USE OF FREQUENCY-VOLUME ANALYSES TO ESTIMATE REGIONALIZED YIELDS AND LOADS OF SEDIMENT, PHOSPHORUS, AND POLYCHLORINATED BIPHENYLS TO LAKES MICHIGAN AND SUPERIOR

By Dale M. Robertson

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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
meter (m)	3.281	foot
kilometer (km)	.6215	mile
meter per kilometer (m/km)	5.280	foot per mile
hectare (ha)	2.471	acre
square kilometer (km^2)	.3861	square mile
milligram (mg)	.0000022045	pound
gram (g)	.0022045	pound
kilogram (kg)	2.2045	pound
gram per hectare (kg/ha)	.00089218	pound per acre
kilogram per hectare (kg/ha)	.89218	pound per acre
cubic feet per second (ft^3/s)	.0283	cubic meter per second

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Milligrams per kilogram (mg/kg) is a unit expressing the concentration of a chemical constituent in the solid phase as mass (milligrams) of constituent per unit mass (kilograms) of dry sediment.

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U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program's Western Lake Michigan Drainages study unit is located in the eastern third of Wisconsin and includes a portion of the Upper Peninsula of Michigan. The goal of the NAWQA program is to describe the status and trends of the Nation's surface- and ground-water resources.

Use of Frequency-Volume Analyses to Estimate Regionalized Yields and Loads of Sediment, Phosphorus, and Polychlorinated Biphenyls to Lakes Michigan and Superior

By Dale M. Robertson

Abstract

In most rivers, transport of various constituents occurs largely during short-term, high-intensity events. A method is described to make regionalized estimates of the long-term average loads of selected streamwater constituents, as well as loads occurring during high-flow events with specified recurrence intervals. This method is used to estimate the load of suspended sediment, total phosphorus, and sediment-borne constituents, such as polychlorinated biphenyls (PCB's), from all the rivers in the United States that drain into Lake Michigan and Lake Superior whose drainage basins are greater than 325 square kilometers. Statistical comparisons of estimated loads and environmental factors indicate that suspended-sediment loads were primarily affected by river gradient and secondarily affected by the texture of surficial deposits, whereas total phosphorus loadings were primarily affected by the texture of surficial deposits and secondarily affected by river gradient. Total phosphorus loads were highest in rivers entering into the middle to southern part of Lake Michigan, especially rivers in areas draining clay surficial deposits and agricultural areas. During high flow, inputs of phosphorus and suspended sediment from rivers entering the southwestern part of Lake Superior become very important to the total input of these constituents; these rivers have steep gradients and drain surficial deposits with high clay content. The single largest contributor of PCB's during the entire period and during each type of high-flow event was the Fox River, which supplied 46 to 64 percent of the total PCB load to both lakes.

INTRODUCTION

The Laurentian Great Lakes system is the largest body of freshwater in the world. Each of the Great Lakes receive water and accompanying nutrients, sediments, and contaminants from many tributaries. Excessive nutrient loading has been shown to cause eutrophication in bays in the Great Lakes, as well as in Lake Erie as a whole (Sonzogni and others, 1979). Excessive sediment loading has caused local water-clarity problems, as well as excessive sedimentation in many harbors. In many tributaries affected by urban areas, organic contaminants, such as polychlorinated biphenyls (PCB's), are commonly bound to the sediment being transported. The problem of nutrient, sediment, and organic-contaminant loading has led the Great Lakes Water Quality Board of the International Joint Commission (IJC) to classify several of the tributaries as "Areas of Concern" and has led to more general concerns for the entire Great Lakes system. Regional estimates of nutrient, sediment, and PCB loading into the Great Lakes are needed so that resource managers and policymakers have a quantitative basis for making decisions regarding these problems.

A few of the many tributaries to the Great Lakes have been intensively sampled to estimate the loading of specific constituents, such as during the Green Bay Mass Balance Study (House and others, 1993) and the Lake Michigan Mass Balance Study (P. Hughes, U.S. Geological Survey, written commun., 1995), but constituent loadings for most tributaries are unknown. Therefore, regionalized estimates of nutrient or contaminant loading are not possible without a method for extrapolating load estimates from a few well-monitored tributaries to the remaining unmonitored areas. Various approaches have been developed to estimate loading from unmonitored or relatively unmonitored areas (Richards, 1989). These range from drainage-area-ratio methods of estimating the load of an unmonitored river to complete modeling of the unmonitored basins. As part of the IJC efforts, the Pollution From Land Use Activities Reference Group (PLUARG) developed regionalized estimates of nutrient, major-ions, and suspended-solids loadings into the entire Great Lakes system for 1975 and 1976 (Sonzogni and others, 1978). These estimates were based on a variable number of samples (3 to 400 samples per year per river) and were computed by use of the ratio-estimator method (Sonzogni and others, 1978). Loads, which were estimated for 43 rivers during 1975 and 110 rivers during 1976, were then used to estimate the loads of nearby unmonitored rivers from unit-area yields. The IJC has continued to make annual regionalized estimates of phosphorus loading for each of the Great Lakes, using the approach developed by Sonzogni and others (1978), on the basis of monthly or less frequent samples collected each year (Lesht and others, 1991; D. Dolan, International Joint Commission, Great Lakes Regional Office, Windsor, Ontario, oral commun., 1995). In most years, if not all, very few samples were collected during very high flows, when concentrations might be expected to be highest; therefore, the annual load estimates may be biased toward low values. Other researchers have estimated loads using statistical relations between flow and concentration for intensively monitored rivers and have extrapolated these loads to estimate the total phosphorus and (or) sediment loads to specific sections of one of the lakes, such as Green Bay (Robertson and Saad, 1996).

A significant proportion of the nutrient, sediment, and contaminant load from many rivers is delivered during short-term, high-flow events. (See for example, Sonzogni and others, 1978.) Because of the randomness of these events, it is difficult to design manual-sampling programs for these periods. Recent advancements in automated equipment, has made sampling during high-flow events more feasible than before; however, studies involving automated equipment have been recent and limited to only a few rivers.

Previous studies have shown the sediment loss from land to streams is a function of land-use practices, the type of surficial deposit or soil, land slope, and the amount and intensity of rainfall. Wischmeier and Smith (1960) incorporated these factors into the frequently used Universal Soil Loss Equation. Phosphorus loading in rivers also has been shown to be a function of land-use practices and types of surficial deposits in the river basin (Clesceri and others, 1986; U.S. Environmental Protection Agency, 1980). Monteith and Sonzogni (1981) state that the two most important physical factors affecting the chemical concentrations in rivers near the Great Lakes are the texture of the soil material and the land use on that soil. Therefore, more accurate load estimations should be obtained by extrapolating the load from a river with similar physical characteristics than simply by extrapolating load estimates from the nearest well-monitored river. Results from regional studies would enable the tributaries to be ranked on the basis of their respective loads and therefore prioritized for possible remediation efforts.

The primary purpose of this report is to present a method to estimate the loads of specific constituents from tributaries to the Great Lakes system. The estimated loads will enable resource managers to prioritize or rank these rivers on the basis of relative constituent contributions, especially for high-flow events. This ranking can be used to prioritize the sampling sites or tributaries where remediation efforts would be most effective. This report examines the loading of phosphorus, sediment, and sediment-borne contaminants (namely, PCB's) to Lake Michigan and the United States part of the Lake Superior Basin for the 16-year period 1975–90 and for specified high-flow events. In this report, methods are presented to do the following:

1. *Estimate frequency-volume relations for the period 1975–90 for selected well-monitored rivers in the United States entering Lakes Michigan and Superior.* Flows are estimated for events of 1, 3, and 7 days duration with recurrence intervals of 10 and 50 years (annual exceedence probabilities of 0.1 and 0.02, respectively).

2. *Compute the total daily load of phosphorus and suspended sediment from the selected well-monitored rivers for the period 1975–90 and during the specified high-flow events.* The high-flow events are examined during spring and summer, because the concentration-streamflow relations vary seasonally.

3. *Extrapolate total phosphorus and suspended-sediment loads from well-monitored rivers to all of the relatively unmonitored rivers with drainage areas greater than 325 km^2 and rank these rivers based on their relative contributions.*

4. *Estimate on a relative basis (rank) the contributions of selected constituents (in this case PCB's) from each tributary using existing sediment and water-column chemistry data.*

ANALYTICAL METHODS

Frequency-Volume Analysis

Seventeen tributaries draining into Lakes Michigan and Superior (identified as 1 through 17 in fig. 1 and table 1) were sampled as part of the U.S. Geological Survey's (USGS) National Stream Quality Assessment Network (NASQAN). Flow and water-quality data for these rivers are extensive. Complete daily flow records for these sites varied in length from 20 to 79 years. For each of these well-monitored tributaries, except the Nemadji River, daily streamflows for the entire period of record were retrieved from the USGS National Water Data Storage and Retrieval System (WATSTORE) (Hutchinson, 1975).

Two types of statistical analysis were done with the retrieved data. First, WATSTORE Program A969 (Hutchinson, 1975) was used to produce a magnitude-frequency distribution of daily streamflows for each site. This program creates a high-value table, listing the highest 1-, 3-, and 7-day average streamflows in each year of the complete record. For the entire period of record, the annual 1-, 3-, and 7-day high values were ranked according to magnitude. The data provided by Program A969 were then input into Program A193 (Hutchinson, 1975) to compute log-Pearson Type III statistics for each river. This analysis produces theoretical 1-, 3-, and 7-day average streamflows for various recurrence intervals (for example, the average streamflow for the Fox River for the 10-year, 7-day event was 18,555 ft^3/s). The theoretical 1-, 3-, and 7-day high streamflows corresponding to recurrence intervals of 10 and 50 years (exceedence probabilities of 0.1 and 0.02, respectively) were selected for each river.

The following procedure was then used to generate the daily sequence of discharges for the theoretical 3-and 7-day high-flow events for each river for each recurrence interval. First, a time-series of moving 3- and 7-day average streamflow was computed for each streamflow record and compared with the theoretical discharges for the respective 3- and 7-day events. Then, the daily discharges encompassed in the 3- or 7-day averaging interval were recorded whenever the moving average streamflow was within plus or minus 10 percent of the theoretical high flow (from the Log Pearson analysis). After all of the daily data meeting the above criteria were recorded for a given site, the average streamflow for each day in a 3-day or 7-day sequence was computed (for example, all of the first days of specific 7-day events were averaged together to estimate the streamflow for the first day in the 7-day sequence). The final output is summarized in table 2. Daily flows in the 3- and 7-day flow sequences occasionally exceeded the flow for the 1-day event. This is an inconsequential artifact of the method used to construct the sequences and should have an insignificant effect on the constituent load calculations.

Alternative computations were used for the Nemadji River and an additional river (Grand Calumet River) which were included after the frequency-volume analyses were completed. For the Nemadji River, the daily streamflows during high-flow events were estimated by multiplying the daily streamflows for the Bad River, in table 2, by the ratio of the drainage area at the Bad River gaging station to that of the Nemadji River. For the Grand Calumet River (identified as 18 in fig. 1), flows during the 16-year period were estimated from data collected from the ongoing Lake Michigan Mass Balance Study. Average daily streamflow was estimated to be 700 ft^3/s and all streamflows during high-flow events were assumed to be 2,000 ft^3/s (S. Morlock, U.S. Geological Survey, oral commun., 1995) (table 1). The drainage area of the Grand Calumet is less than 325 km^2 (225 km^2), but was included to represent a completely urbanized basin.

Ancillary Analyses

Load Estimation

Total daily loads for suspended sediment and total phosphorus were calculated by use of constituent-transport models for each of the 17 well-monitored tributaries. The constituent-transport models were based on the relations between constituent load (in kg) and two variables: streamflow (Q, in ft^3/s) and time of the year (T, in radians) (Cohn and others, 1989). The general form of the model was

$$\log(\text{daily load}) = a + b(\log(Q) - c) + d(\log(Q) - c)^2 + e(\sin(T)) + f(\cos(T)). \quad (1)$$

Values for the regression coefficients (a, b, c, d, e, and f) in equation 1 were obtained for each site by use of multiple regression analyses between daily loads (estimated by multiplying daily streamflows by instantaneous measured concentrations, in mg/L) and daily streamflows (Q) and time of the year (T). Each analysis

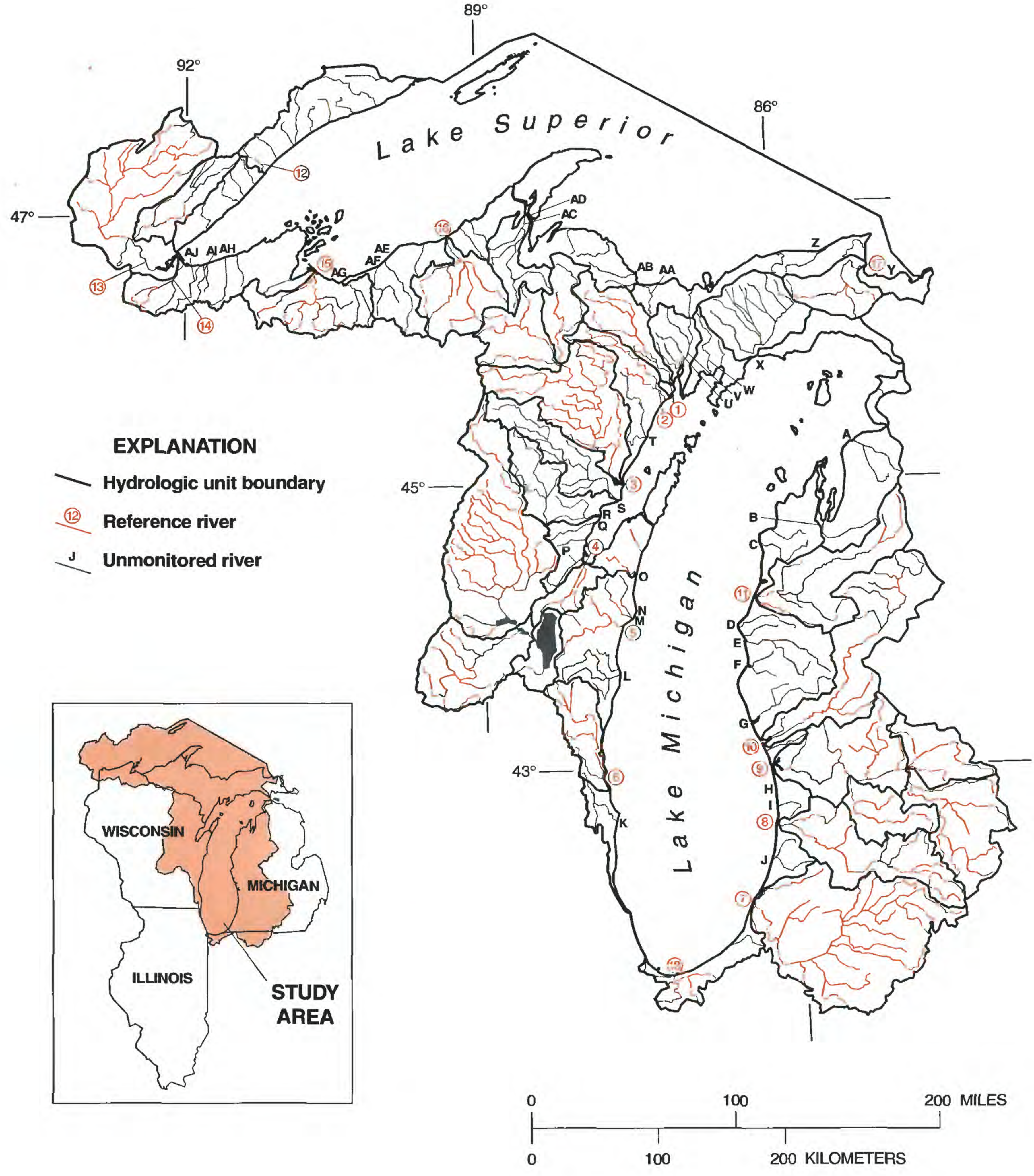

Figure 1. Tributaries to Lake Michigan and Lake Superior (rivers are identified in table 1).

Table 1. Area and average streamflow of selected Lake Michigan and Lake Superior tributaries used in streamflow frequency-volume analysis

[location of rivers shown in figure 1; km^2, square kilometers; ft^3/s, cubic feet per second]

River (identifier number)	Area at gaging station[1] (km^2)	Total drainage area of river[2] (km^2)	Drainage ratio to river mouth	Long-term average daily streamflow (ft^3/s)
Escanaba at Cornell, Mich. (1) 04059000	2,255	2,435	1.082	840[3]
Ford at Hyde, Mich. (2) 04059500	1,165	1,235	1.060	380[3]
Menominee near McAllister, Wis. (3) 04067500	10,155	10,540	1.038	3,480[4]
Fox at Rapid Croche Dam, Wis. (4) 04084500	15,565	16,395	1.053	4,970[4]
Manitowoc at Manitowoc, Wis. (5) 04085427	1,360	1,390	1.019	340[4]
Milwaukee at Milwaukee, Wis. (6) 04087000	1,805	2,260	1.253	430[4]
St. Joseph at Niles, Mich. (7) 04101500	9,495	12,125	1.277	3,410[3]
Kalamazoo at Fennville, Mich. (8) 04108500	4,145	5,335	1.288	1,480[5]
Grand at Grand Rapids, Mich. (9) 04119000	12,690	14,425	1.137	3,770[3]
Muskegon at Newaygo, Mich. (10) 04122000	6,085	6,890	1.132	2,050[5]
Manistee near Manistee, Mich. (11) 04126000	4,345	5,055	1.163	2,080[5]
Baptism near Beaver Bay, Minn. (12) 04014500	365	375	1.036	170[6]
St. Louis at Scanlon, Minn. (13) 0402400	8,885	9,065	1.020	2,350[6]
Nemadji near South Superior, Wis. (14) 04024430	1,090	1,130	1.040	410[4]
Bad near Odanah, Wis. (15) 0402700	1,545	2,615	1.692	620[4]
Ontonagon near Rockland, Mich. (16) 04040000	3,470	3,615	1.037	1,390[3]
Tahquamenon near Paradise, Mich. (17) 04045500	2,045	2,190	1.071	920[3]
Grand Calumet at mouth, Ind. (18) 04092750	225	225	1.000	700[7]

[1]The areas at the gages were obtained from Henrich and Daniel (1983) for the rivers in Wisconsin; Blumer and others (1994) for the rivers in Michigan; Mitten and others (1993) for the rivers in Minnesota.

[2]The area at the mouth of each river was obtained from Henrich and Daniel (1983) for the rivers in Wisconsin; Jerry Fulcher (Michigan Department of Natural Resources–Land and Water Management Division, Lansing, Mich., written commun., 1994) for the rivers in Michigan; James Stark (U.S. Geological Survey, oral commun., 1994) for the rivers in Minnesota; and Timothy Willoughby (U.S. Geological Survey, oral commun., 1994) for the Grand Calumet River.

[3]Average discharge for site from Blumer and others (1994).

[4]Average discharge for site from Holmstrom and others (1994).

[5]Average discharge for site from Blumer and others (1993).

[6]Average discharge for site from Mitton and others (1993).

[7]Flow data were unavailable for the Grand Calumet; therefore, average discharge was assumed to be 700 cubic feet per second (Scott Morlock, U.S. Geological Survey, Indiana, oral commun., 1995).

Table 2. Daily discharges for selected Lake Michigan and Lake Superior tributaries, by duration and recurrence interval (exceedence probability)

[Location of rivers shown in fig. 1. All data are in cubic feet per second and are based on the period of record for each site.]

River (identifier number)	Duration of high-flow event										
	1 day	3 days			7 days						
	Day 1	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Recurrence interval, 10 years (exceedence probability, 0.1)											
Escanaba at Cornell, Mich. (1)	8,400	7,800	8,000	7,600	6,050	7,350	8,650	8,450	7,650	7,150	6,800
Ford at Hyde, Mich. (2)	4,200	3,850	3,950	3,900	3,750	3,900	3,950	4,000	3,950	3,900	3,800
Menominee near McAllister, Wis. (3)	20,600	17,900	18,550	18,050	14,400	17,000	18,550	18,700	18,950	18,400	16,950
Fox at Rapid Croche Dam, Wis. (4)	19,250	19,300	19,400	19,350	18,800	19,150	19,250	19,250	19,250	19,250	19,000
Manitowoc at Manitowoc, Wis. (5)	4,800	4,100	4,100	4,250	4,950	4,500	4,000	3,850	3,650	3,300	3,100
Milwaukee at Milwaukee, Wis. (6)	7,700	7,700	6,550	5,350	6,800	6,750	6,300	5,100	4,250	3,250	2,650
St. Joseph at Niles, Mich. (7)	14,950	13,850	14,000	13,700	13,500	14,300	14,300	14,050	13,600	13,100	12,700
Kalamazoo at Fennville, Mich. (8)	6,800	6,250	5,950	5,450	6,950	6,750	6,150	5,600	5,550	5,100	4,800
Grand at Grand Rapids, Mich. (9)	31,800	30,850	31,000	28,600	27,350	29,200	29,750	27,900	24,800	21,850	19,050
Muskegon at Newaygo, Mich. (10)	10,350	9,300	9,500	9,350	8,450	9,100	9,300	9,250	8,950	8,000	7,350
Manistee near Manistee, Mich. (11)	6,600	5,650	5,950	5,750	4,900	5,750	5,950	5,700	5,450	4,800	4,450
Baptism near Beaver Bay, Minn. (12)	4,100	3,450	3,650	3,150	2,550	3,300	3,100	2,550	2,350	2,250	1,950
St. Louis at Scanlon, Minn. (13)	25,200	23,700	24,100	23,450	23,000	24,450	24,350	23,600	22,100	20,950	19,350
Nemadji near South Superior, Wis. (14)	8,650	6,850	7,550	6,150	5,250	6,100	6,200	5,600	5,050	4,950	4,350
Bad near Odanah, Wis. (15)	12,300	9,750	10,700	8,750	7,450	8,650	8,800	7,950	7,150	7,000	6,200
Ontonagon near Rockland, Mich. (16)	17,600	15,650	16,250	12,650	10,850	15,150	14,250	12,800	10,650	10,550	10,100
Tahquamenon near Paradise, Mich. (17)	6,000	5,900	5,950	5,900	5,700	5,900	5,950	6,000	5,950	5,900	5,850
Grand Calumet at mouth, Ind.[1] (18)	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000

Table 2. Daily discharges for selected Lake Michigan and Lake Superior tributaries, by duration and recurrence interval (exceedence probability)—Continued

River (identifier number)	Duration of high-flow event										
	1 day	3 days			7 days						
	Day 1	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
Recurrence interval, 50 years (exceedence probability, 0.02)											
Escanaba at Cornell, Mich.	10,750	9,400	10,200	9,300	7,200	8,450	9,100	9,150	9,350	8,300	6,650
Ford at Hyde, Mich.	5,450	5,950	5,500	4,250	3,900	6,550	6,850	5,950	5,500	4,250	3,200
Menominee near McAllister, Wis.	27,700	25,250	25,750	24,300	14,700	23,800	26,700	24,800	23,800	18,000	15,000
Fox at Rapid Croche Dam, Wis.	22,400	23,250	23,200	23,300	22,900	23,050	23,250	23,300	23,400	23,250	22,950
Manitowoc at Manitowoc, Wis.	7,853	7,100	7,200	5,900	6,200	8,000	6,400	5,400	4,300	4,000	3,900
Milwaukee at Milwaukee, Wis.	9,750	10,650	9,650	7,050	6,250	8,500	8,650	8,950	8,850	7,250	6,000
St. Joseph at Niles, Mich.	18,350	15,650	16,300	16,750	15,700	16,550	16,300	16,200	16,150	16,050	15,650
Kalamazoo at Comstock, Mich.	9,300	8,350	7,900	6,800	9,250	8,150	8,400	8,700	9,800	8,550	6,200
Grand at Grand Rapids, Mich.	44,302	40,800	41,600	36,300	27,600	34,400	40,800	41,600	36,300	29,600	24,400
Muskegon at New Aygo, Mich.	14,750	16,900	11,000	9,250	9,300	20,500	11,000	16,900	11,000	9,250	7,300
Manistee near Manistee, Mich.	7,600	6,600	6,550	6,100	4,700	4,700	6,400	6,550	6,400	5,600	5,150
Baptism near Beaver Bay, Minn.	6,350	4,350	5,150	3,750	2,500	4,500	4,250	4,100	3,500	3,000	2,450
St. Louis at Scanlon, Minn.	30,750	29,300	29,800	30,750	25,150	26,950	27,800	27,600	26,700	25,150	23,250
Nemadji near South Superior, Wis.	12,350	12,550	10,000	7,500	4,950	15,500	8,800	6,300	3,950	2,450	1,750
Bad near Odanah, Wis.	17,550	17,850	14,200	10,700	7,000	22,000	12,500	8,950	5,650	3,500	2,500
Ontonagon near Rockland, Mich.	21,150	15,650	14,300	17,000	10,000	13,900	24,000	21,300	14,700	10,000	10,200
Tahquamenon near Paradise, Mich.	7,100	6,650	6,650	6,550	6,250	6,550	6,700	6,700	6,600	6,400	6,200
Grand Calumet at mouth, Ind.[1]	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000

[1]Flow data were unavailable for the Grand Calumet; therefore, storm discharge was assumed to be 2,000 cubic feet per second (Scott Morlock, U.S. Geological Survey, oral commun., 1995).

involved all the available data for the site from 1970 through 1993. The coefficients for equation 1, the coefficient of determination (R^2), and the variance of the residuals (S^2) are summarized in table 3 for each river.

Total event loads for these rivers were then estimated for spring events (starting May 1) and summer events (starting July 1) by use of the calibrated forms of equation 1 (table 3) and the daily streamflows for each site for each event (table 2). Because a logarithmic transformation was used in equation 1, the estimated loads were adjusted for bias using equation 2 (Gilroy and others, 1990).

$$\text{Adjusted Daily Load} = \text{Estimated Daily Load} * \exp(S^2/2). \qquad (2)$$

The constituent-transport models provided load estimates at the gaging stations for each of the 17 well-monitored rivers. Total loads at the mouths of each river were then obtained by multiplying the estimated loads, which were generally for sites several miles upstream from the mouth, by the ratio of drainage area at the mouth of the river to the drainage area at the monitored site (table 1). These ratios were usually close to 1.0; however, at the Bad River, the ratio was 1.7, an indication that a significant amount of the drainage was unmonitored.

Total loads for the Grand Calumet River were estimated by multiplying the average daily flows in table 2 by concentrations measured by the Indiana Department of Environmental Management, Office of Water Management. The long-term average daily load was obtained by multiplying the average concentration from 72 monthly samplings from 1986 through 1991 (9.8 mg/L for suspended sediment and 0.117 mg/L for total phosphorus) by the average daily streamflow. The loads during the high-flow events were obtained by multiplying the maximum concentration from the 72 monthly samplings (25.0 mg/L for suspended sediment and 1.62 mg/L for total phosphorus) by the event streamflow.

Load Extrapolation

For each high-flow event and for the entire 1975–90 period, suspended-sediment and total phosphorus loads were estimated for all of the remaining rivers draining into Lake Michigan and the United States part of Lake Superior with drainage basins greater than 325 km^2, an additional 36 rivers (locations of the remaining rivers are identified as A through AJ in fig. 1). The drainage basins of these 54 rivers account for 81 percent of the area draining into Lake Michigan and the United States part of Lake Superior (87 and 66 percent for Lakes Michigan and the United States part of Lake Superior, respectively). The total load from each of these additional rivers was obtained by multiplying the total estimated load of one of the 18 reference rivers by the ratio of drainage area of the unmonitored river to that of the reference river. The choice of the reference river for each of the remaining rivers was based on which reference river basin had the most similar environmental characteristics. The three environmental characteristics thought to be most important factors affecting total phosphorus and suspended-sediment loading—texture of surficial deposits, land-use type, and stream gradient—were used in this selection process (table 4). The relative importance of each of these characteristics was determined by statistically examining the relation between suspended-sediment (and total phosphorus) yield (load per unit area) and the three environmental characteristics for each of the 17 well-monitored rivers (yields from the Grand Calumet River were not included in the statistical analysis). After these three environmental characteristics were ranked by importance, a reference river was chosen for each of the unmonitored rivers. The reference river for suspended sediment was not necessarily the same as that for total phosphorus.

Ranking of Tributaries by Relative PCB Load

For each high-flow event and the long-term average, the relative PCB loads were estimated for all 54 rivers. Relative PCB loads were computed for each river by multiplying the suspended-sediment load by the concentration of PCB's in the sediments. Bed-sediment PCB concentrations in the Lakes Michigan and Superior Basins were obtained from the U.S. Environmental Protection Agency (K. Klewin, U.S. Environmental Protection Agency, written commun., 1994). These sediment concentrations were either from the river or the harbor at the river mouth. For each river where sediment-chemistry data were available, the median PCB concentration was used in this analysis (table 5). A median PCB concentration of 0.001 mg/kg was assumed for rivers where PCB data were unavailable. The partitioning coefficient between concentrations of PCB's in the bed sediment and suspended sediment was assumed to be 1.0 for all of the rivers examined and assumed not to vary seasonally. Because

Table 3. Coefficients for equation 1, and the variance of the residuals (S^2) and coefficient of determination (R^2) of the regressions between measured and predicted daily loads for suspended sediment and total phosphorus in selected Lake Michigan and Lake Superior tributaries
[location of rivers shown in fig. 1]

River (identifier)	Coefficients for equation 1						S^2	R^2
	a	b	c	d	e	f		
			Suspended sediment					
Escanaba (1)	8.946	1.144	6.801	0.075	0.085	-0.137	0.465	0.642
Ford (2)	7.455	1.627	5.496	.266	-.134	-.079	.461	.872
Menominee (3)	10.793	1.836	8.376	.189	-.010	-.341	.405	.726
Fox (4)	11.791	1.409	8.184	.210	-.380	-.733	.599	.615
Manitowoc (5)	9.838	1.423	5.761	.088	-.383	-.344	.978	.812
Milwaukee (6)	10.299	1.503	6.242	.018	-.479	-.388	.483	.788
St. Joseph (7)	12.061	1.640	8.284	.421	-.212	-.462	.309	.644
Kalamazoo (8)	11.205	1.429	7.466	-.227	-.335	-.753	.227	.588
Grand (9)	12.808	1.548	8.476	-.034	-.393	-.603	.287	.804
Muskegon (10)	11.892	2.026	7.897	-.010	-.126	-.254	.326	.760
Manistee (11)	10.782	1.532	7.786	.042	.014	-.066	.298	.364
Baptism (12)	6.437	1.303	4.196	.027	.011	-.002	1.115	.736
St. Louis (13)	10.947	1.579	7.778	.245	-.208	-.262	.664	.751
Nemadji (14)	10.723	1.856	5.815	.008	-.348	-.931	.378	.951
Bad (15)	9.690	1.958	6.256	.339	-.209	-.429	.671	.873
Ontonagon (16)	11.817	1.926	7.274	.276	.037	-.160	.230	.933
Tahquamenon (17)	9.176	1.227	6.868	.057	-.176	-.204	.338	.733
			Total phosphorus					
Escanaba (1)	3.493	1.070	6.796	.044	-.044	.061	.440	.623
Ford (2)	1.690	1.062	5.412	.149	-.041	-.102	.627	.685
Menominee (3)	5.502	.944	8.369	-.078	-.170	-.101	.465	.343
Fox (4)	6.849	.895	8.216	.126	-.226	-.274	.251	.543
Manitowoc (5)	4.659	1.135	5.445	-.024	-.189	-.618	.281	.859
Milwaukee (6)	5.009	1.087	6.149	.118	-.137	-.283	.227	.826
St. Joseph (7)	6.330	1.445	8.287	.457	-.255	-.371	.208	.725
Kalamazoo (8)	5.606	1.322	7.463	-.291	-.634	-.632	.362	.539
Grand (9)	6.855	1.061	8.422	.188	-.060	-.031	.356	.640
Muskegon (10)	5.247	1.415	7.911	.239	-.223	-.177	.423	.558
Manistee (11)	4.861	1.390	7.765	.521	-.174	-.104	.320	.300
Baptism (12)	.777	1.212	4.271	.030	.046	.020	.918	.757
St. Louis (13)	5.272	1.147	7.669	.202	-.029	-.086	.592	.727
Nemadji (14)	3.819	1.487	5.751	.005	-.094	-.256	.350	.928
Bad (15)	3.339	1.309	6.048	.177	.001	-.108	.355	.844
Ontonagon (16)	5.287	1.523	7.352	-.050	.038	-.208	.321	.820
Tahquamenon (17)	3.965	.918	6.890	-.096	.011	.037	.490	.536

Table 4. Environmental characteristics of rivers in the United States draining into Lakes Michigan and Superior with drainage areas greater than 325 square kilometers

[km^2, square kilometers; Ag, agriculture; HD, near Holland, Mich.; SH, near South Haven, Mich.; Locations of rivers shown in fig. 1]

River	Identifier	Total drainage area of river[1] (km^2)	Stream gradient[2] (m/km)	Land use (percent)						Surficial deposit (percent)				
				Ag[3]	Forest[4]	Wetland	Urban	Open water	Other	Clay	Loam	Sand and gravel	Peat	Other
LAKE MICHIGAN														
Lower Michigan														
Jordan	A	410	4.19	46.52	43.59	0.00	0.00	5.85	4.05	0.00	0.00	100.00	0.00	0.00
Boardman	B	735	NA	46.52	43.59	.00	.00	5.85	4.05	.00	.00	100.00	.00	.00
Betsie	C	655	NA	51.77	38.63	.00	.00	4.73	4.86	.00	9.45	90.55	.00	.00
Manistee	11	5,055	.73	28.07	71.38	.00	.00	.55	.00	.00	.47	99.53	.00	.00
Big Sable	D	535	NA	46.47	51.80	.00	.70	.35	.68	10.27	.04	89.69	.00	.00
Pere Marquette	E	1,915	1.10	46.47	51.80	.00	.70	.35	.68	10.27	.04	89.69	.00	.00
Pentwater	F	445	NA	46.47	51.80	.00	.70	.35	.68	10.27	.04	89.69	.00	.00
White	G	1,360	1.15	46.47	51.80	.00	.70	.35	.68	10.27	.04	89.69	.00	.00
Muskegon	10	6,890	.40	44.99	52.51	.00	.61	1.88	.00	5.79	.00	94.21	.00	.00
Grand	9	14,425	.38	80.45	15.96	.00	3.38	.21	.00	9.81	58.48	31.71	.00	.00
Pigeon	H	325	NA	73.26	25.87	.00	.00	.00	.87	38.28	4.76	56.96	.00	.00
Black (HD)	I	455	NA	73.26	25.87	.00	.00	.00	.87	38.28	4.76	56.96	.00	.00
Kalamazoo	8	5,335	.64	71.02	26.45	.00	2.53	.00	.00	3.21	19.08	77.71	.00	.00
Black (SH)	J	715	.72	73.26	25.87	.00	.00	.00	.87	38.28	4.76	56.96	.00	.00
St. Joseph	7	12,125	.41	72.72	24.24	.00	3.02	.00	.02	2.01	.99	96.99	.00	.00
Indiana														
Grand Calumet	18	225	NA	78.69	2.34	.00	5.40	.00	13.56	22.43	.00	77.57	.00	.00
Wisconsin														
Root	K	515	.41	32.09	3.33	.00	59.17	.00	5.41	90.78	.00	9.22	.00	.00
Milwaukee	6	2,260	1.01	66.78	3.20	.00	29.29	.00	0.73	29.11	.00	70.89	.00	.00
Sheboygan	L	1,105	.83	97.76	.00	.00	.46	.00	1.78	63.83	.28	36.16	.00	.00
Manitowoc	5	1,390	1.09[5]	97.76	.00	.00	.46	.00	1.78	63.83	.00	36.16	.00	.00
West Twin	M	455	NA	97.76	.00	.00	.46	.00	1.78	63.83	.28	36.16	.00	.00

Table 4. Environmental characteristics of rivers in the United States draining into Lakes Michigan and Superior with drainage areas greater than 325 square kilometers—Continued

River	Identifier	Total drainage area of river[1] (km²)	Stream gradient[2] (m/km)	Land use (percent)						Surficial deposit (percent)				
				Ag[3]	Forest[4]	Wetland	Urban	Open water	Other	Clay	Loam	Sand and gravel	Peat	Other
LAKE MICHIGAN—Continued														
Wisconsin—Continued														
East Twin	N	345	1.17	97.76	.00	.00	.46	.00	1.78	63.83	.28	36.16	.00	.00
Kewaunee	O	355	1.99	79.94	14.17	.00	.04	.00	5.84	96.23	.28	3.48	.00	.01
Fox	4	16,395	1.01[5]	61.21	32.61	.83	.50	4.85	.00	38.92	7.00	54.08	.00	.00
Duck	P	400	.91	97.76	.00	.00	.46	.00	1.78	63.83	.28	36.16	.00	.00
Pensaukee	Q	375	2.08	97.76	.00	.00	.46	.00	1.78	63.83	.28	36.16	.00	.00
Oconto	R	2,545	1.42	26.10	73.63	.00	.00	.00	.27	18.10	30.41	51.49	.00	.00
Peshtigo	S	2,850	1.18	24.92	72.99	.00	.00	1.54	.54	.08	30.87	69.05	.00	.00
Menominee	3	10,540	1.24[5]	8.31	90.68	.00	.00	1.01	.00	.54	30.57	68.62	.28	.00
Upper Michigan														
Cedar	T	1000	NA	8.35	91.52	.00	.00	.00	.12	.00	71.90	26.83	1.26	.00
Ford	2	1,235	1.25	8.35	91.52	.00	.00	.00	.12	.00	71.90	26.83	1.26	.00
Escanaba	1	2,440	1.85	5.68	83.11	11.15	.00	.03	.02	.00	53.09	34.32	12.59	.00
Rapid	U	355	NA	10.14	88.66	.32	.00	.00	.88	.00	70.78	28.28	.94	.00
Whitefish	V	840	NA	10.14	88.66	.32	.00	.00	.88	.00	70.78	28.28	.94	.00
Sturgeon	W	550	1.19	9.44	88.01	.01	.00	.00	2.53	.00	11.55	85.95	2.50	.00
Manistique	X	3,755	.51	2.89	50.31	46.81	.00	.00	.00	.00	2.03	75.14	22.84	.00
LAKE SUPERIOR														
Upper Michigan														
Waiska	Y	395	NA	33.19	64.37	.00	.00	.00	2.44	40.53	.00	59.40	.07	.00
Tahquamenon	17	2,190	.18	1.85	68.37	29.78	.00	.00	.00	.00	.00	58.60	41.40	.00
Two Hearted	Z	530	NA	2.44	82.26	9.08	.00	.00	6.12	.00	28.08	61.85	10.02	.05
Chocolay	AA	415	NA	2.44	82.26	9.08	.00	.00	6.12	.00	28.08	61.85	10.02	.05
Dead	AB	430	NA	2.106	92.46	.00	.00	.00	5.43	.00	35.68	64.32	.00	.00
Sturgeon	AC	1,890	3.60	2.94	96.87	.00	.00	.00	.19	5.78	6.02	88.20	.00	.00
Portage Creek	AD	2,565	NA	3.71	88.52	.00	.00	.00	7.77	31.23	.00	68.77	.00	.00

Table 4. Environmental characteristics of rivers in the United States draining into Lakes Michigan and Superior with drainage areas greater than 325 square kilometers—Continued

River	Identifier	Total drainage area of river[1] (km²)	Stream gradient[2] (m/km)	Land use (percent)						Surficial deposit (percent)				
				Ag[3]	Forest[4]	Wetland	Urban	Open water	Other	Clay	Loam	Sand and gravel	Peat	Other
LAKE SUPERIOR—Continued														
Upper Michigan—Continued														
Ontonagon	16	3,615	2.03	6.38	91.87	.00	.00	1.74	.01	35.74	.00	64.02	.24	.00
Presque Isle	AE	930	NA	3.71	88.52	.00	.00	.00	7.77	31.23	.00	68.77	.00	.00
Black	AF	665	NA	3.71	88.52	.00	.00	.00	7.77	31.23	.00	68.77	.00	.00
Wisconsin														
Montreal	AG	685	1.63	8.19	90.21	.80	.00	.00	.80	29.67	.00	68.88	1.45	.00
Bad	15	2,615	3.56[5]	8.26	90.93	.00	.00	.00	.81	29.67	.00	68.88	1.45	.00
Iron	AH	370	NA	13.74	82.74	.02	.84	.00	2.66	48.39	.00	44.97	2.77	3.85
Bois Brule	AI	470	.68	13.74	82.74	.02	.84	.00	2.66	48.39	.00	44.97	2.77	3.85
Amnicon	AJ	340	NA	13.74	82.74	.02	.84	.00	2.66	48.39	.00	44.97	2.77	3.85
Nemadji	14	1,130	1.89	13.74	82.74	.02	.84	.00	2.66	48.39	.00	44.97	2.77	3.85
Minnesota														
St. Louis	13	9,065	1.86	10.17	68.18	19.52	1.68	0.42	.04	26.50	0.00	53.26	15.95	4.29
Baptism	12	375	10.91	1.87	95.62	.00	.00	1.69	.82	9.90	.00	89.72	.37	.00

[1]The area at the mouth of each river was obtained from Henrich and Daniel (1983) for the rivers in Wisconsin; Jerry Fulcher (Michigan Department of Natural Resources—Land and Water Management Division, Lansing, Mich., written commun., 1994) for the rivers in Michigan; James Stark (U.S. Geological Survey, oral commun., 1994) for the rivers in Minnesota; and Scott Morlock (U.S. Geological Survey, oral commun., 1994) for Grand Calumet River.

[2]Stream-gradient data were retrieved from the USGS National Water Data Storage and Retrieval System (WATSTORE) program (basin characteristic file) (Hutchinson, 1975).

[3]Percent agriculture was calculated assuming 100 percent agriculture for mostly cropland category, 75 percent agriculture for cropland with other category, and 25 percent agriculture for forest with other category.

[4]Percent forest was calculated assuming 100 percent forest for mostly forest category, 75 percent forest for forest with other category, and 25 percent forest for cropland with other category.

[5]Stream gradients were estimated from 1:2,500,000 USGS topographic maps.

the concentration of PCB's in the suspended sediment is not the same as that in the bed sediment, these estimated loads of PCB's are not, by any means, considered to be absolute loads. Each of the 54 rivers was ranked on the basis of its relative contribution of PCB's to Lakes Michigan and Superior, combined and independently.

Assumptions

The approach used to estimate the loads from these 54 rivers and rank them by their relative contributions of total phosphorus, suspended sediment, and PCB's during the defined high-flow events and the long-term average requires several assumptions.

1. *The constituent-transport models accurately estimate the streamflow-concentration and streamflow-load relations throughout all flow regimes, especially during extremely high flows.* Only a small amount of data, however, was available for very high flows. The paucity of data collected during extreme flow constitutes a problem with all load estimations. The calibration of the constituent-transport model uses all the available data to develop the streamflow-load relation, then uses this relation with measured daily average streamflows to estimate daily loads for any given year. In most other approaches, however, data collected only in a specific year are used to estimate the load for that year.

2. *Load estimates for the monitoring sites can be accurately extrapolated to the river mouth by use of a simple drainage-area ratio.* This assumption would be expected to be valid if environmental characteristics in the downstream area are similar to those upstream from the site; however, many of the rivers have large urban areas downstream from the monitoring site and often have low-gradient reaches where sediment and phosphorus may be deposited.

3. *Unmonitored rivers and their most similar reference rivers produce similar unit-area yields.* However, most of the reference rivers had larger drainage basins than the unmonitored rivers. Rivers with larger drainage basins often produce less load per unit area than do smaller rivers (Richards, 1989).

4. *Point-source loadings of total phosphorus and suspended sediment are small compared to nonpoint-source loadings.* This is a valid assumption for suspended sediment, but not entirely valid for total phosphorus. Loadings from point sources within the basins have been estimated to contribute as much as 15 percent of the long-term average load of total phosphorus from the mouth of the Fox River (a river expected to be strongly affected by point sources); however, this was a worse case scenario and assumed that 100 percent of the load from point sources within the basin reaches the river mouth (Robertson and Saad, 1996).

5. *The partitioning coefficient between PCB concentrations in the bed sediment and suspended sediment is similar among all the rivers examined and does not vary seasonally.* Because the partitioning coefficient is not 1.0, only relative loads of PCB's were estimated.

ENVIRONMENTAL CHARACTERISTICS OF LAKE MICHIGAN AND LAKE SUPERIOR BASINS

The topography of Lake Michigan and Lake Superior Basins is highly variable. Most rivers draining into the southern two-thirds of Lake Michigan and those in the eastern half of the Upper Peninsula of Michigan have low gradients (mild slopes, generally less than 1.5 m/km; table 4). However, those draining into the northern one-third of Lake Michigan, and into the western part of Lake Superior have relatively high gradients (steep slopes, generally greater than 1.5 m/km). In the statistical analysis, the topography of each basin was quantified by the gradient of each river.

A generalized map of the surficial deposits for the area (fig. 2) was derived from Quaternary geologic maps published by Richmond and Fullerton (1983), Farrand and Bell (1982), and Hobbs and Goebel (1982). Sand and gravel deposits predominate throughout most of the area; however, extensive clay deposits extend along the western side of Lake Michigan and the southwestern side of Lake Superior. Extensive areas of loamy deposits cover the Upper Peninsula of Michigan and the area near the Grand River in lower Michigan. The percentages of each type of surficial deposit in each river basin are given in table 4. These values were based on the percentages of each type of surficial deposit for the entire hydrologic units through which the rivers flowed (fig. 1). For most of the reference rivers, the drainage basin of the river represented almost the entire hydrologic unit; however, the drainage basin of many of the smaller rivers represented only a portion of the hydrologic unit. In the statistical analysis, the surficial deposits of each river basin larger

Table 5. Polychlorinated biphenyls (PCB's) concentration in the bed sediment and water column of rivers in the United States draining into Lakes Michigan and Superior with drainage areas greater than 325 square kilometers

[HD, near Holland, Mich.; SH, near South Haven, Mich.; Locations of rivers shown in fig. 1]

River	Identifier	PCB concentration bed sediment[1] (mg/kg)	PCB concentration water column[2] (mg/kg)
		LAKE MICHIGAN	
		Lower Michigan	
Jordan	A	0.001	
Boardman	B	.001	
Betsie	C	.001	
Manistee	11	.12	0.010
Big Sable	D	.001	
Pere Marquette	E	.022	.014
Pentwater	F	.001	
White	G	5.0	
Muskegon	10	.02	.009
Grand	9	.04	.057
Pigeon	H	.001	
Black (HD)	I	12.55	
Kalamazoo	8	22.7	.040
Black (SH)	J	.2	
St. Joseph	7	.11	.014
Indiana			
Grand Calumet	18	12.48	.231
		Wisconsin	
Root	K	.001	
Milwaukee	6	5.9	.097
Sheboygan	L	4.2	.103
Manitowoc	5	.153	
West Twin	M	.001	
East Twin	N	.001	
Kewaunee	O	.05	
Fox	4	14.3	.098
Duck	P	.001	
Pensaukee	Q	.1	
Oconto	R	.01	.007
Peshtigo	S	.001	.011
Menominee	3	.8	.015

Table 5. Polychlorinated biphenyls (PCB's) concentration in the bed sediment and water column of rivers in the United States draining into Lakes Michigan and Superior with drainage areas greater than 325 square kilometers—Continued

River	Identifier	PCB concentretion bed sediment[1] (mg/kg)	PCB concentration weter column[2] (mg/kg)
		LAKE MICHIGAN—Continued	
		Upper Michigan	
Cedar	T	.001	
Ford	2	.001	
Escanaba	1	.001	.041
Rapid	U	.001	
Whitefish	V	.01	
Sturgeon	W	.001	
Manistique	X	15.62	.024
		LAKE SUPERIOR	
		Upper Michigan	
Waiska		.001	
Tahquamenon	17	.001	
Two Hearted	Z	.001	
Chocolay	AA	.001	
Dead	AB	.001	
Sturgeon	AC	.001	
Portage Creek	AD	.001	
Ontonagon	16	.001	
Presque Isle	AE	.001	
Black	AF	.001	
		Wisconsin	
Montreal		.001	
Bad	15	.001	
Iron	AH	.001	
Bois Brule	AI	.001	
Amnicon	AJ	.001	
Nemadji	14	.001	
		Minnesota	
St. Louis	13	.056	
Baptism	12	.001	

[1]Bed-sediment PCB concentrations were obtained from K. Klewin (U.S. Environmental Protection Agency, written commun., 1994).
[2]Water-column PCB concentrations were obtained from Marti and Armstrong (1990).

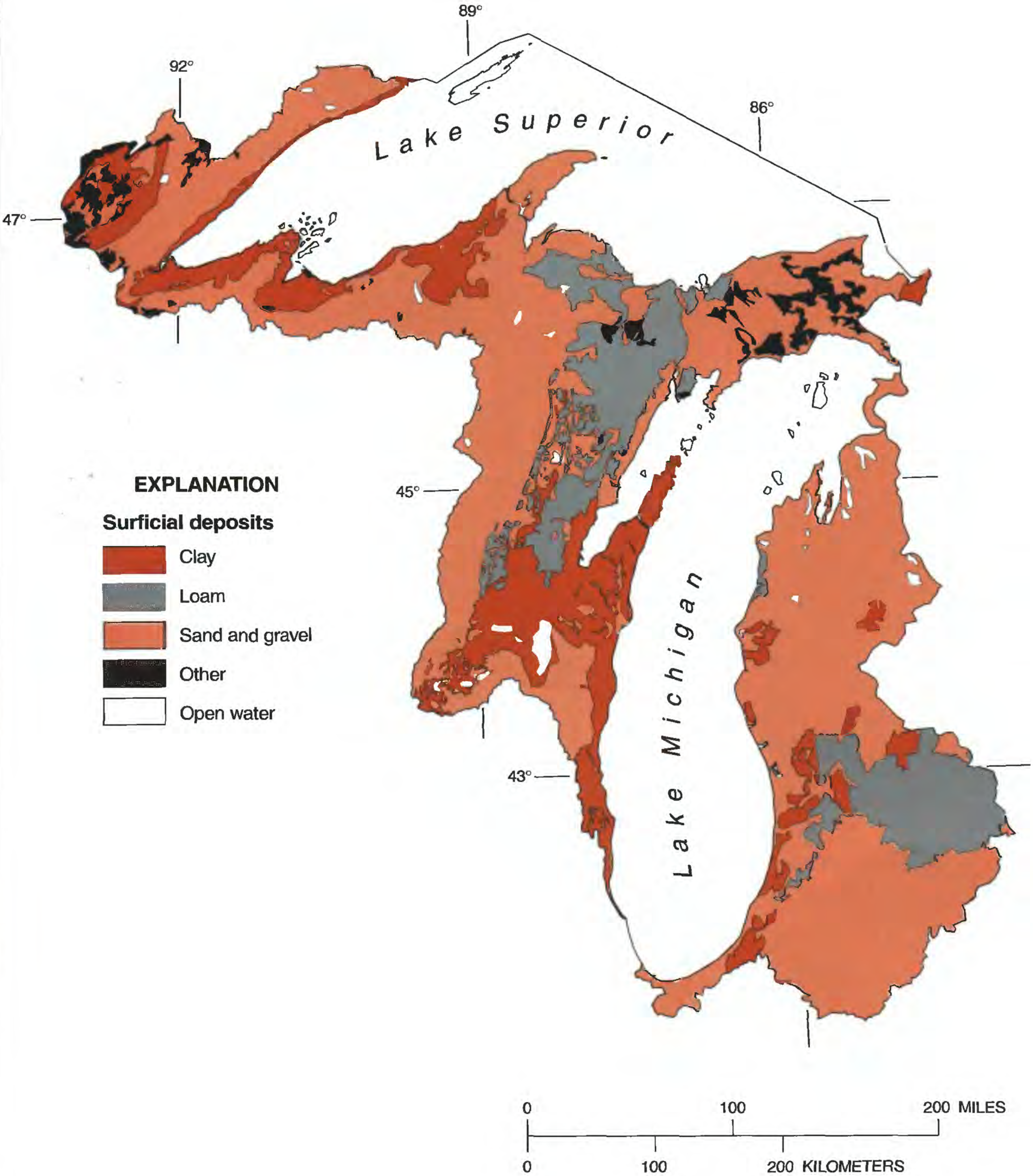

Figure 2. Texture of surficial deposits in the Lake Michigan and Lake Superior Basins.

than 325 km^2 were quantified by the percentage of clay in each basin.

A generalized map of land-use/land-coverage (hereafter referred to as "land use"; fig. 3) was digitized from a map published in the National Atlas of the United States of America (U.S. Geological Survey, 1970). The area is dominated by forested areas in the northern half and agricultural areas in the southern half. The percentages of each type of land use in each river basin are given in table 4. These values were based on the percentages of each type of land use for the entire hydrologic units through which the rivers flow (fig. 1). In the statistical analysis, the land use of each river basin larger than 325 km^2 was quantified by the percentage of agriculture in the basin.

RIVER YIELDS AND ESTIMATES OF REGIONAL LOADS

Suspended-Sediment Yields and Loads

Daily suspended-sediment loads were calculated for the 16-year period and the high-flow events for the reference rivers and used to compute average daily and annual suspended-sediment yields (load per unit area) for the 16-year period and daily yields for each high-flow event. The suspended-sediment yields for the 16-year period and the 10-year, 1-day event are given in table 6. Rankings of yields for all types of high-flow events were very similar; therefore, just the 10-year, 1-day event is discussed in detail. Average daily suspended-sediment yields for the entire 16-year period range from 0.05 kg/ha (Escanaba) to 2.95 kg/ha (Nemadji). These two extremes are both from basins dominated by forest. For the 10-year, 1-day high-flow event, daily suspended-sediment yields range from 0.7 kg/ha (Manistee) to 3,200 kg/ha (Bad); again both areas are dominated by forest. The fact that the extremes in average and event yields were found in areas dominated by forest indicate that factors other than, or in addition to, land use are important.

To determine how the environmental characteristics (land use, surficial deposits, and topography) relate to suspended-sediment yields, multivariate analyses were done for the daily average yields and for the 10-year, 1-day event yields. Both sets of suspended-sediment yields were positively correlated with stream gradient and percentage of clay in the basin and were negatively correlated with percentage of agriculture in the basin. The negative correlation between yields and percentage of agriculture may be due to a strong inverse relation between stream gradient (the factor with the highest correlation with yields) and percentage of agriculture.

The statistical model that explained the most variability in daily average suspended-sediment yields was a function of stream gradient and percentage of clay in the basin; collectively, these two factors explained 59 percent of the variance, if the Baptism River was omitted from the data set (fig. 4). Stream gradient alone, explained 53 percent of the variance. Therefore, the most important environmental factor affecting suspended-sediment yields was the topography of the area (stream gradient), and the second most important factor was the type of surficial deposit (percentage of clay). The Baptism River has the highest gradient, but it flows over extensive bedrock outcrops and has several waterfalls; therefore, little erosion occurs.

The statistical model that explained the most variability in the suspended-sediment yields during high flow was a function of stream gradient; this relation explained 59 percent of the variance (fig. 4) (in this model, the Baptism River was omitted from the data set). This analysis was biased by one river; therefore, to see which was the second most important factor, the same analysis was done without stream gradient as an independent variable. The resulting model that explained the most variability in the suspended-sediment yields during high flow was a function of the percentage of agriculture and percentage of clay in the basin; collectively, these two factors explained 46 percent of the variance (fig. 4). The percentage of agriculture and clay in the basins, independently, explained 22 percent and 10 percent, respectively. Therefore, the most important environmental factor affecting suspended-sediment yields during high flows was the topography of the area (stream gradient), and the second most important factor was the land use of the basin (percentage of agriculture).

The relative importance of these environmental factors can be seen by comparing the basins of the three reference rivers with the highest yields of suspended sediment (Bad, Ontonagon, and Nemadji Rivers). These three basins have different surficial deposits, but all have high gradients and are almost completely forested (table 4). The high yields from forested areas with varied surficial deposits but similar steep terrain demonstrates the importance of the topography. Most

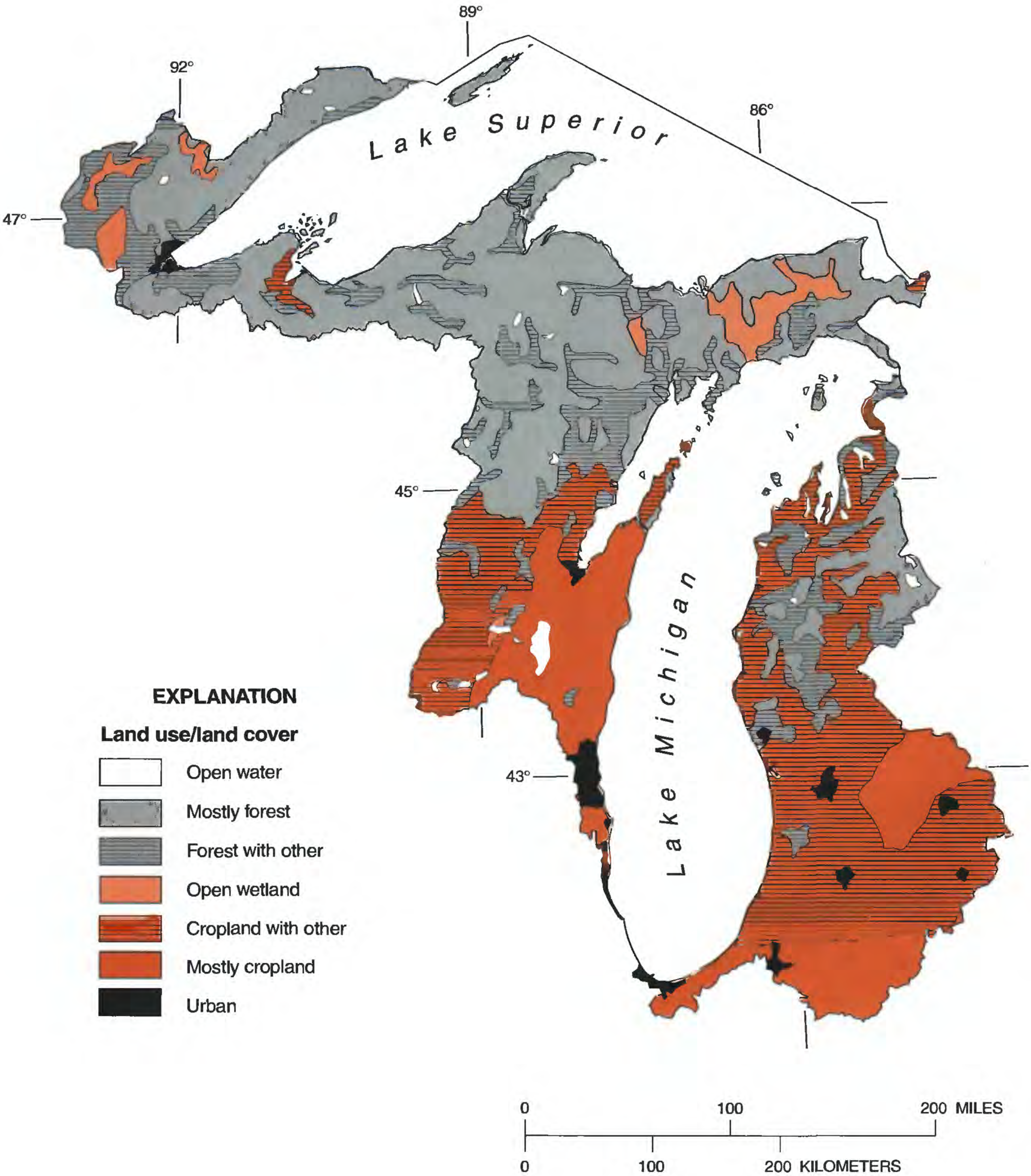

Figure 3. Land-use categories for the Lake Michigan and Lake Superior Basins.

Table 6. Suspended-sediment and total phosphorus yields from the reference rivers
[kg/ha/d, kilograms per hectare per day; g/ha/d, grams per hectare per day; kg/ha/yr, kilograms per hectare per year. Location of rivers is shown in fig. 1]

River (identification number)	Suspended sediment			Total phosphorus		
	Average		10-year,1-day event[1]	Average		10-year, 1-day event[1]
	(kg/ha/d)	(kg/ha/yr)	(kg/ha/d)	(g/ha/d)	(kg/ha/yr)	(g/ha/d)
Escanaba (1)	0.05	17	0.9	0.18	0.06	2.3
Ford (2)	.19	68	17.9	.18	.07	5.7
Menominee (3)	.06	23	2.3	.25	.09	1.2
Fox (4)	.22	79	4.6	.86	.31	5.5
Manitowoc (5)	.39	141	28.7	1.32	.48	41.2
Milwaukee (6)	.29	106	20.4	1.30	.47	65.1
St. Joseph (7)	.28	102	6.2	.80	.29	14.3
Kalamazoo (8)	.20	74	1.9	.76	.28	5.2
Grand (9)	.29	107	10.0	.920	.33	14.8
Muskegon (10)	.25	92	5.5	.33	.12	4.6
Manistee (11)	.11	41	.7	.33	.12	2.8
Baptism (12)	.15	56	10.2	.37	.14	20.4
St. Louis (13)	.24	89	18.6	.48	.18	16.4
Nemadji[2] (14)	2.95	1,080	213.0	1.31	.48	93.3
Bad (15)	2.81	1,030	3,200.0	.85	.31	148.0
Ontonagon (16)	2.01	730	356.0	.74	.27	24.5
Tahquamenon (17)	.10	38	.8	.28	.10	1.2
Grand Calumet (18)	.74	270	5.4	8.78	3.20	344.0

[1]Yields for the 10-year, 1-day high-flow event that occurs during summer.
[2]Yields during 10-year, 1-day event were estimated using the flows calculated for the Bad River, adjusted for the difference in drainage areas.

of the time these forested areas produced small loadings; however, the yields during the few high-flow events were so great that these rivers were the dominant contributors over extended periods. These areas, primarily found along the south shore of western Lake Superior (fig. 1), produced not only the highest yields but also the highest overall loads of suspended sediment. In the Bad River Basin, for example, high-flow events cause substantial stream-bank slumping and erosion. Land use appears to be only a minor factor affecting the ranking of these rivers for suspended-sediment contributions.

Only one reference river was chosen to represent both the high-flow and the long-term loading of suspended sediment for each of the remaining 36 rivers. The relative importance of each of the three environmental factors for both cases was considered in choosing the reference river; however, the factors for the long-term loading were more highly weighted than the factors for high-flow loading. Therefore, the most important environmental characteristic was the topography of the area, and the second most important characteristic was the type of surficial deposit. If the topography and surficial deposits of an unmonitored river were similar to more than one reference river, then the reference river with the most similar land use was chosen. With the environmental information for each of the remaining 36 rivers (table 4) and this rank-

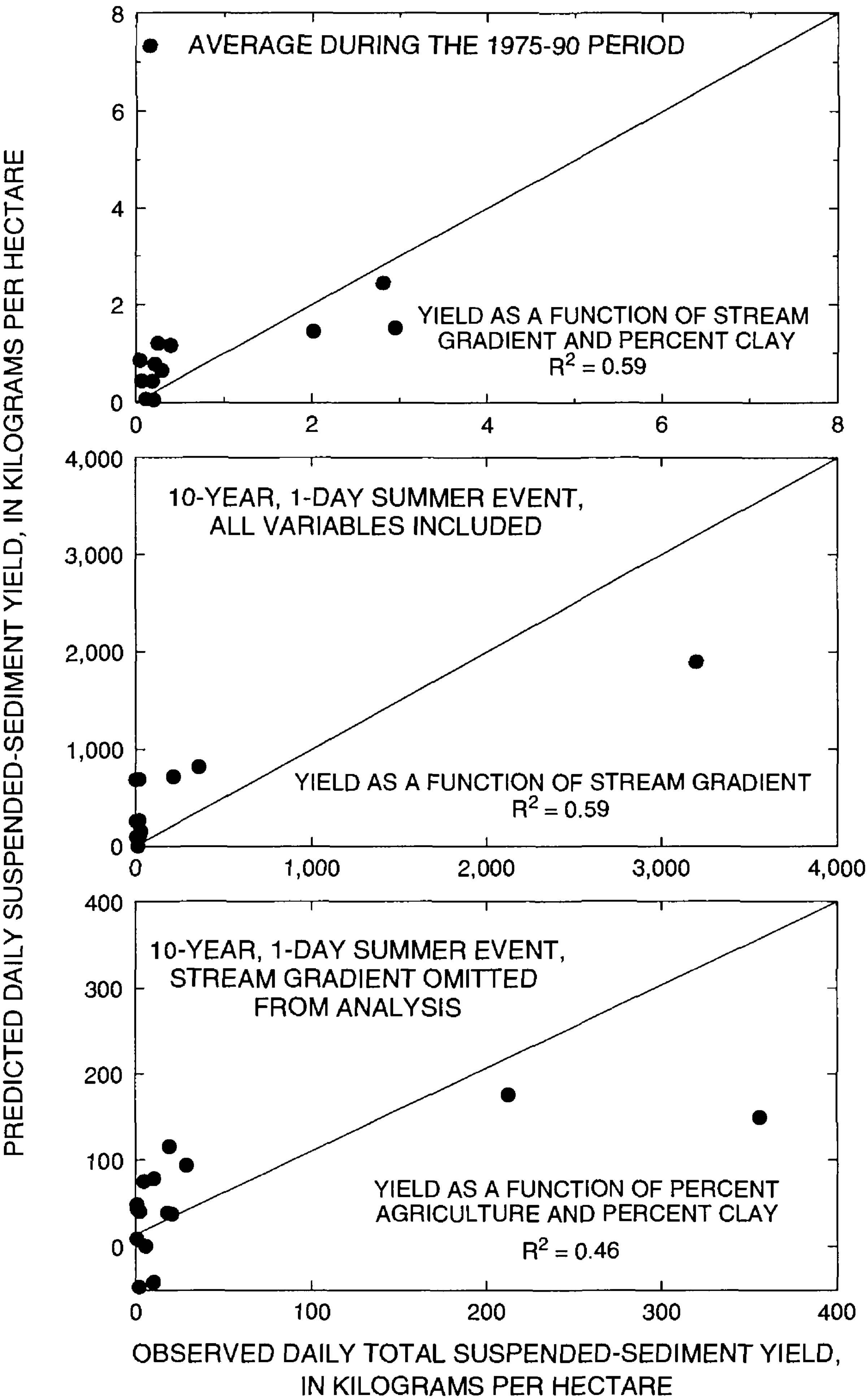

Figure 4. Results of multiple regression analyses between suspended-sediment yield and stream gradient, percentage of clay in basin, and percentage of agriculture in basin for the average daily yield of the 1975–90 period and the 10-year, 1-day summer event for selected tributaries to Lakes Michigan and Superior.

ing of environmental factors, a reference river was chosen for each remaining river (table 7).

Once a reference river for suspended sediment was chosen for each of the unmonitored rivers, the total load from each unmonitored river was obtained by multiplying the total estimated load of the reference river by the ratio of drainage area of the unmonitored river to that of the reference river. The average daily loads of suspended sediment into Lakes Michigan and Superior, collectively, and Lake Michigan and Lake Superior, independently, for the 16-year period and total load for each type of event are summarized in tables 8, 9 and 10, respectively. The daily loads are illustrated in figure 5 for the average and for the 10-year, 1-day event during summer. The rivers in tables 8, 9 and 10 are ordered by their relative contributions during the 10-year, 1-day summer event. The average daily load of suspended sediment into Lakes Michigan and Superior from these 54 rivers during this 16-year period is estimated to be approximately 5.9 million kg; loads are between 1.3 billion kg (spring) and 1.9 billion kg (summer) for the 10-year, 1-day event (table 8). These estimates indicate that, for similar streamflows a higher load of suspended sediment (usually by 25 to 30 percent) would occur during the summer event in almost all cases a higher. However, high-flow events are more common during spring. Much of the runoff in spring is caused by snowmelt that may not directly flow over exposed soils. Therefore, lower suspended-sediment concentrations (and loads) are measured during spring events than measured during summer events.

The total event load of suspended sediment increased by approximately 40 percent (10-year) to 60 percent (50-year) when the total load over a 3-day event was estimated; total event load increased by approximately 55 percent (10-year) to 210 percent (50-year) when a 7-day event was considered, even though significantly longer periods were being integrated. This nonlinear increase in loading resulted from lower streamflows during the extended events.

The 50-year event increased the total load of suspended sediment from the 10-year event by factors of approximately 4 for the 1- and 3-day event, but by approximately 8 during the 7-day event.

On average, the rivers draining into Lake Superior contributed 1.8 times more suspended sediment than those draining into Lake Michigan. During high-flow events, the difference was much more extreme: rivers draining into Lake Superior contributed 7 to 60 times more suspended sediment. The most extreme differences in loadings was for the short-term (1-day), extreme (50-year) events. The single largest contributor of suspended sediment during events and during the entire period was the Bad River, which supplied more than 12 percent of the total load to both lakes over the entire period and between 31 and 52 percent during events (fig. 5). The top three contributors during the entire period (Bad, Ontonagon, and Sturgeon Rivers) and the top nine contributors during high-flow events drain into Lake Superior. During the entire period, the Grand, Fox, and St. Joseph Rivers also were significant contributors of suspended sediment (7, 6, and 6 percent, respectively).

The Grand River, the largest contributor of suspended sediment to Lake Michigan, contributed approximately 20 percent of the total load during the 16-year period and 13 to 23 percent during high-flow events (table 9). The Fox River was the second largest contributor during the entire period (17 percent); however, during high-flow events, the Fox River usually contributed less than the St. Joseph River (9 to 12 percent). Other significant contributors of suspended sediment during high-flow events included the Milwaukee, Manitowoc, and Muskegon Rivers.

The Bad River, the largest contributor of suspended sediment to Lake Superior, contributed approximately 19 percent of the load during the entire period and 39 to 52 percent of that delivered during high-flow events (table 10). The Sturgeon River was the third largest contributor during the entire period (14 percent); however, during high-flow events it was the second largest contributor (25 to 38 percent). For the entire period, the Ontonagon River was the second largest contributor (19 percent), and the Portage River was the fourth largest contributor (14 percent).

Total Phosphorus Yields and Loads

Average daily total phosphorus yields for the 16-year period and the 10-year, 1-day event are listed in table 6 for each reference river. Rankings of yields for all types of high-flow events again were very similar; therefore, just the 10-year, 1-day event is discussed in detail. Average daily total phosphorus yields ranged from 0.18 g/ha (0.06 kg/ha per year) (Escanaba) to 8.78 g/ha (3.20 kg/ha per year) (Grand Calumet). For the 10-year, 1-day event, daily total phosphorus yields ranged from 1.2 kg/ha (Menominee and Tahquamenon) to 344 kg/ha (Grand Calumet). Basins dominated by forest

Table 7. Reference rivers for suspended sediment and total phosphorus for all rivers
[HD, near Holland, Mich.; SH, near South Haven, Mich.; Location of rivers is shown in fig. 1]

River	Identifier	Reference River	
		Suspended sediment	Total phosphorus
		LAKE MICHIGAN	
		Lower Michigan	
Jordan	A	Baptism	Baptism
Boardman	B	Muskegon	Muskegon
Betsie	C	Muskegon	Muskegon
Manistee	11	Manistee	Manistee
Big Sable	D	Muskegon	Muskegon
Pere Marquette	E	Muskegon	Muskegon
Pentwater	F	Muskegon	Muskegon
White	G	Muskegon	Muskegon
Muskegon	10	Muskegon	Muskegon
Grand	9	Grand	Grand
Pigeon	H	Grand	Fox
Black (HD)	I	Grand	Fox
Kalamazoo	8	Kalamazoo	Kalamazoo
Black (SH)	J	Kalamazoo	Fox
St. Joseph	7	St. Joseph	St. Joseph
		Indiana	
Grand Calumet	18	Grand Calumet	Grand Calumet
		Wisconsin	
Root	K	Milwaukee	Milwaukee
Milwaukee	6	Milwaukee	Milwaukee
Sheboygan	L	Manitowoc	Manitowoc
Manitowoc	5	Manitowoc	Manitowoc
West Twin	M	Manitowoc	Manitowoc
East Twin	N	Manitowoc	Manitowoc
Kewaunee	O	Manitowoc	Manitowoc
Fox	4	Fox	Fox
Duck	P	Manitowoc	Manitowoc
Pensaukee	Q	Manitowoc	Manitowoc
Oconto	R	Menominee	St. Louis
Peshtigo	S	Menominee	Menominee
Menominee	3	Menominee	Menominee

Table 7. Reference rivers for suspended sediment and total phosphorus for all rivers—Continued

River	Identifier	Reference River	
		Suspended sediment	Total phosphorus
		LAKE MICHIGAN—Continued	
		Upper Michigan	
Cedar	T	Ford	Ford
Ford	2	Ford	Ford
Escanaba	1	Escanaba	Escanaba
Rapid	U	Ford	Ford
Whitefish	V	Ford	Ford
Sturgeon	W	Ford	Ford
Manistique	X	Tahquamenon	Tahquamenor
		LAKE SUPERIOR	
		Upper Michigan	
Waiska	Y	Fox	Fox
Tahquamenon	17	Tahquamenon	Tahquamenor
Two Hearted	Z	Tahquamenon	Tahquamenor
Chocolay	AA	Tahquamenon	Tahquamenor
Dead	AB	Tahquamenon	Tahquamenor
Sturgeon	AC	Bad	Baptism
Portage Creek	AD	Ontonagon	Ontonagon
Ontonagon	16	Ontonagon	Ontonagon
Presque Isle	AE	Ontonagon	Ontonagon
Black	AF	Ontonagon	Ontonagon
		Wisconsin	
Montreal	AG	Ontonagon	Ontonagon
Bad	15	Bad	Bad
Iron	AH	Nemadji	Nemadji
Bois Brule	AI	Tahquamenon	Nemadji
Amnicon	AJ	Nemadji	Nemadji
Nemadji	14	Nemadji	Nemadji
		Minnesota	
St. Louis	13	St. Louis	St. Louis
Baptism	12	Baptism	Baptism

Table 8. Percentages of the total load of suspended sediment to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the 10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.; LS, Lake Superior; LM, Lake Michigan]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Bad	12.42	44.81	41.80	51.28	49.45	39.72	36.44	51.73	50.32	33.64	30.61	50.22	48.30
Sturgeon (LS)	8.97	32.34	30.17	37.01	35.69	28.67	26.30	37.33	36.32	24.28	22.09	36.25	34.86
Ontonagon	12.23	6.87	9.08	3.23	4.42	8.95	11.61	2.29	3.16	10.23	13.13	3.53	4.82
Portage	8.71	4.89	6.47	2.30	3.15	6.37	8.27	1.63	2.25	7.29	9.35	2.51	3.43
Presque Isle	3.16	1.77	2.35	.83	1.14	2.31	3.00	.59	.82	2.64	3.39	.91	1.24
Montreal	2.32	1.30	1.72	.61	.84	1.70	2.21	.43	.60	1.94	2.49	.67	.92
Nemadji	5.64	1.29	1.54	1.19	1.47	1.28	1.50	1.27	1.57	1.22	1.41	1.07	1.31
Black	2.26	1.27	1.68	.60	.82	1.65	2.15	.42	.58	1.89	2.43	.65	.89
St. Louis	3.72	.90	.92	.40	.42	1.68	1.67	.70	.74	3.14	3.10	.58	.60
Grand	7.18	.77	.56	.31	.23	1.56	1.12	.51	.39	2.68	1.91	.49	.37
Iron	1.85	.42	.50	.39	.48	.42	.49	.41	.51	.40	.46	.35	.43
St. Joseph	5.71	.40	.37	.18	.17	.72	.65	.25	.23	1.48	1.32	.29	.27
Fox	5.96	.40	.28	.14	.10	.89	.60	.29	.21	1.86	1.26	.35	.25
Amnicon	1.69	.39	.46	.36	.44	.39	.45	.38	.47	.37	.42	.32	.39
Milwaukee	1.11	.25	.19	.09	.07	.42	.31	.16	.12	.61	.44	.15	.12
Manitowoc	.91	.21	.18	.14	.12	.35	.29	.20	.17	.69	.56	.17	.14
Muskegon	2.92	.20	.22	.10	.12	.36	.39	.15	.17	.65	.69	.18	.20
Sheboygan	.72	.17	.14	.11	.10	.28	.23	.16	.14	.55	.45	.13	.12
Menominee	1.14	.13	.15	.07	.08	.21	.24	.10	.12	.41	.46	.08	.10
Ford	.39	.12	.14	.07	.09	.21	.24	.12	.15	.43	.50	.16	.20
Cedar	.32	.10	.11	.06	.07	.17	.19	.10	.12	.35	.40	.13	.16
Whitefish	.26	.08	.10	.05	.06	.14	.16	.08	.10	.29	.34	.11	.14
West Twin	.30	.07	.06	.05	.04	.12	.10	.07	.06	.23	.18	.05	.05
Duck	.26	.06	.05	.04	.03	.10	.08	.06	.05	.20	.16	.05	.04
Pensaukee	.25	.06	.05	.04	.03	.10	.08	.05	.05	.19	.15	.05	.04
Root	.25	.06	.04	.02	.02	.10	.07	.04	.03	.14	.10	.03	.03
Pere Marquette	.81	.06	.06	.03	.03	.10	.11	.04	.05	.18	.19	.05	.06
Kalamazoo	1.82	.05	.04	.02	.01	.11	.07	.03	.02	.22	.16	.04	.03

Table 8. Percentages of the total load of suspended sediment to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Kewaunee	.23	.05	.05	.04	.03	.09	.07	.05	.04	.18	.14	.04	.04
East Twin	.23	.05	.04	.03	.03	.09	.07	.05	.04	.17	.14	.04	.04
Sturgeon (LM)	.17	.05	.06	.03	.04	.09	.11	.05	.07	.19	.22	.07	.09
White	.58	.04	.04	.02	.02	.07	.08	.03	.03	.13	.14	.04	.04
Peshtigo	.31	.03	.04	.02	.02	.06	.06	.03	.03	.11	.13	.02	.03
Rapid	.11	.03	.04	.02	.02	.06	.07	.04	.04	.12	.14	.05	.06
Oconto	.27	.03	.04	.02	.02	.05	.06	.02	.03	.10	.11	.02	.02
Black (HD)	.23	.02	.02	.01	.01	.05	.04	.02	.01	.08	.06	.02	.01
Jordan	.11	.02	.03	.01	.02	.04	.05	.01	.02	.05	.07	.01	.01
Boardman	.31	.02	.02	.01	.01	.04	.04	.02	.02	.07	.07	.02	.02
Baptism	.10	.02	.03	.01	.01	.03	.05	.01	.02	.05	.06	.01	.01
Betsie	.28	.02	.02	.01	.01	.03	.04	.01	.02	.06	.07	.02	.02
Manistee	.96	.02	.02	.01	.01	.03	.04	.01	.01	.06	.08	.01	.01
Pigeon	.16	.02	.01	.01	.01	.04	.03	.01	.01	.06	.04	.01	.01
Manistique	.66	.02	.02	.01	.01	.03	.04	.01	.01	.07	.07	.01	.01
Big Sable	.23	.02	.02	.01	.01	.03	.03	.01	.01	.05	.05	.01	.02
Pentwater	.19	.01	.01	.01	.01	.02	.03	.01	.01	.04	.04	.01	.01
Escanaba	.19	.01	.02	.00	.01	.02	.03	.01	.01	.05	.06	.01	.01
Waiska	.14	.01	.01	.00	.00	.02	.01	.01	.01	.04	.03	.01	.01
Tahquamenon	.38	.01	.01	.00	.00	.02	.02	.01	.01	.04	.04	.01	.01
Black (SH)	.24	.01	.01	.00	.00	.01	.01	.00	.00	.03	.02	.01	.00
Grand Calumet	.28	.01	.01	.00	.00	.00	.01	.00	.00	.00	.01	.00	.00
Two Hearted	.09	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Bois Brule	.08	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Dead	.08	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Chocolay	.07	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Total load (millions of kilograms)	5.92	1,870	1,340	7,380	5,130	2,580	1,900	11,700	8,090	2,850	2,120	23,000	16,100

Table 9. Percentages of the total load of suspended sediment to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the 10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Grand	19.91	20.95	17.22	17.55	14.10	23.09	19.25	18.20	14.76	20.95	17.43	16.67	13.39
St. Joseph	15.84	10.99	11.34	10.31	10.40	10.60	11.10	8.82	8.98	11.55	12.05	9.79	9.86
Fox	16.54	10.92	8.49	7.94	6.04	13.10	10.36	10.43	8.02	14.52	11.52	11.89	9.10
Milwaukee	3.09	6.71	5.72	5.13	4.31	6.19	5.33	5.68	4.76	4.76	4.06	5.06	4.16
Manitowoc	2.52	5.79	5.48	7.89	7.31	5.20	4.98	7.12	6.63	5.39	5.11	5.72	5.23
Muskegon	8.10	5.47	6.76	5.84	7.06	5.34	6.68	5.33	6.48	5.10	6.33	6.19	7.40
Sheboygan	2.00	4.61	4.37	6.29	5.82	4.14	3.97	5.67	5.28	4.29	4.07	4.56	4.17
Menominee	3.15	3.49	4.56	3.82	4.88	3.05	4.04	3.60	4.65	3.20	4.24	2.86	3.64
Ford	1.08	3.22	4.33	3.94	5.18	3.03	4.11	4.42	5.83	3.38	4.53	5.61	7.24
Cedar	.88	2.61	3.51	3.20	4.21	2.46	3.34	3.59	4.73	2.75	3.68	4.55	5.87
Whitefish	.73	2.17	2.92	2.66	3.50	2.05	2.78	2.98	3.94	2.28	3.06	3.78	4.89
West Twin	.83	1.90	1.80	2.59	2.40	1.71	1.63	2.34	2.18	1.77	1.68	1.88	1.72
Duck	.72	1.66	1.58	2.27	2.10	1.49	1.43	2.05	1.91	1.55	1.47	1.64	1.50
Pensaukee	.68	1.57	1.48	2.13	1.98	1.41	1.35	1.93	1.79	1.46	1.38	1.55	1.42
Root	.70	1.53	1.31	1.17	.98	1.41	1.22	1.30	1.09	1.09	.93	1.15	.95
Pere Marquette	2.25	1.52	1.88	1.63	1.96	1.49	1.86	1.48	1.80	1.42	1.76	1.72	2.06
Kalamazoo	5.04	1.49	1.19	.99	.77	1.57	1.27	1.04	.82	1.75	1.43	1.27	1.00
Kewaunee	.64	1.48	1.40	2.02	1.87	1.33	1.27	1.82	1.69	1.38	1.31	1.46	1.34
East Twin	.62	1.44	1.36	1.96	1.81	1.29	1.24	1.77	1.65	1.34	1.27	1.42	1.30
Sturgeon	.48	1.43	1.92	1.75	2.30	1.35	1.83	1.96	2.59	1.50	2.01	2.49	3.22
White	1.60	1.08	1.34	1.16	1.40	1.06	1.32	1.05	1.28	1.01	1.25	1.22	1.46
Peshtigo	.85	.94	1.23	1.03	1.32	.82	1.09	.97	1.26	.87	1.15	.77	.98
Rapid	.31	.92	1.24	1.13	1.49	.87	1.18	1.27	1.68	.97	1.30	1.61	2.08

Table 9. Percentages of the total load of suspended sediment to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Oconto	.76	.84	1.10	.92	1.18	.74	.98	.87	1.12	.77	1.02	.69	.88
Black (HD)	.63	.66	.54	.55	.45	.73	.61	.57	.47	.66	.55	.53	.42
Jordan	.30	.61	.97	.63	.98	.55	.89	.44	.69	.41	.64	.35	.53
Boardman	.86	.58	.72	.62	.75	.57	.71	.57	.69	.54	.68	.66	.79
Betsie	.77	.52	.64	.55	.67	.51	.63	.50	.61	.48	.60	.59	.70
Manistee	2.67	.50	.76	.33	.49	.47	.73	.30	.45	.46	.71	.28	.41
Pigeon	.45	.47	.39	.39	.32	.52	.43	.41	.33	.47	.39	.37	.30
Manistique	1.83	.43	.52	.29	.34	.50	.61	.31	.37	.56	.68	.35	.41
Big Sable	.63	.42	.52	.45	.55	.41	.52	.41	.50	.39	.49	.48	.57
Pentwater	.52	.35	.44	.38	.46	.35	.43	.34	.42	.33	.41	.40	.48
Escanaba	.54	.33	.52	.25	.38	.35	.55	.25	.39	.36	.58	.23	.35
Black (SH)	.68	.20	.16	.13	.10	.21	.17	.14	.11	.24	.19	.17	.14
Grand Calumet	.79	.18	.28	.09	.14	.07	.11	.04	.06	.03	.05	.02	.03
Total load (millions of kilograms)	2.13	68.8	43.8	131	85.4	175	110	326	212	364	233	671	445

Table 10. Percentages of the total load of suspended sediment to Lake Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the 10-year, 1-day summer event, the largest contributor being first.]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Bad	19.43	46.53	43.21	52.20	50.29	42.60	38.69	53.21	51.67	38.57	34.37	51.73	49.67
Sturgeon	14.02	33.58	31.19	37.68	36.30	30.75	27.93	38.40	37.30	27.84	24.81	37.34	35.85
Ontonagon	19.13	7.13	9.39	3.29	4.49	9.60	12.33	2.35	3.24	11.73	14.74	3.63	4.96
Portage	13.63	5.08	6.69	2.34	3.20	6.83	8.78	1.68	2.31	8.35	10.50	2.59	3.53
Presque Isle	4.94	1.84	2.42	.85	1.16	2.48	3.18	.61	.84	3.03	3.81	.94	1.28
Montreal	3.63	1.35	1.78	.63	.85	1.82	2.34	.45	.62	2.23	2.80	.69	.94
Nemadji	8.83	1.34	1.59	1.21	1.49	1.38	1.59	1.30	1.61	1.40	1.58	1.10	1.35
Black	3.54	1.32	1.74	.61	.83	1.77	2.28	.44	.60	2.17	2.73	.67	.92
St. Louis	5.82	.94	.95	.40	.43	1.80	1.78	.72	.76	3.60	3.48	.59	.62
Iron	2.89	.44	.52	.40	.49	.45	.52	.43	.53	.46	.52	.36	.44
Amnicon	2.65	.40	.48	.36	.45	.41	.48	.39	.48	.42	.47	.33	.40
Baptism	.15	.02	.03	.01	.02	.04	.05	.01	.02	.05	.07	.01	.01
Waiska	.23	.01	.01	.00	.00	.02	.02	.01	.01	.05	.03	.01	.01
Tahquamenon	.60	.01	.01	.00	.00	.02	.02	.01	.01	.05	.05	.01	.01
Two Hearted	.15	.00	.00	.00	.00	.01	.01	.00	.00	.01	.01	.00	.00
Bois Brule	.13	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Dead	.12	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Chocolay	.11	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Total load (millions of kilograms)	3.78	1,800	1,300	7,250	5,050	2,410	1,790	11,400	7,880	2,480	1,890	22,300	15,600

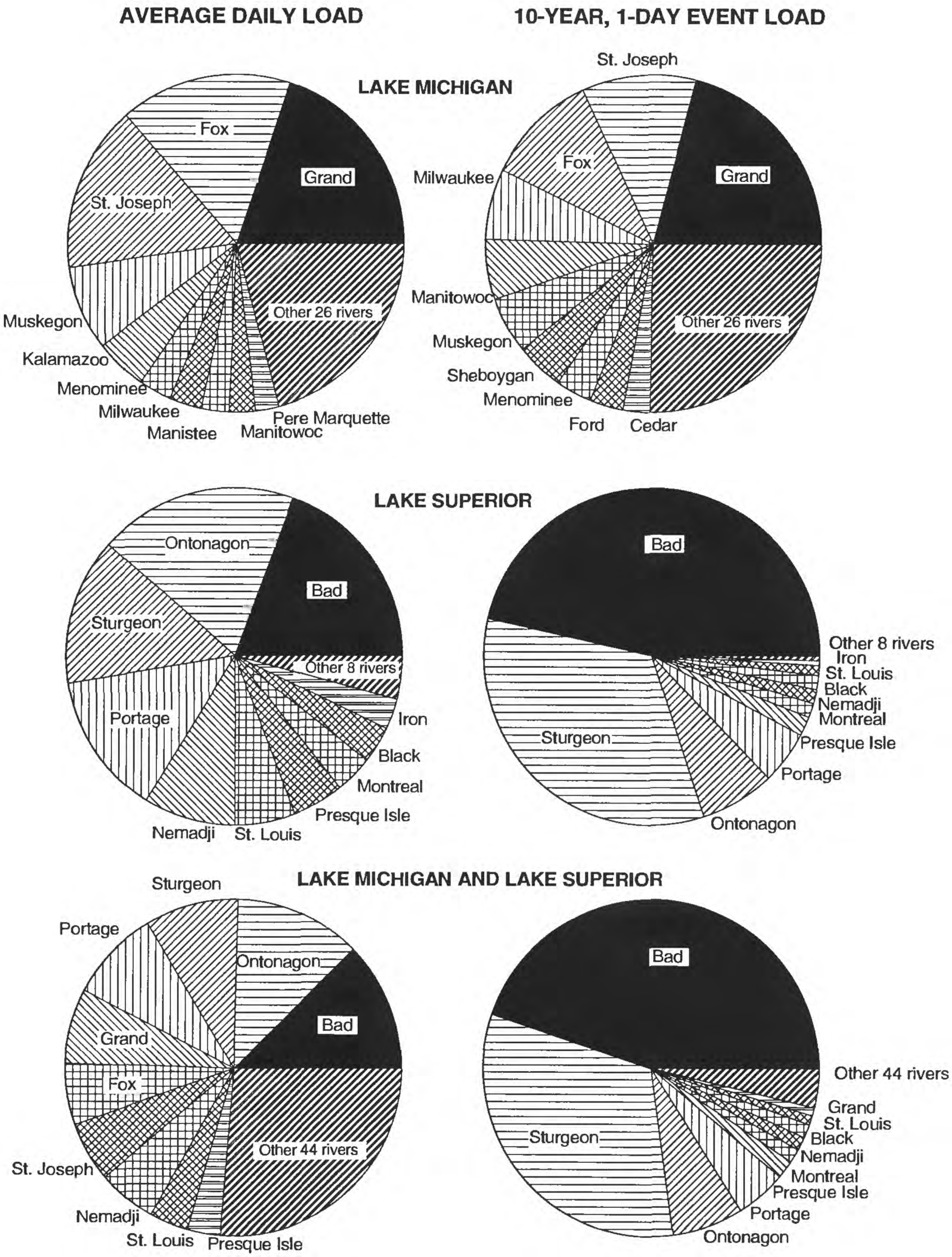

Figure 5. Total suspended-sediment contributions to Lake Michigan and the United States part of Lake Superior, independently and collectively, for the average day of the 1975–90 period and the 10-year, 1-day event.

were near the extremes for both the average daily and 10-year, 1-day event yields. This variability indicates factors other than, or in addition to, land use are important, similar to that found for suspended sediment.

Both the average daily and the 10-year, 1-day event total phosphorus yields were positively correlated with stream gradient and the percentages of clay and agriculture in the basin. The statistical model that explained the most variability in the average daily yields of total phosphorus was a function of the percentages of clay and agriculture in the basin; collectively these two factors explained 78 percent of the variance (fig. 6). The percentage of clay in the basin alone explained 62 percent of the variance. Therefore, the most important environmental factor affecting average total phosphorus yields was the type of surficial deposit (percentage of clay), and the second most important factor was the type of land use (percentage of agriculture).

The statistical model that explained the most variability in the total phosphorus yields during high-flow events was a function of stream gradient and the percentage of clay in the basin; collectively, these two factors explained 60 percent of the variance (fig. 6) if the Baptism River was omitted from the data set. Variability in stream gradient alone explained 53 percent of the variance, if the Baptism River was omitted from the data set. Therefore, the most important environmental factor affecting total phosphorus yields during high-flow events was the topography of the area (stream gradient), and the second most important factor was the type of surficial deposit in the basin (percentage of clay).

The primary factor affecting total phosphorus yields was the type of surficial deposit, and the secondary factor was the topography of the area. The importance of the type of surficial deposit and the steepness of the terrain agrees with the findings by Monteith and Sonzogni (1981) for the area around all of the Great Lakes. Monteith and Sonzogni also found the highest concentrations and accompanying yields over extended periods were from areas of clay surficial deposits and agricultural land practices, such as the Manitowoc River Basin. During short-term, high-flow events, they also found that the steepness of the terrain was the most important factor, and that the highest yields came from areas with high gradients and high clay content, such as the Nemadji and Bad River Basins. Nevertheless, localized areas of urban inputs, such as around the Grand Calumet River, can produce very high yields; the yield from the Grand Calumet area was, in fact, estimated to be the highest in this study.

Therefore, in choosing reference rivers for total phosphorus, the important environmental characteristics were first, the type of surficial deposits in the basin and second, the topography of the area (unless the basin represented a completely urbanized area such as the Grand Calumet Basin). If the surficial deposits and topography of an unmonitored river were similar to more than one reference river, then the reference river with the most similar land use was chosen. With the environmental information for each of the remaining 36 rivers (table 4) and this ranking of environmental factors, a reference river was chosen for each remaining river (table 7).

Once a reference river for total phosphorus was chosen for each of the unmonitored rivers, the total load from each unmonitored river was obtained by multiplying the total estimated load of the reference river by the ratio of drainage area of the unmonitored river to that of the reference river. The average daily total phosphorus load into Lakes Michigan and Superior, collectively, and Lake Michigan and Lake Superior, independently, and the loads during each type of event are summarized in tables 11, 12, and 13. The daily loads are illustrated in fig. 7 for the average and for the 10-year, 1-day event occurring during summer. The average daily total phosphorus load into Lakes Michigan and Superior from these 54 rivers is estimated to be approximately 8,500 kg; loads are between 180,000 kg (spring) and 214,000 kg (summer) for the 10-year, 1-day event (table 11). These estimates again indicate that, for similar flows a higher load (usually by 15 to 18 percent) would occur during summer in almost all cases.

The total event load of total phosphorus during the 10-year event increased by approximately 130 percent when the total load over a 3-day event was estimated and increased by approximately 300 percent when a 7-day event was considered. Therefore, a 3-day event delivers about 2 times as much phosphorus as a 1-day event and a 7-day event delivers about 4 times as much phosphorus as the 1-day event. During the 50-year event, the loads of total phosphorus increase by a factor of approximately 1.7 from those during 10-year event.

The average daily load of total phosphorus into Lake Michigan (6,660 kg/d; table 12)) was 3.7 times larger than that estimated for Lake Superior (1,810

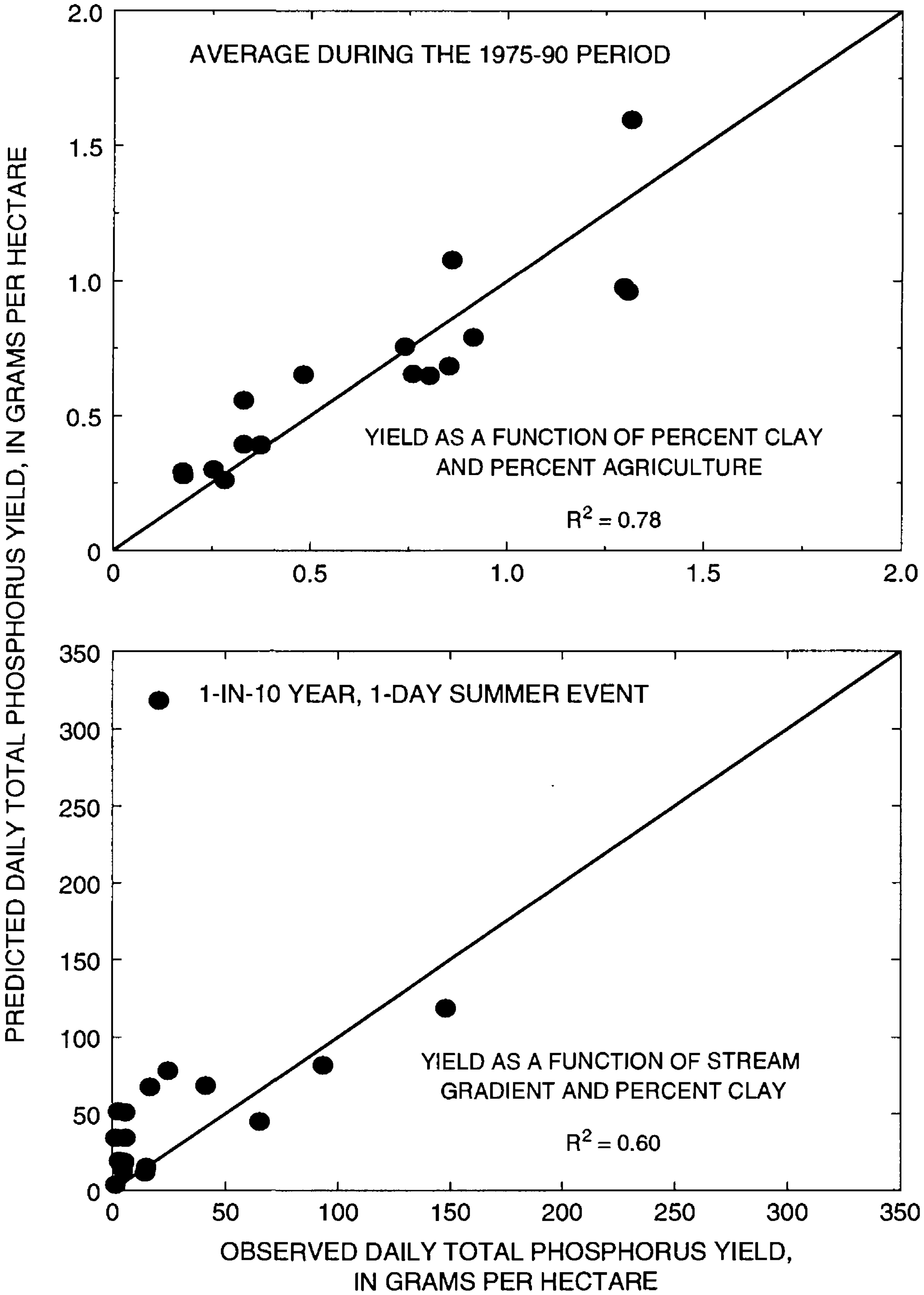

Figure 6. Results of multiple regression analyses between total phosphorus yield and stream gradient, percentage of clay in basin, and percentage of agriculture in basin for the average daily yield of the 1975–90 period and the 10-year, 1-day summer event for selected tributaries to Lakes Michigan and Superior.

Table 11. Percentages of the total load of total phosphorus to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.; LS, Lake Superior; LM, Lake Michigan]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Bad	2.63	18.11	20.35	26.02	28.94	13.43	15.27	21.82	24.54	9.52	11.01	16.95	19.34
Grand	15.59	9.98	11.07	10.60	11.65	11.82	13.25	11.38	12.63	11.48	13.06	11.32	12.73
St. Joseph	11.50	8.12	6.40	8.17	6.38	8.69	6.95	7.76	6.14	10.68	8.72	10.00	8.07
St. Louis	5.16	6.97	7.72	6.19	6.78	8.00	8.97	7.72	8.57	9.10	10.36	7.54	8.48
Milwaukee	3.46	6.87	6.27	5.98	5.41	6.83	6.31	7.20	6.60	5.79	5.45	7.13	6.66
Nemadji	1.75	4.94	4.74	4.89	4.64	4.52	4.40	4.79	4.60	3.94	3.91	3.56	3.48
Fox	16.63	4.25	3.61	2.99	2.51	5.58	4.80	4.17	3.55	6.98	6.12	5.49	4.76
Ontonagon	3.15	4.13	4.55	3.00	3.28	4.33	4.84	2.71	2.99	4.15	4.74	3.37	3.81
Grand Calumet	2.36	3.66	4.35	2.10	2.47	1.59	1.90	.93	1.10	.86	1.04	.52	.63
Portage	2.25	2.94	3.24	2.14	2.33	3.08	3.44	1.93	2.13	2.96	3.38	2.40	2.71
Manitowoc	2.16	2.68	1.97	2.48	1.81	3.01	2.25	2.84	2.10	3.60	2.77	3.05	2.31
Sheboygan	1.72	2.13	1.57	1.98	1.44	2.40	1.79	2.26	1.67	2.87	2.21	2.43	1.84
Bois Brule	.72	2.05	1.96	2.03	1.92	1.87	1.82	1.98	1.91	1.63	1.62	1.48	1.44
Oconto	1.45	1.96	2.17	1.74	1.90	2.25	2.52	2.17	2.40	2.55	2.91	2.11	2.38
Sturgeon (LS)	.83	1.80	2.25	1.97	2.43	1.82	2.29	1.55	1.94	1.53	1.96	1.44	1.82
Iron	.57	1.62	1.55	1.60	1.52	1.48	1.44	1.57	1.51	1.29	1.28	1.17	1.14
Root	.79	1.57	1.43	1.37	1.23	1.56	1.44	1.64	1.51	1.32	1.24	1.63	1.52
Muskegon	2.69	1.49	1.33	1.83	1.62	1.60	1.44	1.83	1.64	1.72	1.58	2.54	2.31
Amnicon	0.52	1.48	1.42	1.47	1.39	1.36	1.32	1.43	1.38	1.18	1.17	1.07	1.04
Kalamazoo	4.79	1.29	.64	.85	.42	1.56	.79	1.05	.52	1.98	1.02	1.46	.75
Presque Isle	.81	1.07	1.18	.78	.85	1.12	1.25	.70	.77	1.07	1.22	.87	.98
West Twin	.71	.88	.65	.82	.59	.99	.74	.93	.69	1.18	.91	1.00	.76
Montreal	.60	.78	.87	.57	.62	.82	.92	.51	.57	.79	.90	.64	.72
Duck	.62	.77	.56	.71	.52	.87	.65	.82	.60	1.04	.80	.88	.66
Black	.58	.76	.84	.56	.61	.80	.89	.50	.55	.77	.88	.62	.70
Pensaukee	.58	.72	.53	.67	.49	.82	.61	.77	.57	.97	.75	.82	.63
Kewaunee	.55	.68	.50	.64	.46	.77	.58	.73	.54	.92	.71	.78	.59
Manistee	1.97	.67	.65	.54	.52	.63	.62	.47	.46	.66	.66	.48	.47

Table 11. Percentages of the total load of total phosphorus to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
East Twin	.54	.66	.49	.62	.45	.75	.56	.70	.52	.89	.69	.76	.57
Menominee	3.17	.60	.58	.42	.41	.71	.70	.52	.51	.88	.88	.61	.60
Pere Marquette	.75	.41	.37	.51	.45	.44	.40	.51	.46	.48	.44	.71	.64
Jordan	.18	.39	.49	.43	.53	.40	.50	.34	.42	.33	.43	.31	.40
Baptism	.17	.36	.45	.39	.48	.36	.46	.31	.38	.31	.39	.29	.36
Ford	.26	.33	.36	.32	.34	.37	.41	.39	.43	.47	.52	.53	.59
White	.53	.29	.26	.36	.32	.32	.29	.36	.32	.34	.31	.50	.46
Escanaba	.51	.27	.32	.21	.25	.32	.38	.24	.28	.38	.45	.26	.32
Cedar	.21	.27	.29	.26	.28	.30	.33	.32	.35	.38	.42	.43	.47
Whitefish	.18	.22	.24	.21	.23	.25	.28	.27	.29	.32	.35	.36	.40
Manistique	1.25	.21	.26	.14	.16	.28	.34	.17	.21	.35	.44	.22	.28
Black (SH)	.73	.19	.16	.13	.11	.24	.21	.18	.16	.31	.27	.24	.21
Peshtigo	.86	.16	.16	.11	.11	.19	.19	.14	.14	.24	.24	.16	.16
Boardman	.29	.16	.14	.19	.17	.17	.15	.20	.18	.18	.17	.27	.25
Sturgeon (LM)	.12	.15	.16	.14	.15	.17	.18	.18	.19	.21	.23	.24	.26
Betsie	.26	.14	.13	.17	.15	.15	.14	.17	.16	.16	.15	.24	.22
Tahquamenon	.73	.13	.15	.08	.10	.16	.20	.10	.12	.20	.25	.13	.16
Black (HD)	.46	.12	.10	.08	.07	.16	.13	.12	.10	.19	.17	.15	.13
Big Sable	.21	.12	.10	.14	.13	.12	.11	.14	.13	.13	.12	.20	.18
Waiska	.40	.10	.09	.07	.06	.13	.12	.10	.09	.17	.15	.13	.11
Pentwater	.17	.10	.09	.12	.10	.10	.09	.12	.11	.11	.10	.16	.15
Rapid	.07	.09	.10	.09	.10	.11	.12	.11	.12	.13	.15	.15	.17
Pigeon	.33	.08	.07	.06	.05	.11	.09	.08	.07	.14	.12	.11	.09
Two Hearted	.18	.03	.04	.02	.02	.04	.05	.02	.03	.05	.06	.03	.04
Dead	.14	.02	.03	.02	.02	.03	.04	.02	.02	.04	.05	.03	.03
Chocolay	.14	.02	.03	.02	.02	.03	.04	.02	.02	.04	.05	.02	.03
Total Load (thousands of kilograms)	8.47	214	180	372	317	493	411	844	710	913	750	1,500	1,250

Table 12. Percentages of the total load of total phosphorus to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Grand	19.82	18.94	22.80	22.00	26.48	20.88	25.36	21.78	26.38	18.74	23.06	19.44	23.76
St. Joseph	14.62	15.41	13.18	16.96	14.50	15.36	13.29	14.87	12.84	17.44	15.39	17.17	15.06
Milwaukee	4.40	13.05	12.92	12.42	12.30	12.06	12.08	13.80	13.78	9.45	9.63	12.24	12.42
Fox	21.14	8.07	7.44	6.20	5.71	9.86	9.19	7.98	7.42	11.40	10.82	9.42	8.88
Grand Calumet	3.00	6.95	8.95	4.37	5.62	2.80	3.64	1.78	2.30	1.40	1.84	.90	1.17
Manitowoc	2.75	5.08	4.05	5.15	4.11	5.32	4.31	5.44	4.39	5.88	4.89	5.23	4.31
Sheboygan	2.19	4.05	3.22	4.11	3.27	4.24	3.43	4.33	3.50	4.69	3.90	4.17	3.44
Oconto	1.84	3.71	4.46	3.60	4.33	3.97	4.81	4.15	5.02	4.17	5.13	3.63	4.44
Root	1.00	2.98	2.95	2.83	2.81	2.75	2.76	3.15	3.14	2.16	2.20	2.79	2.84
Muskegon	3.42	2.82	2.74	3.79	3.68	2.82	2.76	3.51	3.43	2.81	2.80	4.36	4.30
Kalamazoo	6.10	2.45	1.32	1.77	.95	2.75	1.51	2.01	1.10	3.24	1.81	2.50	1.39
West Twin	.90	1.67	1.33	1.69	1.35	1.75	1.42	1.79	1.44	1.93	1.61	1.72	1.42
Duck	.79	1.46	1.16	1.48	1.18	1.53	1.24	1.56	1.26	1.69	1.41	1.50	1.24
Pensaukee	.74	1.38	1.09	1.39	1.11	1.44	1.17	1.47	1.19	1.59	1.32	1.41	1.17
Kewaunee	.70	1.30	1.03	1.32	1.05	1.36	1.10	1.39	1.12	1.50	1.25	1.34	1.10
Manistee	2.51	1.26	1.33	1.13	1.19	1.12	1.19	.91	.96	1.08	1.16	.82	.88
East Twin	.68	1.26	1.00	1.28	1.02	1.32	1.07	1.35	1.09	1.46	1.21	1.30	1.07
Menominee	4.02	1.14	1.20	.87	.92	1.26	1.35	1.00	1.07	1.44	1.56	1.04	1.12
Pere Marquette	.95	.78	.76	1.05	1.02	.78	.77	.98	.95	.78	.78	1.21	1.20
Jordan	.23	.75	1.01	.89	1.21	.70	.96	.65	.88	.55	.76	.54	.74
Ford	.33	.63	.74	.66	.78	.66	.78	.75	.90	.76	.92	.91	1.09
White	.68	.56	.54	.75	.73	.56	.55	.69	.68	.56	.55	.86	.85
Escanaba	.65	.51	.65	.44	.56	.56	.72	.46	.60	.62	.80	.45	.59

Table 12. Percentages of the total load of total phosphorus to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Cedar	.27	.51	.60	.54	.63	.53	.64	.61	.73	.62	.75	.74	.89
Whitefish	.22	.42	.50	.45	.53	.44	.53	.51	.61	.51	.62	.61	.74
Manistique	1.60	.41	.54	.28	.37	.49	.65	.33	.44	.57	.77	.38	.52
Black (SH)	.93	.35	.33	.27	.25	.43	.40	.35	.32	.50	.47	.41	.39
Peshtigo	1.09	.31	.33	.24	.25	.34	.36	.27	.29	.39	.42	.28	.30
Boardman	.37	.30	.29	.40	.39	.30	.29	.37	.37	.30	.30	.47	.46
Sturgeon	.15	.28	.33	.29	.35	.29	.35	.34	.40	.34	.41	.40	.49
Betsie	.32	.27	.26	.36	.35	.27	.26	.33	.32	.27	.27	.41	.41
Black (HD)	.59	.22	.21	.17	.16	.27	.26	.22	.21	.32	.30	.26	.25
Big Sable	.27	.22	.21	.29	.28	.22	.21	.27	.27	.22	.22	.34	.33
Pentwater	.22	.18	.18	.24	.24	.18	.18	.23	.22	.18	.18	.28	.28
Rapid	.09	.18	.21	.19	.22	.19	.22	.22	.26	.22	.26	.26	.31
Pigeon	.42	.16	.15	.12	.11	.19	.18	.16	.15	.23	.21	.19	.18
Total Load (thousands of kilograms)	6.66	113	88	179	139	279	215	441	340	559	425	873	668

Table 13. Percentages of the total load of total phosphorus to Lake Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The total daily load contributed by all rivers is given at the bottom of the table. The rivers are ordered by their relative contributions during the 10-year, 1-day summer event, the largest contributor being first]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Bad	12.34	38.28	39.55	50.24	51.66	30.95	31.99	45.66	47.07	24.57	25.38	40.60	41.66
St. Louis	24.18	14.73	15.00	11.94	12.11	18.44	18.78	16.17	16.43	23.48	23.88	18.06	18.28
Nemadji	8.19	10.44	9.21	9.44	8.29	10.42	9.21	10.02	8.83	10.18	9.02	8.54	7.50
Ontonagon	14.77	8.73	8.85	5.80	5.85	9.97	10.13	5.66	5.74	10.72	10.92	8.08	8.20
Portage	10.52	6.22	6.31	4.13	4.16	7.10	7.21	4.03	4.09	7.64	7.78	5.76	5.84
Bois	3.39	4.32	3.81	3.91	3.43	4.32	3.81	4.15	3.66	4.21	3.73	3.54	3.11
Sturgeon	3.89	3.81	4.37	3.81	4.34	4.19	4.80	3.25	3.71	3.96	4.52	3.45	3.92
Iron	2.68	3.42	3.01	3.09	2.71	3.41	3.01	3.28	2.89	3.33	2.95	2.79	2.46
Amnicon	2.45	3.13	2.76	2.83	2.49	3.12	2.76	3.00	2.65	3.05	2.70	2.56	2.25
Presque Isle	3.81	2.26	2.29	1.50	1.51	2.58	2.62	1.46	1.48	2.77	2.82	2.09	2.12
Montreal	2.81	1.66	1.68	1.10	1.11	1.89	1.92	1.08	1.09	2.04	2.07	1.54	1.56
Black	2.73	1.61	1.64	1.07	1.08	1.84	1.87	1.05	1.06	1.98	2.02	1.49	1.52
Baptism	.77	.76	.87	.76	.86	.83	.95	.65	.74	.79	.90	.69	.78
Tahquamenon	3.43	.26	.30	.15	.17	.37	.42	.21	.24	.52	.59	.31	.35
Waiska	1.88	.22	.17	.14	.11	.31	.24	.21	.16	.44	.34	.32	.25
Two Hearted	.83	.06	.07	.04	.04	.09	.10	.05	.06	.13	.14	.08	.08
Dead	.67	.05	.06	.03	.03	.07	.08	.04	.05	.10	.11	.06	.07
Chocolay	.65	.05	.06	.03	.03	.07	.08	.04	.04	.10	.11	.06	.07
Total Load (thousands of kilograms)	1.81	101	93	193	177	214	196	403	370	354	326	626	579

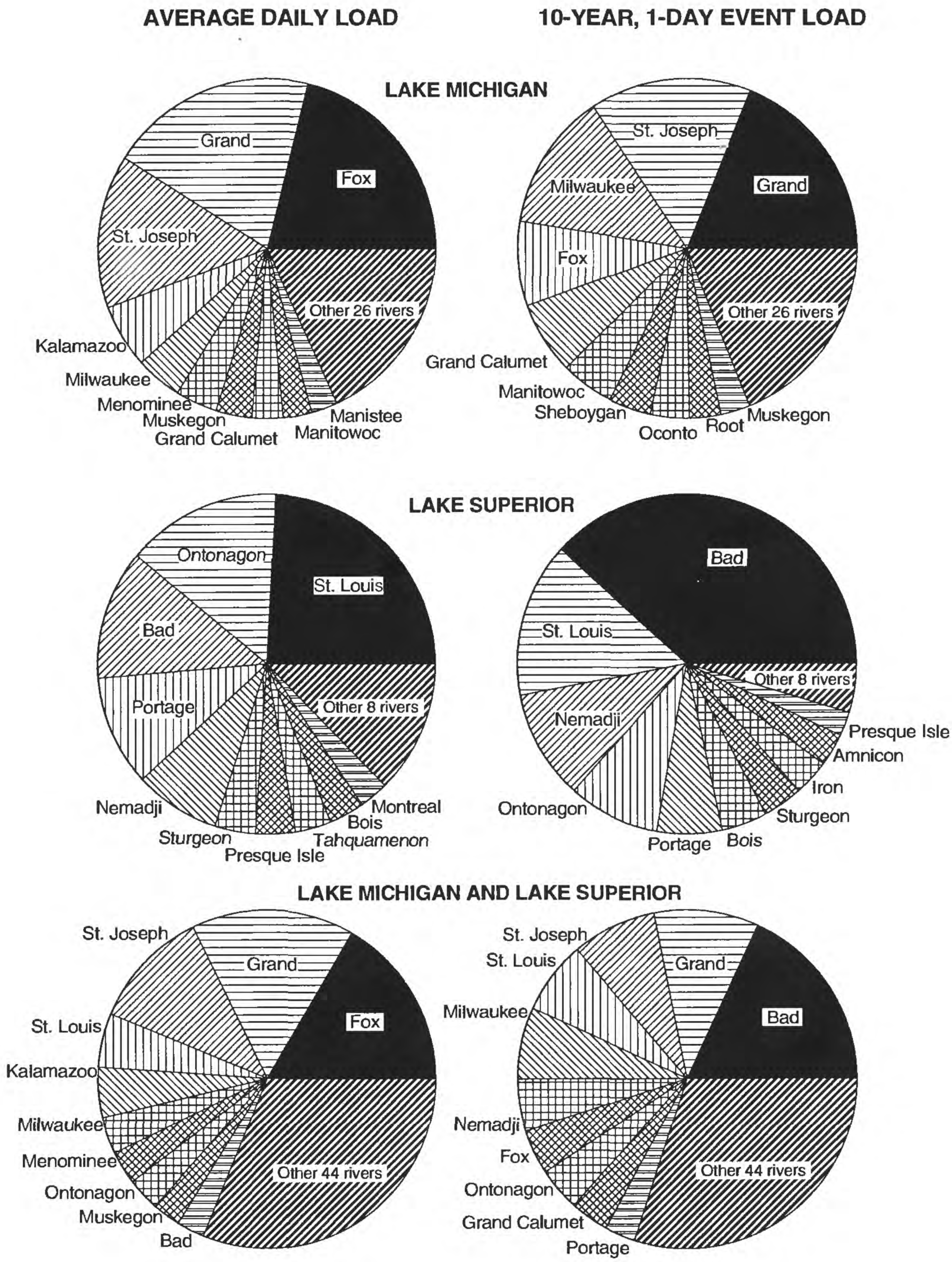

Figure 7. Total phosphorus contributions to Lake Michigan and the United States part of Lake Superior, independently and collectively, for the average day of the 1975–90 period and the 10-year, 1-day event.

kg/d; table 13), although only the United States part of the Lake Superior Basin was considered here. During high-flow events, the difference was less extreme: rivers draining into Lake Michigan contributed 0.8 to 1.6 times more total phosphorus than those draining into Lake Superior. The largest contributors of total phosphorus over the entire period were the Fox, Grand, and St. Joseph Rivers (17, 16, and 12 percent, respectively) (table 11; fig. 7). The high overall loads were the result of moderate yields per unit area from very large basins. However, during high-flow events, the contribution from some of the smaller basins with steeper slopes, especially in areas high in clay content, became very important. In fact, the single largest contributor during almost all high-flow events was the relatively small Bad River Basin.

The IJC estimates annual phosphorus loading into each of the Great Lakes. D. Dolan (International Joint Commission, Great Lakes Regional Office, Windsor, Ontario, written commun., 1996) estimated the average total phosphorus load from tributaries and unmonitored areas draining into Lake Michigan from 1980 to 1991 to be 8,560 kg/d compared to 6,660 kg/d estimated in this study. In this study, approximately 13 percent of the Lake Michigan Basin was neglected by only estimating the load from rivers with drainage basins greater than 325 km^2; this would account for part of the discrepancy in the estimated loading rates. Neither loading rate includes the loadings from direct industrial and municipal discharges and from atmospheric deposition, which were estimated by the IJC for 1980 to 1991 to be 960 kg/d and 990 kg/d, respectively.

The Fox, Grand, and St. Joseph Rivers, the largest contributors of total phosphorus to Lake Michigan, contributed approximately 21, 20, and 15 percent of the overall load, respectively (table 12). During high-flow events, the Grand and St. Joseph Rivers were usually the most significant contributors; the Fox River became slightly less important, and the Milwaukee River became more important.

Over the entire 16-year period, the St. Louis River was the largest (24 percent) contributor of total phosphorus to Lake Superior; however, during high-flow events, the Bad River was the dominant contributor (25 to 52 percent; table 13). Other significant contributors were the Nemadji, Ontonagon, and Portage Rivers.

Relative PCB Loads

A relative PCB loading for each river was obtained by multiplying the suspended-sediment loads by the PCB concentration measured in the bed sediments of each river in table 5. The resulting relative average daily loads and design-event loads are summarized for Lakes Michigan and Superior, collectively, and independently, in tables 14, 15, and 16. The daily loads into Lake Michigan are illustrated in figure 8 for the average and the 10-year, 1-day event during summer. Because a constant partitioning coefficient was assumed, the higher loads of suspended sediment during summer than during spring for a given flow also result in higher estimates of PCB loadings during summer. Likewise, differences in the loads of PCB's among high-flow events would be similar to those for suspended sediment.

Very little information on PCB concentrations was available for the rivers draining into Lake Superior; therefore, all of the PCB concentrations were assumed to be 0.001 mg/kg, except for the St. Louis River (0.056 mg/kg). This assumption resulted in almost all of the major contributors of PCB's being tributaries to Lake Michigan, and so only the rivers draining into Lake Michigan are illustrated in figure 8. The single largest contributor of PCB's during the entire period and during each type of event was the Fox River, which supplied 46 to 64 percent of the total load to both lakes (table 14). During the entire period, the Kalamazoo River was the second largest contributor, and supplied 26 percent of the load. During the high-flow events, the Milwaukee, Kalamazoo, and Sheboygan Rivers alternated in the second through fourth rankings. The Manistique River ranked third in the loadings over the entire period (6.5 percent), but dropped to fifth or sixth in loading during high-flow events. The only river draining into Lake Superior that ranked in the top-ten contributors, was the St. Louis River which ranked about tenth during a few high-flow events.

Because almost all the major contributors of PCB's were rivers draining into Lake Michigan, the relative ranking for Lake Michigan alone was similar to that for both lakes combined. The Fox River was the largest contributor of PCB's (48 to 65 percent; table 15, fig. 8).

The St. Louis River is estimated to be the largest contributor of PCB's to Lake Superior during the entire period (table 16). During a few high-flow events, how-

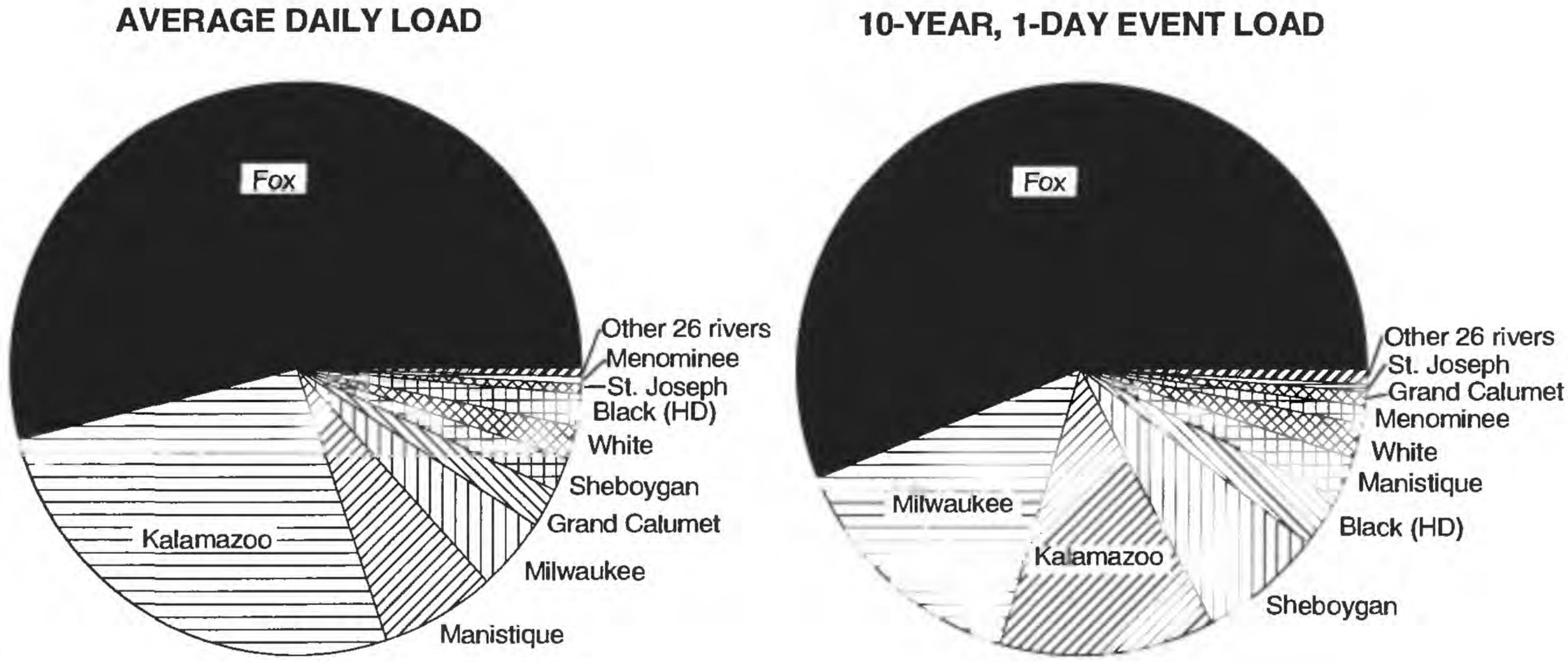

Figure 8. Relative PCB contributions to Lake Michigan for the average day of the 1975–90 period and the 10-year, 1-day event. [HD, near Holland, Mich.]

ever, the Bad and Nemadji Rivers were estimated to be very significant and even more important than the St. Louis River. This difference is the result of very high estimated loads of suspended sediment delivered from these rivers during high flows, even though PCB concentrations were assumed to be only 0.001 mg/kg.

At present, few data are available for PCB concentrations in the water column and bed sediment. This study used the data available for the bed sediment because that data set was more extensive and less variable than the data set for the few water samples that had been collected. Marti and Armstrong (1990) analyzed 3 to 8 water-column samples for PCB's in 15 of the tributaries to Lake Michigan in 1980–83 (table 5). If these data were multiplied by the respective average daily streamflows to estimate the PCB loading, the dominant contributor of PCB's to Lake Michigan would be the Fox River, followed by the Grand, Grand Calumet, and Kalamazoo Rivers. Whereas, using PCB concentration in the bed sediment (this study) indicated the Kalamazoo is the second most dominant contributor, followed by the Manistique, Milwaukee, and Grand Calumet Rivers.

Variability in Flows and Loadings

The duration and intensity of high-flow events differs among rivers. In some rivers, such as the Bad River, high-flow events are intense but short in duration (a few days), whereas high flows in other rivers, such as the Grand and Fox Rivers, are less extreme and extend over several days. Therefore, the importance of the infrequent high-flow events to the long-term average loading also varies among rivers. The variability in streamflow and loads of a tributary may be quantified on the basis of its responsiveness during high-flow events compared to the average over extended periods. Monteith and Sonzogni (1981) divided rivers into three categories based on their response: stable response, event response, and variable response. Richards (1990) further divided the stable category into stable and superstable. For each reference tributary, the 10-year, 1-day event streamflow (and loading of suspended sediment and total phosphorus) was divided by the average daily flow (and average daily load of suspended sediment and total phosphorus) during the 16-year period to quantify the responsiveness. The resulting index is referred to herein as "flashiness" (table 17). The flashiness values represent the number of days of average streamflow or average loading needed to equal the flow or load for the 10-year, 1-day event.

The flashiness values for streamflow range from 3 to approximately 11 in the nonresponsive rivers. Richards (1990) classified these types of rivers as superstable (Richards classified the Manistee River into this category) or stable (flashiness ranging from 4

Table 14. Percentages of the relative load of polychlorinated biphenyls (PCB's) to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The rivers are ordered by their relative contributions during the10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.; LS, Lake Superior; LM, Lake Michigan]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Fox	53.90	55.43	51.19	50.60	45.90	60.76	56.98	57.59	53.44	64.08	60.62	61.57	57.85
Milwaukee	4.15	14.05	14.23	13.47	13.53	11.83	12.09	12.92	13.07	8.67	8.81	10.80	10.92
Kalamazoo	26.07	12.00	11.40	9.99	9.32	11.53	11.12	9.12	8.71	12.28	11.94	10.48	10.13
Sheboygan	1.92	6.87	7.74	11.76	13.00	5.64	6.40	9.20	10.34	5.56	6.29	6.93	7.78
Black (HD)	1.80	2.95	2.88	3.10	2.97	2.97	2.94	2.79	2.73	2.56	2.54	2.39	2.36
Manistique	6.51	2.37	3.43	1.99	2.82	2.51	3.65	1.88	2.72	2.69	3.90	1.96	2.82
White	1.82	1.92	2.82	2.57	3.71	1.71	2.54	2.03	2.98	1.56	2.30	2.22	3.26
Menominee	.57	.99	1.54	1.36	2.08	.79	1.24	1.11	1.73	.79	1.25	.83	1.30
Grand Calumet	2.24	.79	1.47	.52	.95	.28	.53	.18	.34	.13	.24	.08	.15
St. Louis	.13	.49	.66	.56	.75	.45	.62	.54	.74	.42	.58	.40	.54
Bad	.01	.43	.54	1.29	1.58	.19	.24	.72	.90	.08	.10	.62	.78
St. Joseph	.40	.43	.53	.51	.61	.38	.47	.37	.46	.39	.49	.39	.48
Manitowoc	.09	.31	.35	.54	.59	.26	.29	.42	.47	.25	.29	.32	.36
Sturgeon (LS)	.01	.31	.39	.93	1.14	.14	.17	.52	.65	.06	.07	.45	.56
Grand	.18	.30	.29	.31	.30	.30	.30	.28	.28	.26	.26	.24	.24
Ontonagon	.01	.07	.12	.08	.14	.04	.08	.03	.06	.02	.04	.04	.08
Pensaukee	.02	.06	.06	.10	.11	.05	.05	.07	.08	.04	.05	.06	.06
Portage	.01	.05	.08	.06	.10	.03	.05	.02	.04	.02	.03	.03	.06
Muskegon	.04	.04	.06	.05	.08	.03	.05	.04	.06	.03	.05	.04	.07
Kewaunee	.01	.03	.03	.04	.05	.02	.02	.04	.04	.02	.02	.03	.03
Manistee	.07	.02	.04	.02	.03	.02	.03	.01	.03	.02	.03	.01	.02
Presque Isle	.00	.02	.03	.02	.04	.01	.02	.01	.01	.01	.01	.01	.02
Black (SH)	.03	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
Montreal	.00	.01	.02	.02	.03	.01	.01	.01	.01	.00	.01	.01	.01
Nemadji	.00	.01	.02	.03	.05	.01	.01	.02	.03	.00	.00	.01	.02
Black	.00	.01	.02	.02	.03	.01	.01	.01	.01	.00	.01	.01	.01
Pere Marquette	.01	.01	.02	.02	.02	.01	.02	.01	.02	.01	.01	.01	.02

Table 14. Percentages of the relative load of polychlorinated biphenyls (PCB's) to Lakes Michigan and Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Whitefish	.00	.01	.01	.01	.02	.01	.01	.01	.02	.01	.01	.01	.02
Iron	.00	.00	.01	.01	.02	.00	.00	.01	.01	.00	.00	.00	.01
Amnicon	.00	.00	.01	.01	.01	.00	.00	.01	.01	.00	.00	.00	.01
Oconto	.00	.00	.00	.00	.01	.00	.00	.00	.01	.00	.00	.00	.00
Ford	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cedar	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
West Twin	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Duck	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Root	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
East Twin	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Sturgeon (LM)	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Peshtigo	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Rapid	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Jordan	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Boardman	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Baptism	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Betsie	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Pigeon	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Big Sable	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Pentwater	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Escanaba	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Waiska	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Tahquamenon	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Two Hearted	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Bois Brule	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Dead	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Chocolay	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table 15. Percentages of the total relative load of polychlorinated biphenyls (PCB's) to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The rivers are ordered by their relative contributions during the10-year, 1-day summer event, the largest contributor being first; HD, near Holland, Mich.; SH, near South Haven, Mich.]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Fox	53.99	56.22	52.18	52.17	47.75	61.30	57.69	58.70	54.79	64.48	61.15	62.57	59.09
Milwaukee	4.16	14.25	14.50	13.89	14.08	11.94	12.24	13.17	13.40	8.72	8.89	10.98	11.16
Kalamazoo	26.11	12.17	11.62	10.30	9.69	11.63	11.26	9.30	8.93	12.36	12.05	10.65	10.35
Sheboygan	1.92	6.97	7.89	12.13	13.52	5.69	6.48	9.37	10.60	5.60	6.35	7.04	7.95
Black (HD)	1.80	2.99	2.93	3.20	3.09	2.99	2.97	2.84	2.80	2.58	2.56	2.43	2.41
Manistique	6.52	2.41	3.49	2.05	2.93	2.53	3.70	1.92	2.78	2.70	3.93	1.99	2.89
White	1.83	1.95	2.87	2.65	3.86	1.73	2.57	2.07	3.06	1.57	2.32	2.25	3.32
Menominee	.58	1.01	1.57	1.40	2.16	.80	1.26	1.13	1.78	.80	1.26	.84	1.32
Grand Calumet	2.24	.80	1.50	.54	.99	.29	.54	.18	.34	.13	.24	.08	.16
St. Joseph	.40	.44	.54	.52	.63	.38	.48	.38	.47	.39	.49	.40	.49
Manitowoc	.09	.32	.36	.55	.62	.26	.30	.43	.48	.26	.29	.32	.36
Grand	.18	.30	.30	.32	.31	.30	.30	.29	.28	.26	.26	.25	.24
Pensaukee	.02	.06	.06	.10	.11	.05	.05	.08	.09	.05	.05	.06	.06
Muskegon	.04	.04	.06	.05	.08	.03	.05	.04	.06	.03	.05	.05	.07
Kewaunee	.01	.03	.03	.05	.05	.02	.02	.04	.04	.02	.02	.03	.03
Manistee	.07	.02	.04	.02	.03	.02	.03	.01	.03	.02	.03	.01	.02
Black (SH)	.03	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
Pere Marquette	.01	.01	.02	.02	.02	.01	.02	.01	.02	.01	.01	.01	.02
Whitefish	.00	.01	.01	.01	.02	.01	.01	.01	.02	.01	.01	.01	.02
Oconto	.00	.00	.00	.00	.01	.00	.00	.00	.01	.00	.00	.00	.00
Ford	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Cedar	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
West Twin	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Duck	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table 15. Percentages of the total relative load of polychlorinated biphenyls (PCB's) to Lake Michigan contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)—Continued

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
Root	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
East Twin	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Sturgeon	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Peshtigo	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Rapid	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Jordan	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Boardman	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Betsie	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Pigeon	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Big Sable	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Pentwater	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Escanaba	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00

Table 16. Percentages of the total relative load of polychlorinated biphenyls (PCB's) to Lake Superior contributed by each river for the average day of the 1975–90 period and 1-, 3-, and 7-day, high-flow events with recurrence intervals of 10 and 50 years for summer (beginning on July 1) and spring (beginning on May 1)

[The rivers are ordered by their relative contributions during the10-year, 1-day summer event, the largest contributor being first]

River	Average	1-day event				3-day event				7-day event			
		10-year		50-year		10-year		50-year		10-year		50-year	
		Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring	Summer	Spring
St. Louis	77.59	34.63	34.93	18.54	19.31	50.63	50.33	28.90	30.12	67.63	66.85	25.03	25.95
Bad	4.62	30.70	28.39	42.70	40.75	21.42	19.57	38.10	36.39	12.95	11.81	39.01	37.02
Sturgeon	3.34	22.16	20.49	30.82	29.41	15.46	14.12	27.50	26.26	9.35	8.52	28.16	26.72
Ontonagon	4.55	4.71	6.17	2.69	3.64	4.82	6.23	1.69	2.28	3.94	5.06	2.74	3.69
Portage	3.24	3.35	4.39	1.92	2.59	3.44	4.44	1.20	1.63	2.81	3.61	1.95	2.63
Presque Isle	1.18	1.22	1.59	.70	.94	1.25	1.61	.44	.59	1.02	1.31	.71	.95
Montreal	.86	.89	1.17	.51	.69	.92	1.18	.32	.43	.75	.96	.52	.70
Nemadji	2.10	.88	1.04	.99	1.21	.69	.80	.93	1.14	.47	.54	.83	1.00
Black	.84	.87	1.14	.50	.67	.89	1.15	.31	.42	.73	.94	.51	.68
Iron	.69	.29	.34	.32	.40	.23	.26	.31	.37	.15	.18	.27	.33
Amnicon	.63	.26	.31	.30	.36	.21	.24	.28	.34	.14	.16	.25	.30
Baptism	.04	.01	.02	.01	.01	.02	.03	.01	.01	.02	.02	.01	.01
Waiska	.05	.01	.00	.00	.00	.01	.01	.01	.00	.02	.01	.01	.00
Tahquamenon	.60	.01	.01	.00	.00	.02	.02	.01	.01	.05	.05	.01	.01
Two Hearted	.15	.00	.00	.00	.00	.01	.01	.00	.00	.01	.01	.00	.00
Bois Brule	.13	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Dead	.12	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00
Chocolay	.11	.00	.00	.00	.00	.00	.00	.00	.00	.01	.01	.00	.00

Table 17. Flashiness (responsiveness) of streamflow, and suspended-sediment and total phosphorus loading of selected Lake Michigan and Lake Superior tributaries

[Flashiness is computed by dividing the 10-year, 1-day summer event streamflow (or load) by the long-term average streamflow (or load). The rivers are ordered by the relative flashiness of streamflow, the least flashy river first. Location of rivers shown in fig. 1]

River	Identifier	Flashiness values		
		Streamflow	Suspended sediment	Total phosphorus
Manistee	11	3	6	9
Grand Calumet	18	3	7	39
Fox	4	4	21	6
St. Joseph	7	4	22	18
Kalamazoo	8	5	10	7
Muskegon	10	5	22	14
Menominee	3	6	36	5
Tahquamenon	17	7	8	4
Grand	9	8	34	16
Escanaba	1	10	20	13
Ford	2	11	96	32
St. Louis	13	11	77	34
Ontonagon	16	13	177	33
Manitowoc	5	14	74	31
Milwaukee	6	18	70	50
Bad	15	20	1,139	174
Nemadji[1]	14	20	72	71
Baptism	12	24	67	55

[1]Flow per unit area during the 10-year, 1-day event was assumed to be similar to that for the Bad River.

to 11). Rivers whose flashiness values range from 13 to 20 are moderately responsive (classified by Richards as variable). Rivers whose flashiness values are greater than 20 are very responsive rivers (classified by Richards as event-dominated rivers). The only river whose flashiness value is greater than 20 is the Baptism River (value of 24, indicating that the 10-year, 1-day event produced a streamflow equivalent to 24 days of average flow).

The flashiness values for suspended-sediment loads were higher than those for streamflow for all the reference rivers, an indication that suspended-sediment concentrations increase with increasing streamflow. The flashiness values for suspended sediment ranged from 6 in the superstable Manistee River to 1,139 in the Bad River. In general, the rivers that were classified as stable on the basis of streamflow had flashiness values for suspended sediment ranging from 6 to 60, and variable-response rivers had values greater than 60. Flashiness values greater than 60 indicate that the 10-year, 1-day event will discharge more suspended sediment than would occur during 60 days of average loading. The Bad River had a flashiness value of 1,139, an indication that the 1-day event may discharge more suspended sediment than during 3 years of average loading. The loading of phosphorus and suspended sediment during high-flow events is very important to the long-term average loading of rivers with high flashiness values.

PCB loadings were estimated by multiplying the suspended-sediment loading by a constant PCB concentration. Hence, the estimated flashiness for PCB loading would be the same as that for suspended sediment.

The flashiness values for total phosphorus loads were usually higher than those for streamflow, again an indication that total phosphorus concentrations generally increase with increasing streamflow. Flashiness values, in general, were not as high for total phosphorus as they were for suspended sediment. Only two of the rivers (Menominee and Tahquamenon Rivers—both classified as stable rivers) had a flashiness value for total phosphorus that was less than that for flow, an indication of a slight decrease in concentration as streamflow increased. In general, the stable rivers had flashiness values for total phosphorus less than about 30, and the variable rivers had values ranging from 30 to 70. The Bad River had a flashiness value for total phosphorus of 174, an indication that loading for the 1-day event may equal almost 6 months of average loading.

SUMMARY AND CONCLUSIONS

In this report, a method is described for estimating regional loads of suspended sediment, total phosphorus, and sediment-borne constituents such as polychlorinated biphenyls (PCB's) during high-flow events with specified recurrence frequencies and over extended periods of time. This was done by extrapolating the load estimates for well-monitored (reference) rivers to many unmonitored rivers by use of a drainage-area ratio. Reference rivers are chosen by first determining how various environmental characteristics are related to the loading of each constituent, then determining which reference river has the most similar environmental characteristics. With loading estimates for all the rivers in a region, each river was then ranked on the basis of its relative loading during specified events and over extended periods of time.

Long-term average suspended-sediment loadings were primarily affected by the topography of the area and secondarily affected by the texture of surficial deposits, whereas average total phosphorus loadings were primarily affected by the texture of surficial deposits and secondarily affected by the topography of the area. Loadings of total phosphorus were highest from rivers draining clay surficial deposits and agricultural areas. During high-flow events, phosphorus and suspended sediment yields and loads were highest and flashiest from rivers with steep gradients that drain surficial deposits with high clay content, such as the Bad River. The loading of phosphorus and suspended sediment during high-flow events is very important to the long-term average loading of rivers with high flashiness values.

Given average sediment concentrations for specific hydrophobic constituents (such as PCB's) and assuming a constant partitioning coefficient, relative loads of the sediment-borne constituents can be obtained. The single largest contributor of PCB's during the entire period and during each type of high-flow event was the Fox River, which supplied 46 to 64 percent of the total PCB load to both lakes.

SUGGESTIONS FOR FUTURE RESEARCH

Ranking all the major rivers by their relative contributions of total phosphorus, suspended sediment, and PCB's required several assumptions dealing not only with concentrations of these constituents during the extreme high-flow events but also with extrapolation of small data sets. To refine and verify these estimates, more detailed data are needed during the extreme high-flow events. The environmental characteristics of each of the rivers was based on the environmental characteristics of the hydrologic units through which they flow. To refine the statistical analyses relating suspended-sediment and total phosphorus yields to the environmental characteristics of the basins and to determine which reference river is most appropriate for each unmonitored rivers, the drainage basin for each river should be delineated and its environmental characteristics determined. To determine the accuracy in extrapolating the loads to relatively unmonitored rivers, detailed load studies are needed for these relatively unmonitored sites. In the detailed load studies, the statistical usability of the data could be maximized by collecting as many samples as possible during the short-term, high-flow events.

Ranking of the rivers on the basis of their relative contributions of PCB's, could be improved if much more water-column and bed-sediment concentration data were available. In addition, information on how PCB's are partitioned between the bed sediment and suspended sediment during different flow regimes and different seasons is needed. PCB concentration data in the water column were collected in 11 tributaries as part of the Lake Michigan Mass Balance Study. By incorporating this additional information with the extrapolation process delineated in this paper, the high-flow event and long-term loading estimates made here may be further refined. A very small amount of PCB data is currently available for Lake Superior tributaries; therefore, any additional data would be very useful in better quantifying loads to Lake Superior.

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