lake was trapping sediment during January 1998 and 1999, probably because the lake surface is frozen, preventing resuspension by wind and boats.

Suspended-sediment loads for the Fox River at Wilmot and Grass Lake Outlet at Lotus Woods stations and the suspended-sediment load estimate for the ungaged areas were used to determine the suspended-sediment budget for Grass Lake. Suspended-sediment loads for the Grass Lake Outlet at Lotus Woods, Nippersink Creek near Spring Grove, and Fox River at Johnsburg stations were used with the suspended-sediment load estimate for the ungaged area between Lotus Woods and Johnsburg to determine the suspended-sediment budget for the lakes between Grass Lake and Johnsburg. The total water discharges and suspended-sediment loads at the four stations and the sediment trapped in Grass Lake and the lakes between Grass Lake and Johnsburg are shown in figure 7. At the Fox River at Wilmot station, the average suspended-sediment concentration over the study period was 58.2 mg/L, and at the Fox River at Johnsburg station, the average suspended-sediment concentration over the study period was 25.4 mg/L.

The suspended-sediment totals from table 4 are equivalent to an average annual inflow of 43,300 tons/yr to Grass Lake and an average annual inflow of 57,100 tons/yr to the lakes downstream. Combining the total suspended-sediment loads for the Nippersink Creek and Wilmot stations and estimating the ungaged drainage area shows 79,900 tons entering the Fox Chain of Lakes during the study or an average annual rate of 53,300 tons/yr. Brabets (1977) reported an annual inflow of 34,100 tons/yr to the Fox Chain of Lakes, and Stall and Bhowmik (1974) reported an annual inflow of 35,535 tons/yr. Metcalf & Eddy, Inc. (1980) estimated a total sediment inflow of 57,440 tons/yr using a nonspecific method of calculation that also included bed-material transport.

During the study described here, a total of 64,900 tons of suspended sediment entered Grass Lake, and a total of 70,600 tons of suspended sediment exited the lake, indicating a net scour of 5,700 tons of sediment. At Johnsburg, a total of 44,100 tons of suspended sediment was measured exiting the Fox Chain of Lakes, whereas 85,600 tons entered the system downstream from Grass Lake. These suspended-sediment loads indicate a net deposition of 41,500 tons downstream from Grass Lake, which represents a trapping efficiency of 48.5 percent. Grass Lake is no longer acting as a sediment trap for the system, although the lake may

Table 4. Drainage area, total discharge, suspended-sediment load, sediment trapped, and sediment yield at four streamflow-gaging stations and ungaged areas, Fox Chain of Lakes, Ill., December 1, 1997–June 1, 1999

[mi^2, square miles; acre-ft, acre-feet; tons/yr, tons per year; (tons/mi^2)/yr, tons per square mile per year; --, not computed]

Location name	Drainage area (mi^2)	Total water discharge (acre-ft)	Total suspended-sediment load		Total sediment trapped above station[2]		Sediment yield [(tons/mi^2)/yr]
			(tons)	(tons/yr)	(tons)	(tons/yr)	
Fox River at Wilmot	868	804,000	63,700	42,500	--	--	48.9
Ungaged area above Lotus Woods	51	71,100	1,200	800	--	--	[3]15.7
Grass Lake Outlet at Lotus Woods	919	848,000	70,600	47,100	–5,700	–3,800	51.2
Nippersink Creek near Spring Grove	192	191,000	12,800	8,500	--	--	44.4
Ungaged area above Johnsburg	94	131,000	2,200	1,500	--	--	[3]15.7
Fox River at Johnsburg[1]	1,205	1,280,000	44,100	29,400	41,500	27,700	24.4

[1] Sediment trapped above Fox River at Johnsburg is for the lakes below Grass Lake, not the entire lake system.
[2] Negative values indicate net scour has occurred.
[3] Value estimated on the basis of R.T. Kay (U.S. Geological Survey, written commun., 1999).

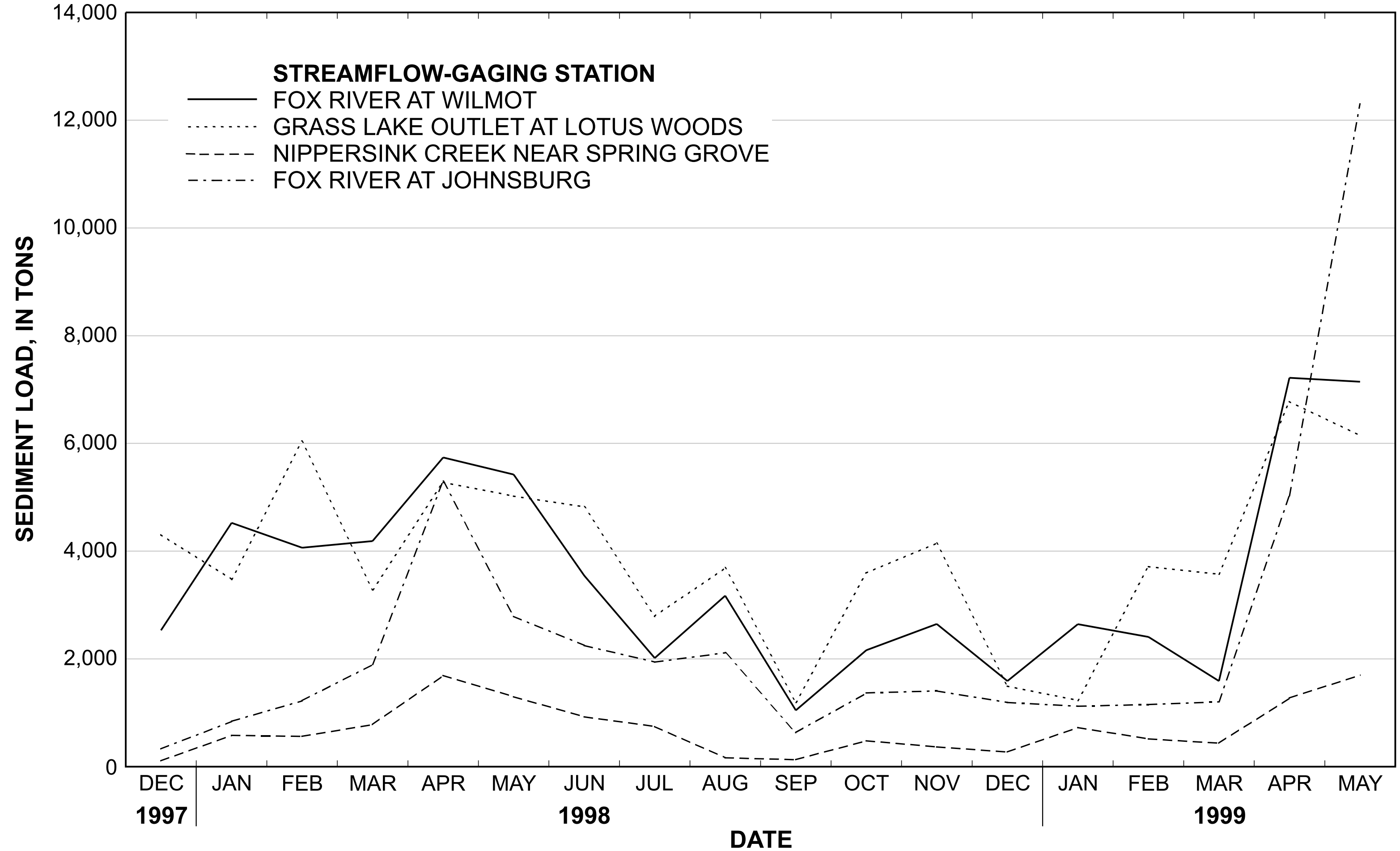

Figure 6. Monthly total suspended-sediment load at four streamflow-gaging stations, Fox Chain of Lakes, Ill.

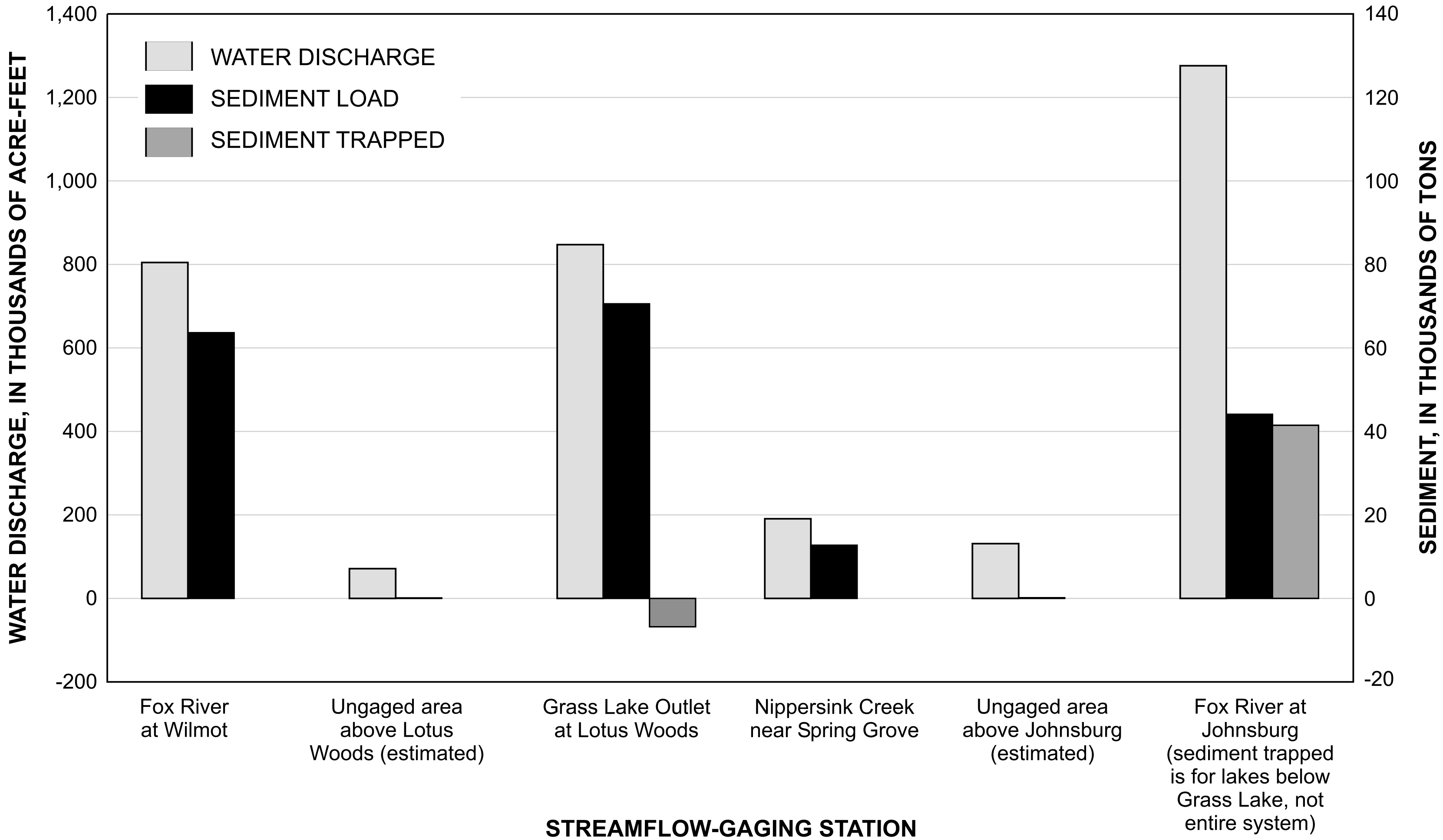

Figure 7. Total water discharge and suspended-sediment load at four streamflow-gaging stations, estimates for ungaged areas, and sediment trapped in Grass Lake and above Johnsburg, Fox Chain of Lakes, Ill., Dec. 1, 1997 to June 1, 1999.

trap some sediment for short periods of time. In earlier work, Brabets (1977) assumed 100 percent trapping efficiency and implied that Stall and Bhowmik (1974) also assumed 100 percent trapping efficiency. Metcalf & Eddy, Inc. (1980) assumed 80 percent trapping efficiency. None of the earlier work measured the suspended sediment leaving the Fox Chain of Lakes. Wonder Lake, located 7 mi upstream from the Nippersink Creek near Spring Grove station, had a trapping efficiency of 75 percent during 1995–97 (Wicker, LaTour, and Maurer, 1996, 1997, 1998).

One method of estimating reservoir trap efficiency is to apply Brune's curve (Brune, 1953). The ratio of reservoir capacity to annual inflow is calculated and referenced to a graph that shows theoretical trapping efficiency. Brune's curve is shown in figure 8. Kothandaraman (1977) lists the Fox Chain of Lakes as having a capacity of 38,718 acre-ft below an altitude of 736.5 ft and Grass Lake as having a capacity of 4,000 acre-ft below an altitude of 736.5 ft. Using an annual inflow of 583,000 acre-ft for Grass Lake, Brune's curve gives a capacity to inflow ratio of 0.0068 and an expected trap efficiency of 36 percent. For the lakes below Lotus Woods, applying Brune's curve using an annual inflow of 780,000 acre-ft and a capacity of 34,718 acre-ft gives a capacity to inflow ratio of 0.045 and an expected trap efficiency of 76 percent.

The density of the bed-material samples collected in Grass Lake is estimated at 70 lbs/ft^3, on the basis of the grain-size analysis (Guy, 1970). The 3,800 tons/yr of sediment released from Grass Lake has a volume of 2.51 acre-ft at 70 lbs/ft^3 and represents an average scour of 0.0014 ft over Grass Lake. The rate of 0.0014 ft/yr corresponds to taking 701 years to scour 1 ft of sediment in Grass Lake. Similarly, the 27,700 tons/yr of sediment trapped in the lower lakes has a volume of 18.1 acre-ft at 70 lbs/ft^3 and represents an average deposition of 0.004 ft in Fox, Nippersink, and Pistakee Lakes. The rate of 0.00399 ft/yr corresponds to taking 251 years to deposit 1 ft of sediment in the lower lakes.

This study covers a relatively short time interval and may not represent the long-term processes of the Fox Chain of Lakes system. The water discharges during the study were higher than the long-term mean discharges of the Fox River and Nippersink Creek (table 4). During the period of record (1967 to 1999), the Nippersink Creek near Spring Grove streamflow-gaging station averaged four discharge peaks greater than 500 (ft^3/s)/yr. During the 18 months of this study, seven discharge peaks greater than 500 ft^3/s were measured, which is not too different from the expected six discharge peaks for that time period. Most of the suspended-sediment transport occurs during periods of high flow. Given the number of peaks during the

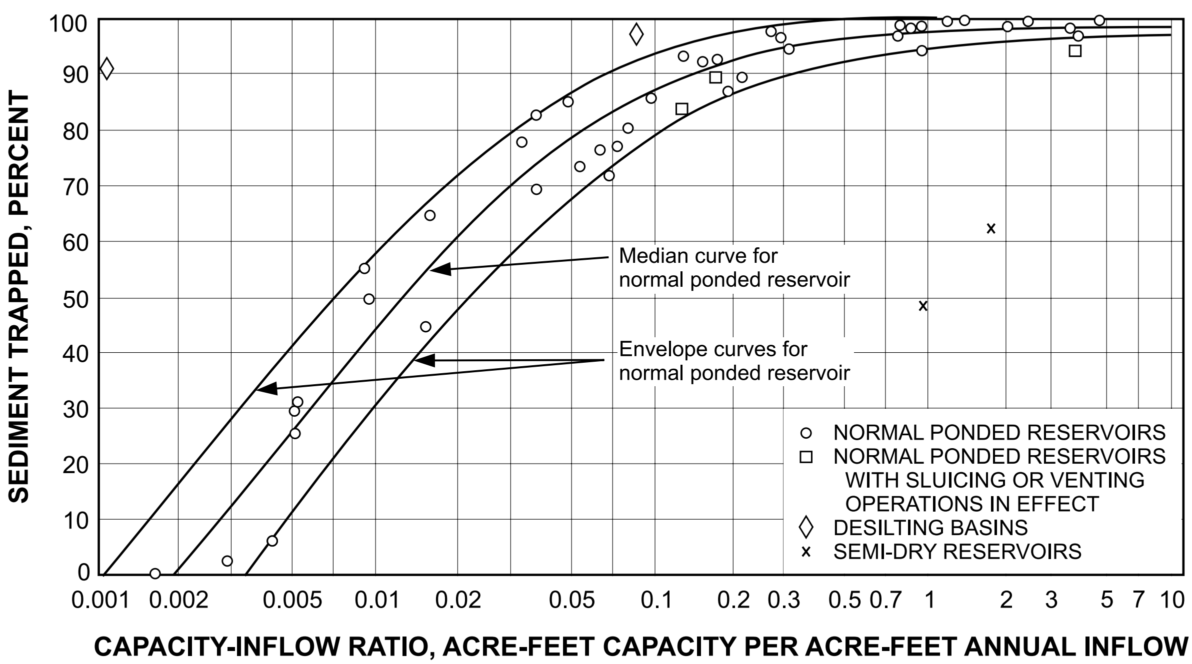

Figure 8. Brune's curve for estimating reservoir sediment trap efficiency (modified from Melching and Avery, 1990).

study and the mean daily discharge, the sediment transport was probably slightly higher than an average year. Other years with similar mean discharges but significantly different numbers of high flow peaks, such as 1 peak above 500 ft^3/s or 10 peaks above 500 ft^3/s, will have significantly different amounts of sediment transported.

FLOW DISTRIBUTION

The water discharges from Dec. 1, 1997, to June 1, 1999, are given on table 5. Discharges computed during the study period are slightly higher than the long-term mean discharges. Daily mean discharges for the four stations during the study period are shown in figure 9. Discharges vary widely during March, April, and November at the outflow of the Fox Chain of Lakes because of gate operations at Stratton Lock and Dam in McHenry.

The drainage area of the streamflow-gaging station at Wilmot accounts for 94 percent of the drainage area of the Grass Lake Outlet at Lotus Woods station. The water discharge at Wilmot (table 5) was 94.8 percent of the discharge at Lotus Woods. When combined, the stations at Lotus Woods and Nippersink Creek near Spring Grove represent 92 percent of the drainage area above the Johnsburg station. The Nippersink Creek discharge is 14.9 percent of the Johnsburg discharge, whereas the Lotus Woods discharge is 66.2 percent of the discharge at Johnsburg. Discharges from four tributaries to the Fox Chain of Lakes were not computed during the study. Discharge was not computed from Squaw Creek (the largest tributary not computed), with a drainage area of 47.6 mi^2 at the mouth at Fox Lake. During the period of the study, the average discharge at a USGS streamflow-gaging station on Squaw Creek at Round Lake, Ill., (drainage area of 17.2 mi^2) was 22.1 ft^3/s. This discharge is higher than the average discharge for the period 1990–98 (15.7 ft^3/s). The discharge at Squaw Creek was used to estimate the ungaged drainage areas above Grass Lake Outlet at Lotus Woods and Fox River at Johnsburg, and these estimates are included in table 5. The rain gage in Antioch recorded 41.51 in. of rain (National Oceanic and Atmospheric Administration, 1998a, 1999a, 1999b, 1999c, 1999d, 1999e, 1999f) during the study period, compared with a normal total of 50.16 in.

Table 5. Drainage area and discharges at four streamflow-gaging stations and estimates for ungaged areas, Fox Chain of Lakes, Ill.

[mi^2, square miles; ft^3/s, cubic feet per second; acre-ft, acre-feet; --, not available]

Station name	Drainage area (mi^2)	Long-term mean discharge (ft^3/s)	Mean discharge, December 1, 1997–June 1, 1999 (ft^3/s)	Total discharge, December 1, 1997–June 1, 1999 (acre-ft)
Fox River at Wilmot	868	561	741	804,000
Ungaged area above Lotus Woods	51	--	66	71,100
Grass Lake Outlet at Lotus Woods	919	--	781	848,000
Nippersink Creek near Spring Grove	192	152	176	191,000
Ungaged area above Johnsburg	94	--	121	131,000
Fox River at Johnsburg	1,205	--	1,176	1,280,000

LAKE CIRCULATION

Water-circulation patterns in the Fox Chain of Lakes are major factors in determining where suspended sediment is deposited and resuspended. The location for sediment deposition is correlated with water velocity. Water moving at faster velocities generally carries more sediment and at slower velocities deposits more sediment. Water-velocity data for the lakes were collected on April 20–22, 1998, and July 27–31, 1998. Water velocities are affected mostly by flow in the tributaries and by wind. The lake system is dynamic; therefore, although these data are representative of conditions during these two short periods, the data do not necessarily represent the long-term circulation of the Fox Chain of Lakes system. These data could be utilized mainly for verification of any future two-dimensional hydrodynamic flow models of the system.

The data from April 20–22, 1998, are from the spring runoff period, when the highest discharges normally occur. Discharges, and hence velocities, during this period are high because 0.9 in. of rain

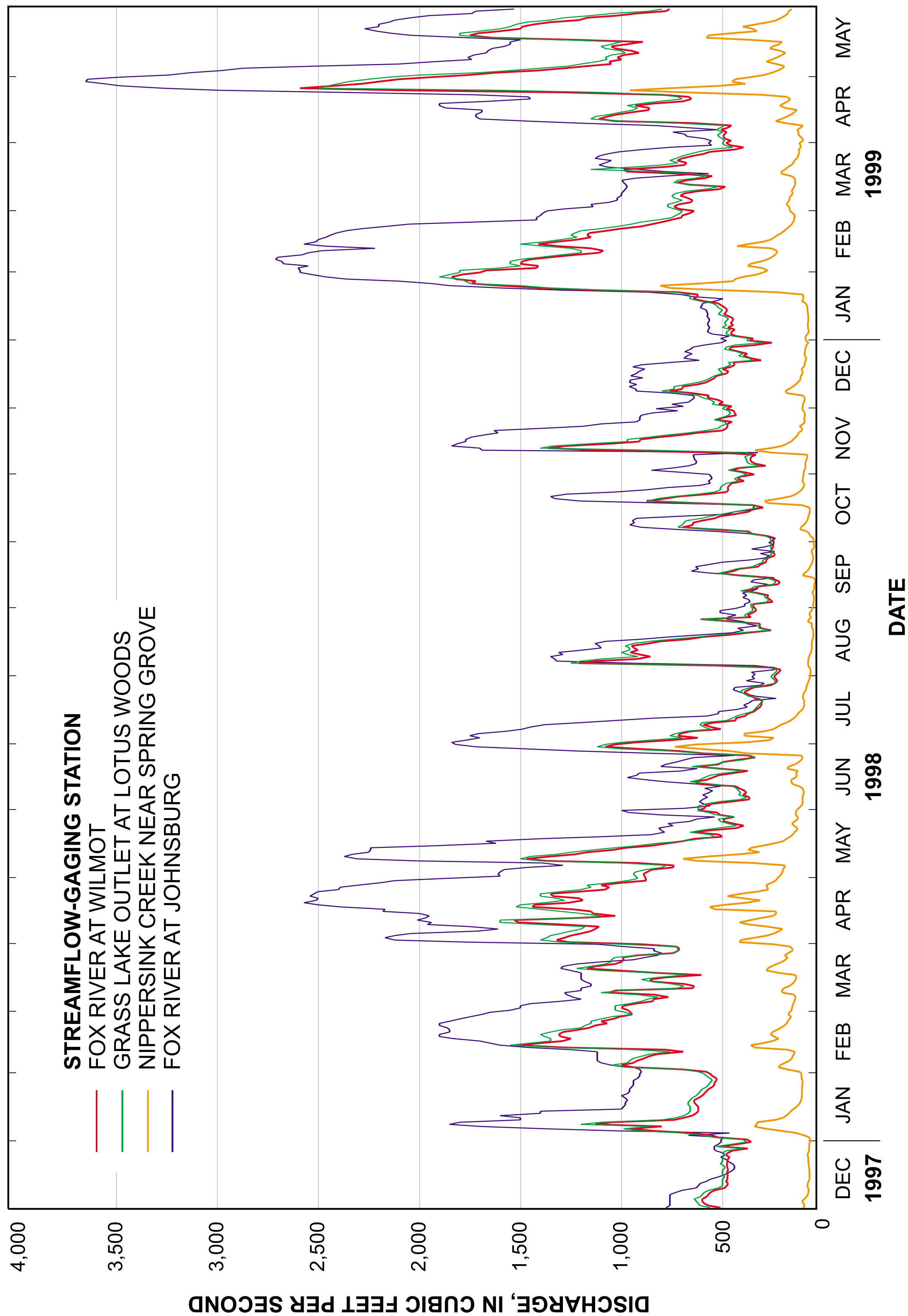

Figure 9. Daily mean discharges at four streamflow-gaging stations, Fox Chain of Lakes, Ill., Dec. 1, 1997 to June 1, 1999.

(National Oceanic and Atmospheric Administration, 1998b) fell in Antioch, Illinois, on April 20. The water level in the lakes had been raised already for recreational purposes in the summer; therefore, the velocities were decreased because of the increased cross-sectional area of the lakes. Higher water velocities would be expected under similar discharges during periods of lower lake levels. The data collected during July 27–31, 1998, are from one of the drier periods during the study. The discharges measured were low because very little rain had fallen immediately prior to or during this period. Another significant difference between the two data-collection periods is the lower amount of boat traffic in the Fox Chain of Lakes in April when compared with July, although boat traffic was not systematically documented in this study.

For the two stations with long-term data, discharges during April 20–22, 1998 (table 6) were about twice the long-term mean discharges. The April 22, 1998, peak discharges are at a level that can be expected to occur at least once on an annual basis. The flow-duration curve for Nippersink Creek near Spring Grove, Ill., is shown in figure 10. The April levels were exceeded about 10 percent of the time during the study, and these levels have been exceeded about 10 percent of the time in the long-term data. Discharges during July 27–31, 1998, were exceeded 60 percent of the time in the long-term data at Nippersink Creek near Spring Grove, Ill., and were about one-half the long-term mean discharges determined for stations with available long-term data. Discharges measured during July 27–31, 1998, were exceeded about 75 percent of the time during the study; therefore, these discharges are representative of typical low-flow conditions. Velocity data illustrating lake circulation are shown on plate 1 in the back of this report.

Wind speeds were mostly low during both lake circulation data-collection periods. During April 20–22, 1998, wind speeds at McHenry (Illinois Department of Natural Resources, 1999) varied from 0 to 14 mi/h and wind direction varied from west-southwest to north-northeast. During July 27–31, 1998, wind speeds at McHenry (Illinois Department of Natural Resources, 1999) varied from 0 to 8 mi/h and wind direction varied from west-southwest to northeast.

Table 6. Instantaneous water discharges, Fox Chain of Lakes, Ill., April 20–22 and July 27–31, 1998

[ft^3/s, cubic feet per second; --, not measured; negative discharge indicates flow reversal]

Location	Map index number (see figure 2)	Discharge, April 20–22, 1998 (ft^3/s)	Discharge, July 27–31, 1998 (ft^3/s)
Fox River at Wilmot	1	1,200	240
Fox River mouth in Grass Lake	2	1,150	55
Trevor Creek at North Avenue	3	19	--
Channel Lake East Outlet	4	62	–13
Channel Lake West Outlet	5	--	1
Sequoit Creek at mouth	6	47	--
Lake Marie-Grass Lake channel[1]	7	10	–63
Lake Marie-Bluff Lake channel	8	140	--
Grass Lake Outlet at Lotus Woods	12	1,230	203
Nippersink Lake side channel	13	65	4
Northwest of Crabapple Island	14	600	627
Fox Lake West boat channel	15	71	10
Petite Lake Outlet	16	143	–120
Southwest of Crabapple Island	17	810	570
Squaw Creek near Round Lake	18	59	.28
Nippersink Lake West Outlet	19	1,540	24
Nippersink Lake East Outlet	20	310	15
Nippersink Creek near mouth	21	334	--
Nippersink Creek main Outlet	22	337	86
Nippersink Creek minor Outlet	23	8	--
Nippersink Creek near Spring Grove	24	313	83
Pistakee Lake outlet to Fox River	25	2,200	357
Fox River at Johnsburg	26	2,500	364

[1] Positive value indicates flow into Lake Marie.

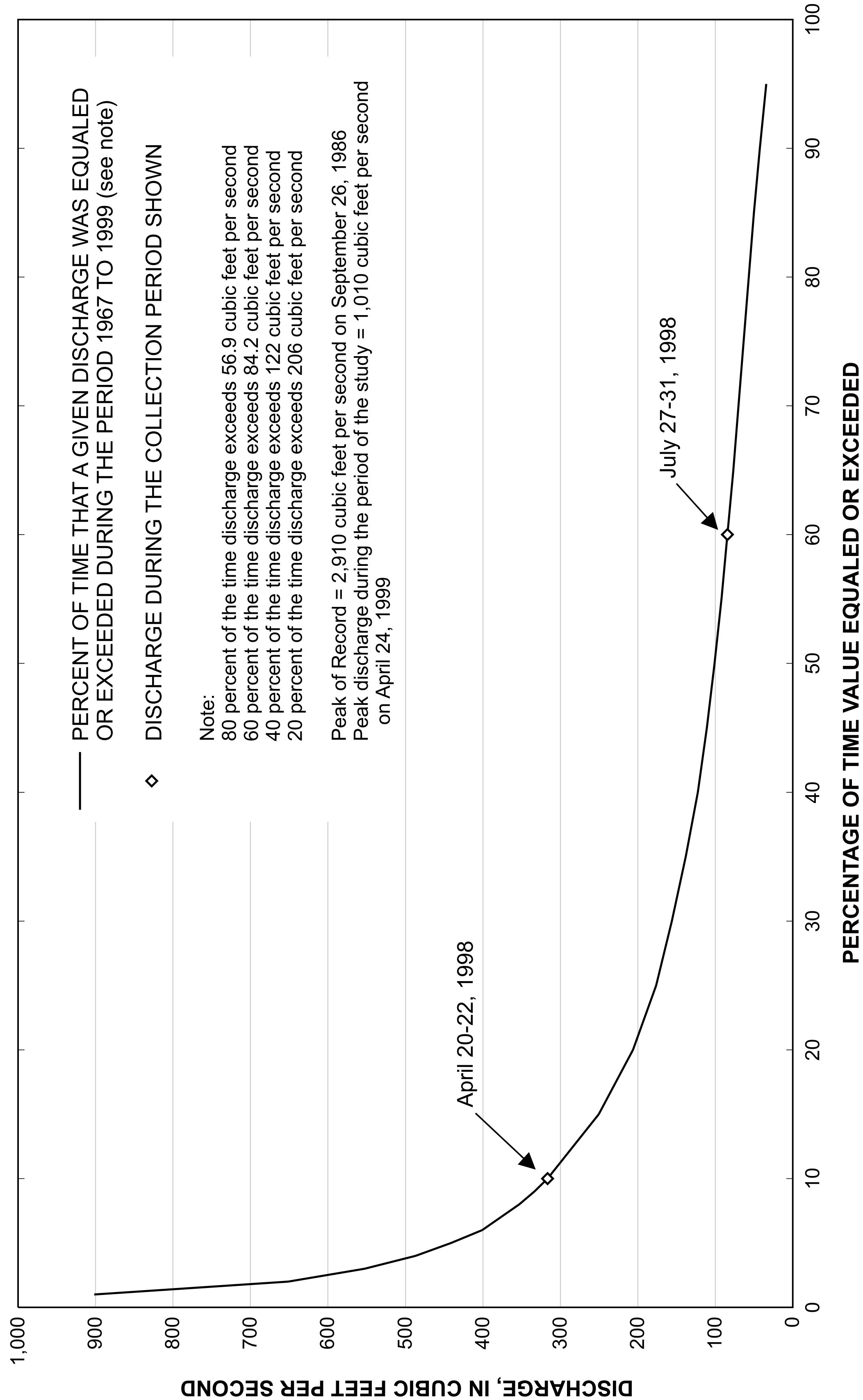

Figure 10. Flow-duration curve for Nippersink Creek near Spring Grove, Ill.

Instantaneous discharges for Trevor Creek, Sequoit Creek, and Squaw Creek (minor tributaries to the Fox Chain of Lakes) also are shown on table 6. These discharges are insignificant compared to the total flow in the system. Discharges shown in table 6 are instantaneous values, and apparent discrepancies may result because the discharge measurements were not made simultaneously. In some cases, the discharges may represent different hydrologic conditions in the lake system.

Strong winds from the southwest can cause negative discharges in the Fox Chain of Lakes as the winds push the water upstream. Negative discharges resulted on November 10, 1998, when wind speeds greater than 30 mi/h were measured at the Stratton Dam in McHenry (Illinois Department of Natural Resources, 1999). The exact wind speed is unknown because both wind-speed monitors malfunctioned on that day. This wind caused the discharge at the Fox River at Johnsburg streamflow-gaging station to decrease from 709 ft^3/s to –1,290 ft^3/s, when the river flowed upstream, meaning the water was moving south to north into Pistakee Lake. The water level at Johnsburg decreased from 3.74 ft to 2.33 ft in 16 hours. Water-level decreases of more than 0.20 ft, apparently induced by wind, were measured 32 times from December 1, 1997, to June 1, 1999. Water-level changes caused by wind are shown in figure 11. Wind from the south on April 6 and 7, 1999, caused water levels at the Fox River at McHenry, Fox River at Johnsburg, and Nippersink Lake at Fox Lake streamflow-gaging stations to decrease while increasing water levels at the Fox Lake at Lake Villa, Channel Lake near Antioch, and Fox River at Wilmot streamflow-gaging stations. Winds from the north on April 8–9, 1999, caused the water level at Johnsburg to increase more than 0.30 ft. At that time, the water level at Johnsburg was higher than the water level in Channel Lake and the remainder of the Fox Chain of Lakes, whereas the water level at Johnsburg normally is lower than the lakes upstream.

SUMMARY

The Fox Chain of Lakes is a glacial lake system in McHenry and Lake Counties in northern Illinois and southern Wisconsin. Sedimentation has occurred in the lake system since the first dam was built (1907) in McHenry, Ill. Grass Lake is considered the sediment catch for the lake system and may have reached its sediment storage capacity; consequently, sedimentation may increase downstream in Fox Lake. The U.S. Geological Survey, in cooperation with the Illinois Department of Natural Resources and the Fox Waterway Agency, conducted a study of the sedimentation problems in the Fox Chain of Lakes from December 1997 to June 1999, specifically to investigate the sediment-trapping capability of Grass Lake and collect hydrodynamic data as a precursor to future studies.

Water levels were measured and water samples were collected and analyzed for suspended-sediment concentration at four U.S. Geological Survey streamflow-gaging stations: Fox River at Wilmot, Wis., Grass Lake Outlet at Lotus Woods, Ill., Nippersink Creek near Spring Grove, Ill., and Fox River at Johnsburg, Ill. Water-velocity data were collected at the Wilmot, Lotus Woods, and Johnsburg stations to enable calculation of water discharges under the backwater conditions caused by the Stratton Lock and Dam. Discharge and sediment data were collected from Dec. 1, 1997, to June 1, 1999. Additionally, water velocities at 80 cross sections in the Fox Chain of Lakes were collected to provide sample circulation patterns during two separate 1-week periods, and discharge was measured at 18 locations in the lakes.

The sediments found in suspension within the Fox Chain of Lakes originate from the following sources: transport into the system by tributary inflow, resuspension from the bed by some forcing functions (boat traffic or wind), or erosion from the lake's banks. The bed sediments found on the bottom of the lake are composed of mainly fine particles in the silt-clay range. Three bed-material cores were collected in Grass Lake. Results of lab tests indicated these sediments are black peat with an organic content of between 9 and 18 percent. These cores indicated that the sediments of Grass Lake have not changed much since an earlier study in 1977. Other bed-material samples were collected at the streamflow-gaging stations. With the exception of Grass Lake Outlet at Lotus Woods, most of the bed sediments are sand-sized or larger. The bed material at the Grass Lake Outlet station contains 31.5 percent silt- and clay-sized particles. The bed material at Nippersink Creek near Spring Grove also has higher silt content (10.7 percent) than the bed material found in the Fox River at Wilmot (2.1 percent) and Johnsburg (1.3 percent).

Suspended-sediment samples were collected at 6-hour intervals by the automatic sampler at Fox River at Johnsburg during the period May 26–31, 1999. During this period, the water discharge at this station

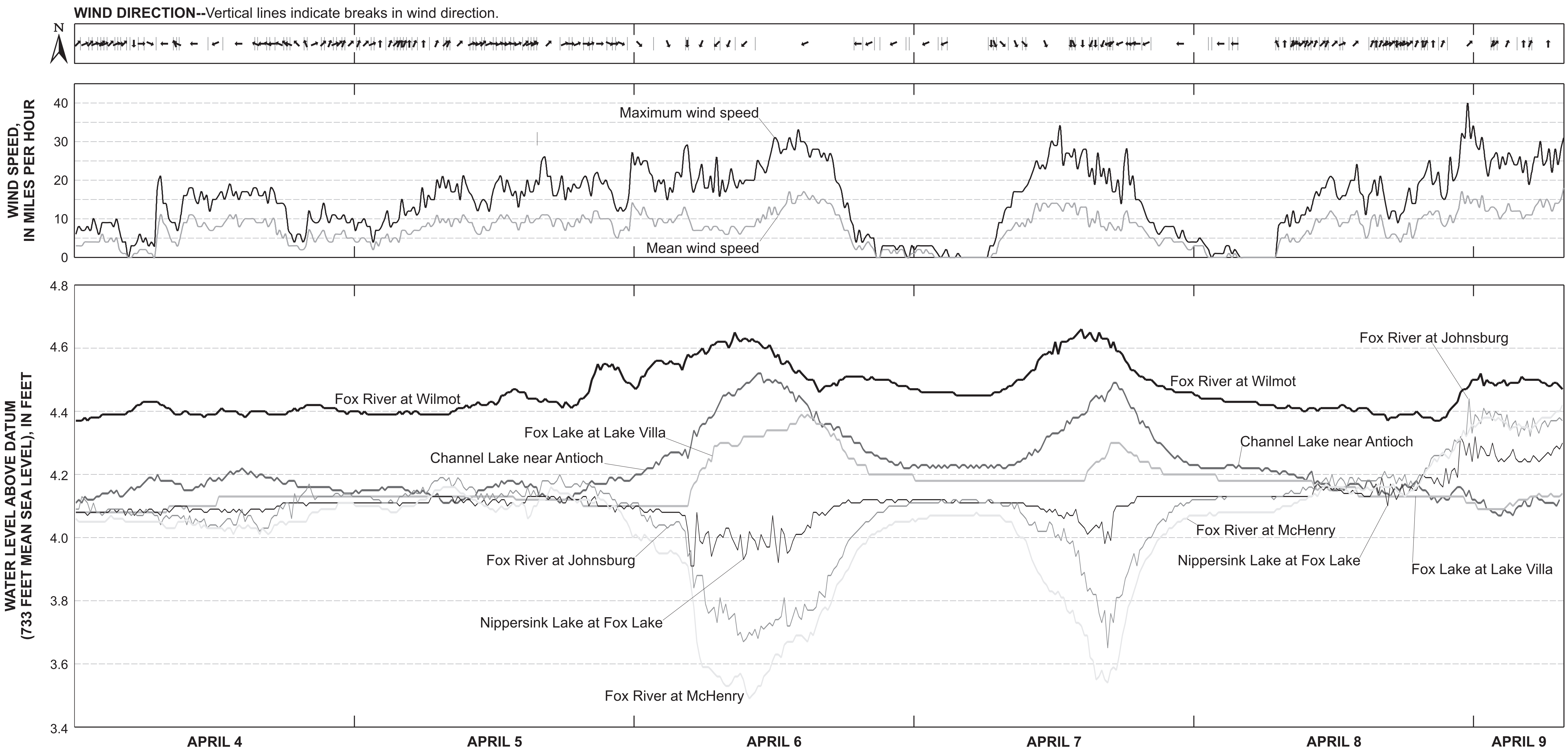

Figure 11. Comparison of wind direction, wind speed, and water levels at selected recording stations, Fox Chain of Lakes, Ill., April 4–9, 1999.

averaged 1,850 cubic feet per second (ft^3/s), and was slowly decreasing, varying from 2,570 ft^3/s to 1,270 ft^3/s. However, the suspended-sediment load increased from 110 tons per day (tons/d) on May 25, 1999, to 339 tons/d on May 29, 1999, and was more than 330 tons/d on May 30 and 31, 1999. A peak instantaneous load equivalent to 889 tons/d was measured on May 30, 1999. The increased suspended-sediment concentration may be attributable to resuspension of bed sediments by boat traffic during the Memorial Day weekend.

The suspended-sediment loads are equivalent to an average annual inflow to Grass Lake of 43,300 tons per year (tons/yr) and an average annual inflow to the lakes downstream of 57,100 tons/yr. Combining the total suspended-sediment loads for the Nippersink Creek and Wilmot stations and estimating the ungaged areas indicates 79,900 tons entered the Fox Chain of Lakes during the study, or an average annual rate of 53,300 tons/yr.

During the study, a total of 64,900 tons of suspended sediment entered Grass Lake and 70,600 tons of suspended sediment exited the lake, indicating a net scour of 5,700 tons of sediment. At Johnsburg, a total of 44,100 tons of suspended sediment was measured exiting the Fox Chain of Lakes, whereas 85,600 tons entered the system downstream from Grass Lake. These suspended-sediment loads indicate a net deposition of 41,500 tons downstream from Grass Lake, which represents a trapping efficiency of 48.5 percent.

Water discharges computed during the study period are slightly higher than the long-term mean discharges. During the study, the mean daily discharge at the Fox River at Wilmot station was 741 ft^3/s, for a total discharge of 804,000 acre-feet (acre-ft) of water in the 18-month period. The mean daily discharge at the Grass Lake Outlet station was 781 ft^3/s, for a total discharge of 848,000 acre-ft. The Nippersink Creek streamflow-gaging station had a mean daily discharge of 176 ft^3/s, for a total discharge of 191,000 acre-ft. During the study the mean daily discharge at the Fox River at Johnsburg station was 1,176 ft^3/s, for a total discharge of 1,280,000 acre-ft.

This study covers a relatively short period in time and may not represent the long-term processes of the Fox Chain of Lakes system. Given the number of peaks during the study and the mean daily discharge, the sediment transport probably was higher than during an average year.

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