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Phosphorus Loadings from Wisconsin Watersheds: Recommended Phosphorus Export Coefficients for Agricultural and Forested Watersheds

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Introduction

Lake water quality models play an important role in the management of Wisconsin lakes. Annualized empirical lake phosphorus (P) response models such as the TROPHIC model (Vennie 1979) and the Wisconsin Lake Model Spreadsheet (WILMS) (Panuska and Wilson 1994) are commonly used lake management tools. Because P is often the nutrient limiting algal growth in natural lakes, it is the principal nutrient of interest in lake modeling. Use of lake models therefore requires an estimate of P-loading to a lake. While monitoring is the most reliable way to quantify runoff and nutrient loadings to a lake, it is often not a feasible method. In the absence of site-specific data, P-export coefficients can be used.

In general, watershed P-export values tend to be highly variable and are affected by watershed size, land use, soil type, topographic relief, annual rainfall, and transport efficiency of the drainage system. We developed predictive export equations using watershed characteristics found to be significantly correlated with P-export. In this article we provide Wisconsin lake managers with the resulting P-export coefficients for use in lake and watershed modeling when site-specific monitoring data are not available. We also provide monitored export values and their corresponding watershed characteristics.

Methods

A data base was compiled from watershed studies conducted throughout Wisconsin during the past 20 years that met all or most of the following criteria: (a) the watershed did not contain point sources (some exceptions were made for very large watersheds), (b) detailed land use data was available, (c) the size was known, (d) one or more years of monitoring data were available, (e) discharge was quantified (continuous flow record), (f) total P-loading estimates were based on flow-weighted automatic storm event and baseflow monitoring (manual grab sample data were used if of sufficient coverage), (g) precipitation data were available (annual records from closest weather station), and (h) no lakes were located directly upstream from the gaging/monitoring station.

The data base included 82 data sets representing 35 separate watersheds throughout the state (Mirror Lake counted as two watersheds) (Fig. 1). Many of the data represented priority watershed study sites or other nonpoint source studies. Precipitation data were lacking for 16 data sets, and runoff estimates were lacking for 13 data sets. A condensation of the raw data is provided in Table 1. Summary descriptive data are provided in Table 2.

Land use on the study watersheds was predominantly agricultural (27 watersheds, or 79%, contained greater than 50% agriculture), while two watersheds were more than 90% urban and two were more than 90% forested. Three watersheds were mixed ag-forested. Most watersheds were located in the southern half of the state. Twenty-seven watersheds were located in either the Southeastern Till Plains ecoregion or the Driftless ecoregion (from Omernik 1987). Several studies conducted in the northern part of the state that contained P-loading information were eliminated due to the presence of lakes immediately upstream of the monitoring stations. Runoff volume was relatively evenly balanced among agricultural watershed data (39% of the data points represented above-normal flows, while 47% represented below-normal flows). Data representing the three mixed land use watersheds were heavily biased towards wet years (88% represented above-normal flows).

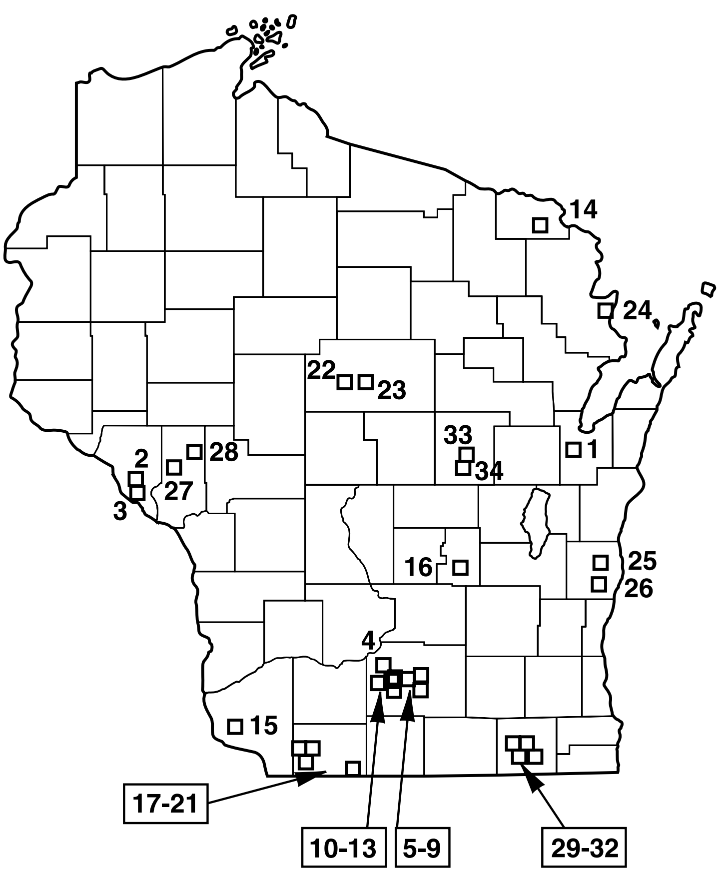

Figure 1. *Location of watersheds used in this analysis. Numbers refer to watersheds listed in Table 1.*

Data were computerized and analyzed using SigmaStat (Fox et al. 1994), including simple linear regression analysis, multiple linear regression analysis, and pair-wise multiple comparison procedures. Where data failed normality or homoscedasticity tests, log or arc-sin transformations were applied and the data were reanalyzed.

Results

Total annual P-export from a watershed was strongly correlated with watershed size ($r^2 = 0.74$, $P < 0.0001$, N = 82). A general loading model may be described by the following linear regression:

$$LOG_{10}\ TP = 2.69 + 0.79\ LOG_{10}\ WATERSHED\ SIZE$$

where TP represents total pounds of P exported from the watershed during the year, and watershed size is measured in square miles. Users are cautioned that this model is most likely valid only for southern Wisconsin as the data base was composed mostly of southern watersheds with agricultural land use.

In simple linear regression analysis, P-export was slightly positively correlated with percent agricultural land use and negatively correlated with percent forest cover and watershed size. Agricultural watersheds exhibited the greatest spread in P-export coefficients, while the few forested watershed data points were narrow in their range (Fig. 2). Differences in P-export rates among ecoregions were primarily a function of differences in predominant land use and runoff volume.

P-export **rates** were found to be primarily controlled by annual **runoff volume**. Both simple linear regression and multiple linear regression analyses indicated that runoff explained 20% of variability in P-export coefficients and as much as 48% of variability in the Southeastern Till Plains ecoregion. Runoff volume, as used in our analysis, is a measure of annual export of water and does not account for variation in the rate or timing of runoff (i.e. seasonal periodicity of occurrences). Runoff volume was independent of watershed size, annual precipitation, and land-use characteristics. In this respect, runoff can not be expected to explain all of the observed variability in P-export. In multiple linear regression analysis, watershed size and percentage land use in agriculture were not found to be significant when included with runoff (<1% variance explained).

Recommendations

Based on results of this study, recommended P-export coefficients for use in lake response modeling are:

	Coefficient in lb mile^{-2} year^{-1} (kg ha^{-1} year^{-1}) by Land Use Type	
P-export Rate	**Agricultural**	**Forested**
Low	111 (0.20)	28 (0.05)
Most Likely	556 (1.00)	50 (0.09)
High	1,667 (3.00)	100 (0.18)

Users may further modify P-export coefficients by selecting more general values from Table 3 or specific watershed values from Table 1. When selecting values from Table 1, it is very important to match geographic area and land use characteristics as closely as possible to the subject watershed.

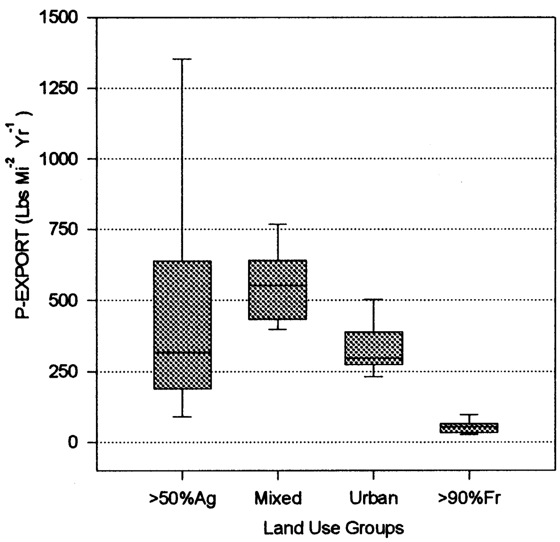

Figure 2. *Range in P-export by land-use type.*

Table 2. *Summary statistics for watersheds used in this study.*

Watershed Characteristic	Mean ± 1SE	Minimum-Maximum	Median	No./Class[a]
Size (miles^2)	21.1[b] ± 5.2	0.05-3,920	—	
% Agriculture	70.2 ± 5.2	0-100	—	19
% Forested	18.0 ± 4.4	0-95	—	2
% Wetland	1.0 ± 0.4	0-13	—	0
% Urban	7.5 ± 3.9	0-100	—	2
Precipitation (inches)	31.4 ± 0.7	21.1-43.0	32.0	
Runoff (inches)	9.2 ± 0.7	0.3-35.3	8.2	
P-export (lb mi^{-2} year^{-1})	466 ± 50	25-2,290	320	

[a] Number of watersheds with >75% of a given land use.
[b] Excludes 3,920 miles^2 watershed of Menominee River.

Table 3. *Phosphorus export coefficients in lb mile^{-2} year^{-1} (kg ha^{-1}) by predominant land use or cover type. Extremes are based on minimum and maximum observations; lows represent approximately the 10th percentiles; highs represent approximately the 90th percentiles; most likely values are based on the median.*

	P-Export Rate				
Land-Use Classification	**Extreme Low**	**Low**	**Most Likely**	**High**	**Extreme High**
Ag > 95% (N=16)	86 (0.15)	100 (0.18)	591 (1.04)	1,750 (3.06)	2,290 (4.01)
Ag > 75% (N=40)	53 (0.09)	86 (0.15)	424 (0.74)	1,400 (2.45)	2,290 (4.01)
Ag > 50% (N=63)	46 (0.08)	91 (0.16)	317 (0.56)	1,340 (2.35)	2,290 (4.01)
Mixed (N=8)	391 (0.68)		553 (0.97)		814 (1.43)
Forest (N=6)	25 (0.04)		54 (0.09)		100 (0.18)
Urban (N=5)[a]	230 (0.40)		296 (0.52)		502 (0.88)

[a] Urban data is for low density residential land use (i.e. roughly 0.5 acre lot size).

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Table 1. *Total phosphorus loads of monitored watersheds in Wisconsin.* [a]

Watershed	County (Location on Fig 1)	Primary Land Use (%)[b]	Size (mi²)	Year[c]	P-Export (lb/mi²/yr)	Runoff (in/yr)[d]	Source[e]
General Studies							
Wisconsin - General		"Forest"		1973-82	64		2
Wisconsin - General		"Agricultural"		1979	149		3
Wisconsin - Row Crops < 1 mi²		"Ag - row crops"		—[f]	811		1
USA		>90 Forest		—	52		13
		>75 Forest		—	74		
		>50 Forest		—	95		
USA		>90 Ag		—	152		13
		>75 Ag		—	146		
		>50 Ag		—	121		
Wisconsin Studies							
1. Bower Creek	Brown	99 Ag	14.80	1990-91	640	6.29 (9)	17
				1991-92	730	5.81	17
2. Joos Valley Creek	Buffalo	63 Fr, 37 Ag	5.89	1990-91	537	6.99 (6)	17
				1991-92	658	9.31	17
3. Eagle Creek	Buffalo	57 Fr, 43 Ag	4.52	1990-91	814	7.36 (6)	17
				1991-92	622	8.64	17
4. Fish Lake Trib.	Dane	>90 Ag	0.40	1990-91	432	0.30[c] (8)	17
5. Sixmile Creek	Dane	93 Ag	41.10	1976	462	6.50 (8)	11
				1977	166	2.80	11
6. Spring Creek	Dane	94 Ag	12.70	1976	485	7.50 (8)	11
7. Token Creek	Dane	95 Ag	24.40	1976	417	13.30 (8)	11
				1977	183	9.40	11
8. Yahara River	Dane	96 Ag	73.70	1976	297	4.50 (8)	11
				1977	91	2.00	11
				1990-91	86	2.53	17
				1991-92	100	3.08	17
9. Willow Creek	Dane	90 Ur	3.20	1976	502	7.90 (8)	11
10. Black Earth Creek	Dane	54 Ag, 31 Fr	14.60	1985	312	15.01 (8.5)	6
				1986	106	16.39	6
11. Brewery Creek	Dane	63 Ag, 24 Fr	7.70	1985	628	4.81 (8.5)	6
				1986	206	5.31	6
				1990-91	91	1.03	17
				1991-92	254	1.59	17
12. Garfoot Creek	Dane	48 Ag, 45 Fr	5.39	1985	569	13.25 (8.5)	6
				1986	454	16.00	6
				1990-91	391	8.26	17
				1991-92	413	10.15	17

(continued on next page)

Table 1. *(continued)*

Watershed	County (Location on Fig 1)	Primary Land Use (%)[b]	Size (mi²)	Year[c]	P-Export (lb/mi²/yr)	Runoff (in/yr)[d]	Source[e]
13. Pheasant Branch	Dane	93 Ag, 7 Ur	18.30	1976	571	3.50 (8)	11
				1977	314	2.10	11
14. Popple River	Florence	95 Fr	139.00		25	Dry year	16
					54	Average year	
					100	Wet year	
15. Rattlesnake Creek	Grant	89 Ag, 8 Fr	42.40	1991-92	722	6.85 (8.8)	17
16. White Creek	Green Lake	92 Ag, 8 Fr	3.05	1981-82	458	24.51 (9)	17
				1983-84	356	21.40	17
				1984-85	473	21.90	17
				1985-86	1,400	35.32	17
				1986-87	150	15.80	17
				1987-88	85	8.41	17
17. Steiner Branch	Lafayette	71 Ag, 29 Fr	5.90	1978	707	9.49 (9)	4,7
				1979	231	11.36	4,7
18. Madden Branch Tributary	Lafayette	100 Ag	2.83	1981	542	6.97 (9)	4
				1982	2,070	13.03	4
19. Pats Creek	Lafayette	100 Ag	5.42	1981	682	6.41 (9)	4
				1982	1,750	12.39	4
20. Apple River	Lafayette	99 Ag	9.34	1981	463	7.91 (9)	4
				1982	1,400	16.67	4
21. Madden Branch	Lafayette	100 Ag	15.10	1981	749	7.08 (9)	4
				1982	2,290	13.58	4
22. Fenwood Creek	Marathon	76 Ag, 23 Fr	37.00	1975	160	?-extr.[g] (11)	18
				1976	80	?-extr.	18
23. Freeman Creek	Marathon	61 Ag, 35 Fr	21.70	1975	206	?-extr. (11)	18
				1976	46	?-extr.	18
24. Menominee River	Marinette	90 Fr, 6 Ag	3,920		33	Dry year	16
					53	Average year	
					64	Wet year	
25. Onion River	Sheboygan	72 Ag, 22 Fr	37.2	1979	331	11.75 (7)	8
				1980	317	10.10	8
26. Otter Creek	Sheboygan	86 Ag	9.5	1990-91	262	8.19 (7)	17
				1991-92	230	9.14	17
27. Elk Creek	Trempealeau	75 Ag, 25 Fr	108	1980	1,340	11.29 (8)	3
28. Bruce Valley Ck.	Trempealeau	72 Ag, 28 Fr	10.1	1980	1,600	10.98 (9)	3
29. Jackson Creek	Walworth	89 Ag	8.96	1984	289	6.62 (8.5)	5
				1985	261	6.66	5

Table 1. *(continued)*

Watershed	County (Location on Fig 1)	Primary Land Use (%)[b]	Size (mi²)	Year[c]	P-Export (lb/mi²/yr)	Runoff (in/yr)[d]	Source[e]
30. Jackson Creek Tributary	Walworth	57Ag, 26 Ur	4.34	1984	876	9.40 (8.5)	5
				1985	801	12.90	5
				1985-86	1,213	17.83	17
				1986-87	359	7.85	17
				1987-88	133	5.85	17
				1989-90	287	8.44	17
				1990-91	285	8.94	17
				1991-92	281	10.52	17
31. Delevan Lake Inlet	Walworth	72 Ag	21.78	1984	323	7.23 (8.5)	5
				1985	309	7.91	5
32. Delevan Lake Tributary # 2	Walworth	80 Ag	7.66	1984	59	2.90 (8.5)	5
				1985	53	2.47	5
				1990-91	125	1.34	17
33. Mirror Lake	Waupaca	100 Ur	0.12	1972	287	10.88 (12.0)	9,10
			0.12	1973	351	?	9,10
			0.05	1977	230	?	9,10
			0.05	1978	296	?	9,10
34. White Clay Lake (East Basin subwatershed)	Waupaca	84 Ag, 13 Wt	1.27	1974-79	438	6.58 (12.0)	14,15

Other watersheds with p-loading data available but not included: Bad River, Ashland Co.; Hay & Red Cedar Rivers, Dunn Co.; Big Eau Pleine River, Marathon Co.; Menominee and Milwaukee Rivers, Milwaukee Co.; Rice Creek, Polk Co.; Silver Creek, Green Lake Co.; Park Lake, Columbia Co.; and Bear River, Iron Co.

[a] Precipitation data are available from the authors.
[b] Land use coded as Ag (=Agriculture), Ur (=Urban), Wr (=Wetland), Fr (=Forest).
[c] USGS water years = October 1st year through September 2nd year.
[d] Average annual runoff in parenthesis.
[e] See list below.
[f] Years not available.
[g] extr. = extrapolated flows only.

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