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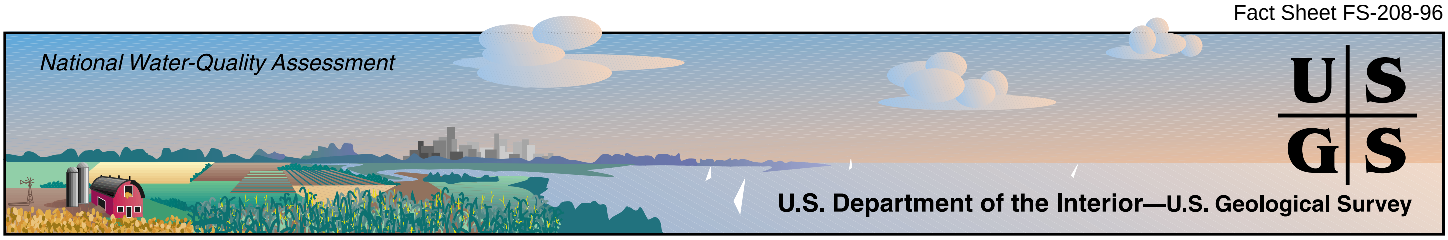

Sources and Transport of Phosphorus in the Western Lake Michigan Drainages

by Dale M. Robertson

Introduction

In 1991, the U.S. Geological Survey (USGS) began full implementation of the National Water-Quality Assessment (NAWQA) Program. The goals of the NAWQA program are to (1) provide a nationally consistent description of water-quality conditions for a large part of the Nation's water resources, (2) define long-term trends (or lack of trends) in water quality, and (3) identify, describe, and explain, as possible, the major factors that affect the observed water-quality conditions and trends (Hirsch and others, 1988). To fulfill the goals of the NAWQA program, the USGS plans to examine 60 areas (study units) across the United States on a rotational cycle. The first 20 of these study units began intensive investigations in 1991. One of these study units is the Western Lake Michigan Drainages (WMIC) (fig. 1).

The WMIC study unit contains many individual drainage basins that empty into Green Bay or directly into Lake Michigan. These basins can be grouped into four main subunits based on land use: the Northern-Forested subunit (88 percent forest and 8 percent agriculture), the Oconto-Peshtigo subunit (71 percent forest and 25 percent agriculture), the Fox-Wolf-Pensaukee subunit (35 percent forest and 53 percent agriculture), and the Direct Lake Michigan subunit (13 percent forest and 73 percent agriculture) (fig. 1 and table 1). Within these subunits, extensive water-quality data have been collected at eight sites. Six sites have large drainage basins: Escanaba (1) and Ford (2) River Basins in Upper Michigan, Menominee River Basin (3) in Wisconsin and Upper Michigan (primarily forest), and Fox River Basin (5) (mixed agriculture and forest), and Manitowoc (7) and Milwaukee (8) River Basins (primarily agriculture) in Wisconsin. Two sites in Wisconsin have small drainage basins with one primary land use: Popple River Basin (4, forest) and White Creek Basin (6, agriculture). These eight rivers are referred to as "reference rivers" and their watersheds are referred to as "reference basins". These reference rivers are identified in figures 1, 2, and 3 and described in table 1. In this report, the inputs of total phosphorus into the reference basins, subunits, and entire WMIC study unit are quantified and used in conjunction with the export rates from the reference rivers to estimate the phosphorus transported from the four subunits and the entire WMIC study unit, as well as to determine the importance of point sources to the overall phosphorus export.

Phosphorus is essential for algal and macrophyte growth in aquatic environments, but in sufficiently high concentrations, it can lead to excess algae and macrophytes. Phosphorus transport from runoff has been identified as a primary water-quality concern throughout the WMIC study unit, especially downstream from large agricultural areas of the study unit, such as Lake Winnebago and Green Bay. With the belief that point sources of phosphorus in the study unit are under control, much of the current effort in improving water quality focuses on quantifying and reducing nonpoint-source loading. Nonpoint-source loading of phosphorus into rivers is primarily a function of land-use practices and the types of surficial deposits (Clesceri and others, 1986; U.S. Environmental Protection Agency, 1980); therefore, the inputs and exports of phosphorus described in this report are discussed with respect to these characteristics.

Forested land covers more than 50 percent of the study unit (fig. 1) and dominates the northern part, where deciduous forests grade to evergreen forests to the northeast. Agricultural land, mostly cropland and pasture, in the southern and central part of the study unit is the second largest land-use category. Areas of urban or developed land are primarily found along Lake Michigan in the southeastern part of the study unit and around Lake Winnebago and Green Bay.

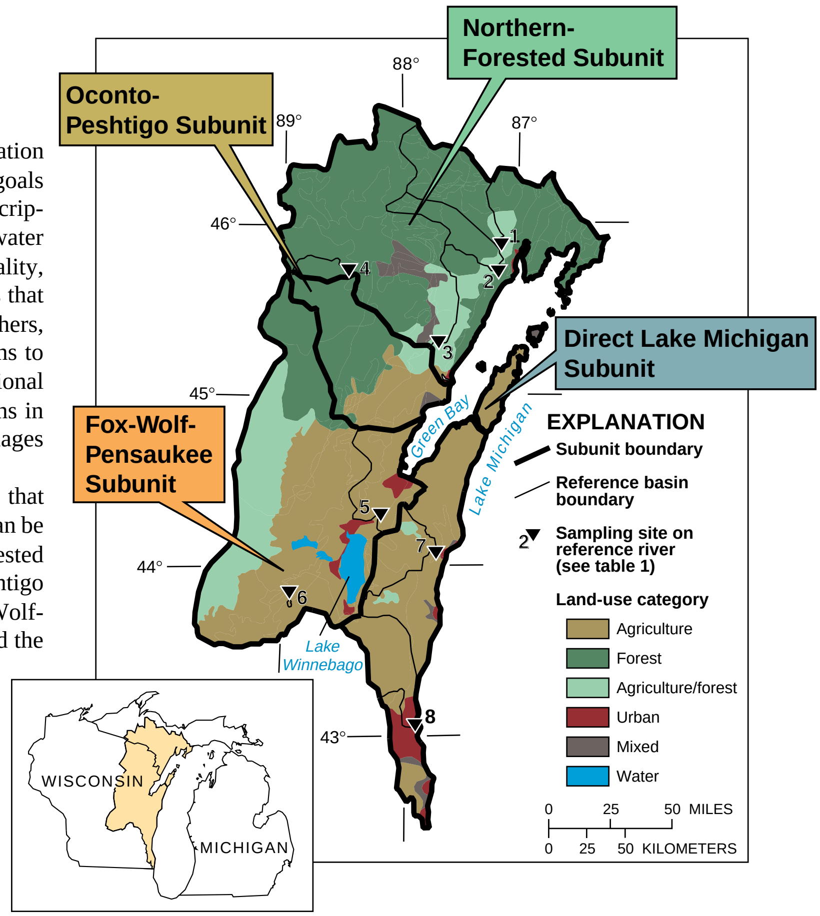

Figure 1. Land-use categories, subunits, and reference basins in the Western Lake Michigan Drainages study unit.

Surficial deposits range in thickness from zero to several hundred feet and consist of glacial and recent-aged deposits. Sand and gravel deposits are interspersed with sandy deposits in the southern and western parts of the study unit and with loamy deposits in the central parts (fig. 2). Loamy deposits dominate in the northeastern part of the study unit and clayey deposits dominate in the central and eastern parts.

Sources of Phosphorus

Fertilizers and Manure

Application of phosphorus to croplands, urban lawns, and golf courses, in the form of fertilizers, is commonplace within the WMIC study unit. Application of manure is common to croplands associated with dairy operations. Application rates of phosphorus from fertilizers for 1985 and manure for 1987 were derived from county application rates estimated by

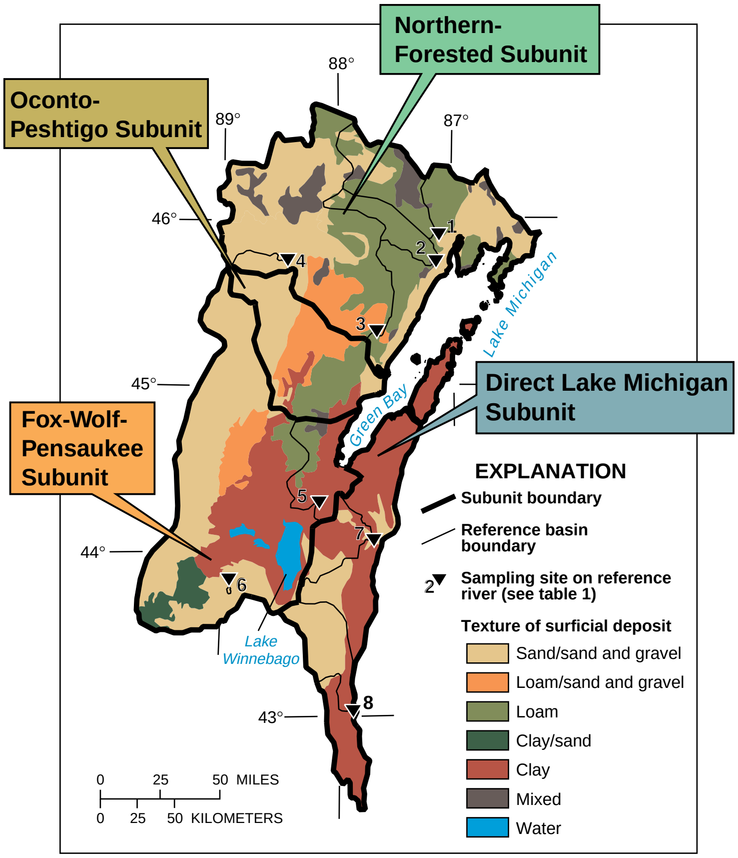

Figure 2. Texture of surficial deposits in the Western Lake Michigan Drainages study unit.

Alexander and Smith (1990) and R.B. Alexander (U.S. Geological Survey, written commun., 1993), respectively. The county rates were proportioned to the individual reference basins on the basis of the percentage of agriculture in each reference basin compared to that in the counties included in the reference basins (Robertson and Saad, 1996) and proportioned to the four subunits by weighting the county application rates by the percentage of the subunit in each county.

Annual application rates of phosphorus from fertilizers ranged from 0.08 kg/ha (kilograms per hectare) in the Popple River Watershed to 11.09 kg/ha in the White Creek Watershed (table 1). Application rate in pounds per acre is obtained by multiplying the rate in kilograms per hectare by 0.89. Application rates in all of the forested reference basins (Escanaba, Ford, Menominee, and Popple River Watersheds) were less than 0.6 kg/ha and in agricultural reference basins (Manitowoc and Milwaukee River Watersheds) were greater than 6 kg/ha. The average application rates for the subunits ranged from 0.50 kg/ha in the Northern-Forested subunit to 6.08 kg/ha in the Direct Lake Michigan subunit (fig. 3).

Annual application rates of phosphorus from manure were generally slightly less than those from fertilizers and ranged from 0.09 kg/ha in the Popple River Watershed to 8.83 kg/ha in the White Creek Watershed (table 1). Application rates in all of the forested reference basins were less than 0.4 kg/ha and in agricultural reference basins were greater than 5 kg/ha. The average application rates for the subunits ranged from 0.31 kg/ha in the Northern-Forested subunit to 5.04 kg/ha in the Direct Lake Michigan subunit (fig. 3).

Atmospheric Deposition

Phosphorus-deposition rates were estimated for two areas near the WMIC study unit: annual deposition of phosphorus near Chicago was estimated to be 0.38 kg/ha (Murphy, 1974) and almost an order of magnitude less, 0.05 kg/ha, in a remote forested area in northern Wisconsin (Rose, 1993). These two areas are expected to represent the extremes in the phosphorus-deposition gradient across the study unit. In estimating the total input of phosphorus into various areas, the total contribution of atmospheric phosphorus was assumed to be 0.05 kg/ha in forested areas and 0.20 kg/ha in agricultural areas (table 1 and fig. 3). Therefore, compared to fertilizer and manure, atmospheric deposition of phosphorus represents only a small source of phosphorus.

Point Sources of Phosphorus

Point-source releases of phosphorus are primarily from sewage-treatment plants, papermills, and cheese factories located mostly in the southern half of the study unit (Robertson and Saad, 1996). The estimated annual inputs of phosphorus from point sources during 1992 were obtained from the Wisconsin Department of Natural Resources (G. North, Office of Technical Services, Wisconsin Department of Natural Resources, written commun., 1994). Input of phosphorus from point sources within the reference basins is very small compared to that from nonpoint sources. Input from point sources was highest in the Fox River reference basin (0.08 kg/ha; table 1). However, point sources of phosphorus at specific locations near major cities can be very important locally, such as from the cities of Green Bay and Milwaukee. Both sites are just downstream from sampling sites on reference rivers, where most is directly discharged to Green Bay and Lake Michigan. The importance of the input from point sources relative to that from nonpoint sources is discussed in detail later in this report.

The total annual input of phosphorus is directly related to the percentage of agriculture in an area; more than 20 kg/ha are input into areas completely in agriculture (White Creek), less than 1 kg/ha are input in forested areas, and intermediate amounts are input in mixed agricultural and forested areas (table 1). Almost all the phosphorus input into each area is from agricultural applications, except in isolated forested areas where the small rate of atmospheric deposition can nevertheless be important (fig. 3). For the entire study unit, greater than 96 percent of the total input of phosphorus comes from fertilizers and manure; point sources contribute only about 1.2 percent of the total input (fig. 4).

Transport of Phosphorus

Reference Basins

Annual exports of phosphorus from each of the eight reference rivers were computed for 1980-90 by Robertson and Saad (1996) using constituent-transport models based on relations between the water-quality-constituent load and two variables: stream discharge and day of the year (Cohn and others, 1989). **Phosphorus export was found to be primarily related to land use and secondarily related to the type of surficial deposits.** No data were available for completely urbanized areas for this extended period. Export of total phosphorus ranged from 3.13 kg/ha in White Creek (small agricultural reference basin) and 0.40 to 0.46 kg/ha in large agricultural reference basins to less than or equal to 0.1 kg/ha in forested reference basins of any size (table 1). Of the agricultural reference basins, the basin with the highest percentage of fine-grained deposits (clay) had the highest phosphorus export rate (Manitowoc River had the highest percentage of clay in the basin (fig. 2) and had the highest export rate, 0.46 kg/ha). During high runoff years, export rates increased significantly, especially in the Manitowoc River; whereas during low runoff years, export rates were significantly reduced in all agricultural and small forested reference basins, but not significantly reduced in large forested basins (Robertson and Saad, 1996). The calculated export rates are similar to those compiled from studies done throughout Wisconsin by Panuska and Lillie (1995). Panuska and Lillie found average annual export rates of phosphorus for forested basins ranged from 0.04 to 0.88 kg/ha (median value of 0.52 kg/ha) and for agricultural basins ranged from 0.15 to 4.01 kg/ha (median value of 1.04 kg/ha).

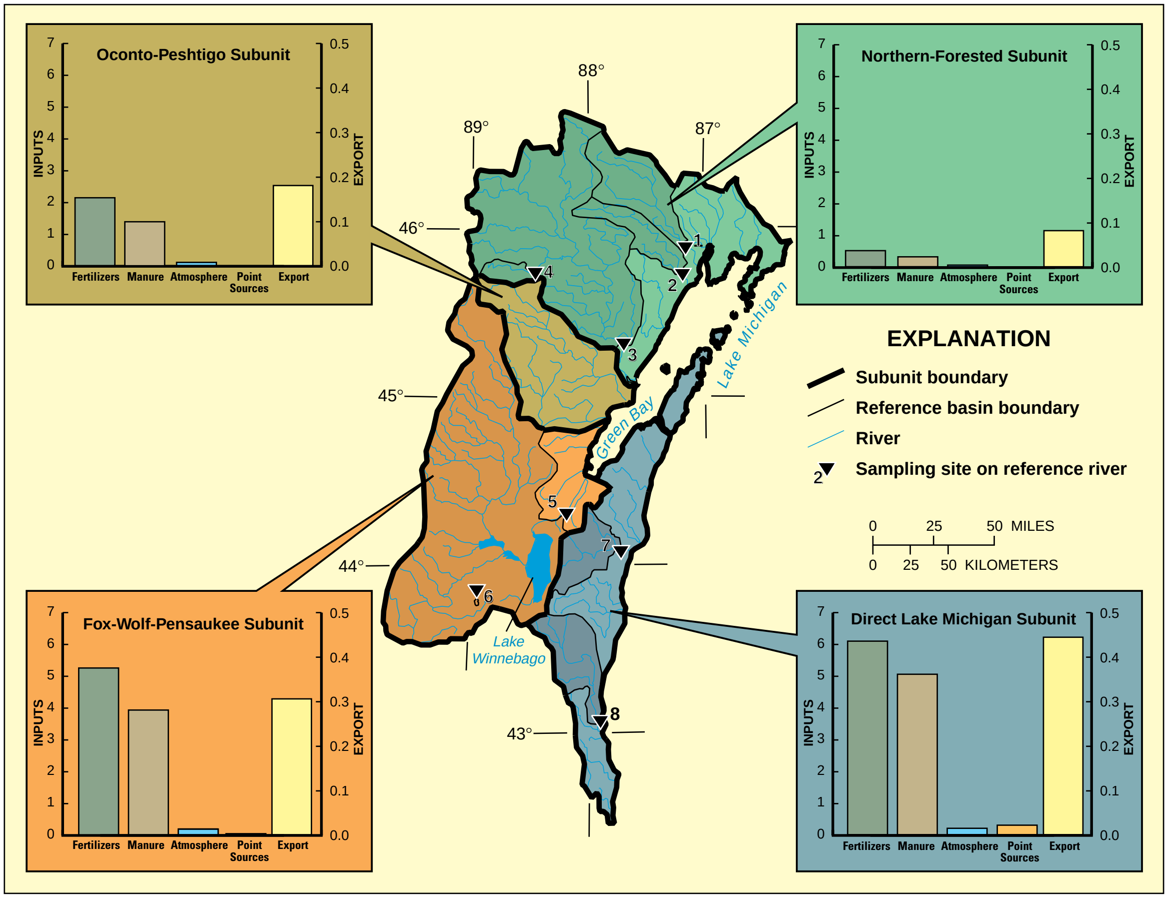

Figure 3. Phosphorus inputs (including input into Lake Michigan and Green Bay) and exports from subunits. (In each subunit the darker shades represent reference basins and the lighter shades represent unmonitored areas. All inputs and exports are in kilograms per hectare; reference rivers are identified in table 1.)

Regional Transport of Phosphorus and Importance of Point Sources

The export rates from the six large reference basins were used to estimate the total phosphorus transported from the four subunits and the entire WMIC study unit. This extrapolation process was based on making one of two assumptions regarding the export of phosphorus from point sources. In the first assumption, all phosphorus from point sources is exported out of the basin and study unit. Therefore, export rates from nonpoint sources were computed by subtracting point-source contributions. In the second assumption, phosphorus inputs from point sources within the study unit are treated as other nonpoint sources and are exported at a rate proportional to its percentage of total input. Therefore, only point sources that are discharged directly to Lake Michigan and Green Bay are completely exported out of the study unit. For example, in the Direct Lake Michigan subunit, the additional phosphorus from point sources in the basin represents 0.2 percent of the total input and therefore represents 0.2 percent of the export. These assumptions represent the extremes in how point sources can be considered. The export of phosphorus from unmonitored areas of each subunit was estimated by determining how much of the unmonitored area resembled each of the reference rivers in the subunit (in terms of similar land use and surficial deposits) and then multiplying the export rates of each of the six large reference basins by the total area each represents (“effective area” in table 1). Therefore, each of the six large reference rivers is used to estimate the total export from an area larger than its own drainage area. For a more detailed description of this extrapolation process see Robertson and Saad (1996). An annual export rate of 0.18 kg/ha was used to estimate the phosphorus transported from the Oconto-Peshtigo subunit. This subunit had no reference basins within it; therefore this rate was computed by weighting the rates of the Fox and Menominee Rivers by the percentage of agriculture in each basin.

With the first assumption, 100 percent of the phosphorus input from point sources is exported from the study unit. For most of the reference basins, point-source contributions upstream from the sampling site are very small and represent less than 15 percent of the export, except for the Fox River where point sources within the basin may represent 27 percent of the export (table 1). More than half of the phosphorus contributed by point sources is input directly into Green Bay or Lake Michigan. If 100 percent of the point sources is exported, then in an average year 1,421,000 kg of phosphorus would be exported out of the WMIC study unit; the overall annual export rate would be 0.28 kg/ha (0.20 kg/ha from nonpoint sources plus 0.08 kg/ha from point sources) (table 1). With this assumption, point sources contribute 27.5 percent of the total export (fig. 4). If point sources directly input into Lake Michigan and Green Bay are neglected, then the overall export rate would be 0.24 kg/ha, and point sources would contribute 15.0 percent of the total export.

If point sources (except those directly discharged to Lake Michigan and Green Bay) are treated as nonpoint sources and are incorporated into the export rates computed for each reference basin, then point sources generally represent less than 2 percent of the total input into any reference basin or subunit, and therefore, contribute less than 2 percent of that exported. By this method, in an average runoff year, the total phosphorus exported from the WMIC study unit again would be 1,421,000 kg (fig. 4). The overall annual export rate would be 0.28 kg/ha (0.23 kg/ha contributed by nonpoint sources plus 0.05 kg/ha contributed by point sources). Of the 0.05 kg/ha contributed by point sources, 0.04 kg/ha is directly input by point sources to Lake Michigan and Green Bay. Point sources within the basins are very small and would contribute approximately 0.01 kg/ha. With this assumption, point sources contribute about 15.3 percent of the total export, almost all of which is directly input into Lake Michigan and Green Bay (fig. 4).

In an average runoff year, the total export of phosphorus from the WMIC study unit is estimated to be about 1,400,000 kg. Point sources contribute between about 15 percent (if it is assumed that only point sources input directly into Green Bay and Lake Michigan are 100 percent exported) and 28 percent (if it is assumed that 100 percent of all point sources are exported from the study unit) of the total phosphorus exported.

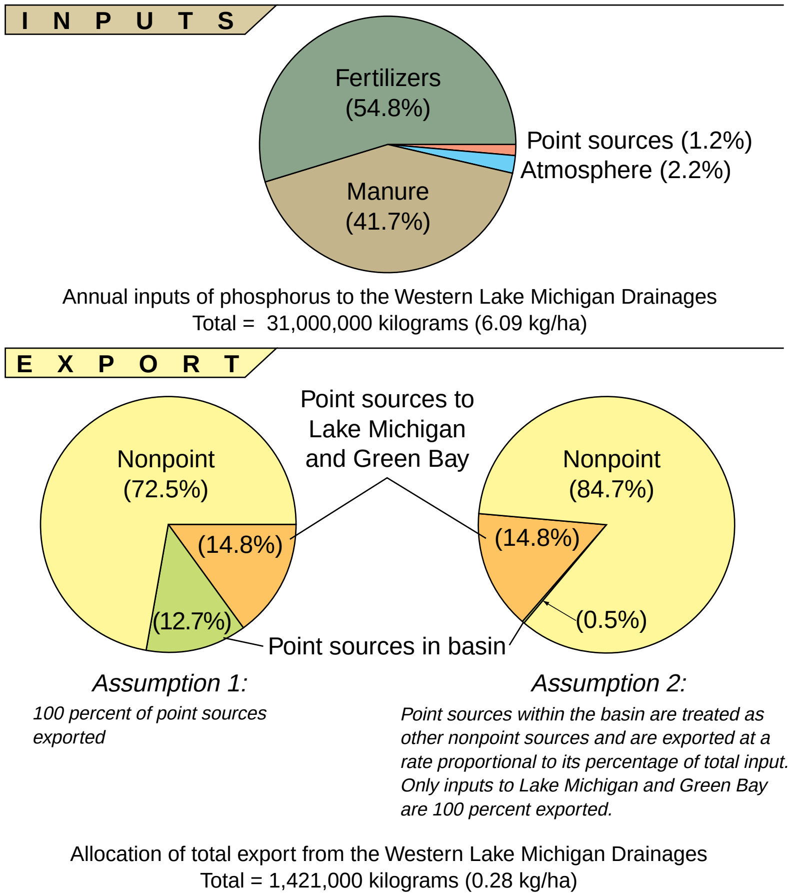

Figure 4. Total annual inputs to (including that input into Lake Michigan and Green Bay) and export of phosphorus from the Western Lake Michigan Drainages and allocation of export to that attributed to point and nonpoint sources.

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Table 1. Average annual inputs and export of phosphorus and the importance of point source contributions from reference basins, subunits, and the Western Lake Michigan Drainages Study Unit [locations of rivers are shown in figures 1, 2, and 3; kg/ha, kilograms per hectare; km^2, square kilometers; Agric., agriculture; Fert., fertilizers; Atm. Dep., atmospheric deposition; %, percent; LM/GB, Lake Michigan/Green Bay; NA, not applicable]

Basin/Subunit/Study Unit (identifier number from figures 1–3 in parentheses)	Area (km^2)	Effective area (km^2)	Percent Forest	Percent Agric.	Phosphorus inputs (kg/ha) Fert.	Manure	Atm Dep.	Basin point sources	Total inputs to basin	Point sources to LM/GB	Phosphorus export (kg/ha)	Point source contribution (percent of total) 100% Export[a]	LM/GB Export[b]
Northern-Forested	18,800	NA	88	8	0.50	0.31	0.05	0.01	0.87	0.00	0.08	9.3	0.9
Escanaba (1)	2,250	5,570	91	4	.57	.33	.05	.00	.95	.00	.06	.0	.0
Ford (2)	1,170	2,690	93	7	.35	.19	.05	.00	.59	.00	.07	.0	.0
Menominee (3)	10,180	13,910	90	6	.33	.21	.05	.01	.60	.00	.10	13.2	2.1
Popple (4)	430	0	96	2	.08	.09	.05	.00	.22	.00	.06	.0	.0
Oconto-Peshtigo	5,630	NA	71	25	2.13	1.38	.11	.01	3.63	.00	.18	3.9	.2
Fox-Wolf-Pensaukee	17,689	NA	35	53	5.26	3.94	.20	.08	9.48	.01	.32(.31)[c]	30.2(27.3)[c]	4.8(9.3)[c]
Fox (5)	15,570	19,940	37	51	5.26	3.94	.20	.08	9.48	.00	.31	27.1	.9
White Creek (6)	8	0	0	100	11.09	8.83	.20	.00	20.11	.00	3.13	.0	.0
Direct Lake Michigan	9,430	NA	13	73	6.08	5.04	.20	.02	11.33	.20	.64(.44)[c]	33.5(3.7)[c]	31.1(.1)[c]
Manitowoc (7)	1,360	6,350	13	83	6.73	7.22	.20	.01	14.15	.00	.46	1.6	.1
Milwaukee (8)	1,800	3,080	12	75	6.43	5.14	.20	.04	11.82	.00	.40	10.7	.4
Western Lake Michigan	51,500	NA	54	37	3.34	2.54	.14	.04	6.05	.04	.28(.24)[c]	27.5(15.0)[c]	15.3(.6)[c]

[a] 100 percent of all point sources are exported out of study unit.

[b] All point sources within study unit exported at a rate proportional to its percentage of total inputs, except that released into Lake Michigan and Green Bay which are all exported.

[c] Number in parentheses does not include that phosphorus released directly into Green Bay and (or) Lake Michigan.

For more information, please contact:

NAWQA Chief
U.S. Geological Survey
6417 Normandy Lane
Madison, WI 53719
(608) 276-3810
www: http://wwwdwimdn.er.usgs.gov

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