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A Phosphorus Budget for the Lake Mendota Watershed

Elena M. Bennett,[1]* Tara Reed-Andersen,[1] Jeffrey N. Houser,[1] John R. Gabriel,[2] and Stephen R. Carpenter[1]

[1]*Center for Limnology, 680 North Park Street; and* [2]*Department of Water Chemistry, University of Wisconsin, Madison, Wisconsin 53706, USA*

ABSTRACT

A phosphorus (P) budget was calculated for the agriculture-dominated Lake Mendota watershed located in Dane and Columbia Counties, Wisconsin, USA. P inputs included fertilizer for agricultural crops and lawns, dietary supplements for dairy cattle, and natural inputs such as dry and wet deposition. Outputs included agricultural crops, livestock and livestock products, and hydrologic export to Lake Mendota. The total P input to the watershed (1,307,000 kg year^{-1}) and total output (732,000 kg year^{-1}) are large relative to the average of 34,000 kg P washing into the lake each year, indicating that the P flux that eutrophies Lake Mendota is a very minor component of the total watershed P budget. Using the formula *inputs* − *outputs* = *change in storage*, we found that 575,000 kg P accumulated in the watershed in 1995. This estimate was corroborated by long-term soil P concentration data, which showed an average annual increase in soil P of over 450,000 kg year^{-1}. Future management programs designed to reduce P inputs to Lake Mendota will be compelled to cope with the large amount of P being stored in the watershed.

Key words: cultural eutrophication; eutrophication; phosphorus; watershed; lake; mass balance; land use.

INTRODUCTION

It is widely accepted that phosphorus (P) is a fundamental driver of lake primary production and that excessive P input can degrade lakes through eutrophication (Vollenweider 1968; Schindler and others 1971; Dillon and Rigler 1974; EPA 1990a). Eutrophied lakes frequently experience noxious algal blooms, increased aquatic plant growth, and oxygen depletion, leading to degradation of their ecological, economic, and aesthetic value by restricting use for fisheries, drinking water, industry, and recreation (NRC 1992; Sharpley and others 1994). The detrimental effects of eutrophication have stimulated efforts to control P input to lakes.

Efforts to reduce point source P pollution of lakes from sewage treatment plants and industrial sites have been largely successful since implementation of the Clean Water Act in 1972 (Sharpley and others 1994). However, non-point source P pollution remains a serious water quality problem (NRC 1992; Duda 1993). In many watersheds, agricultural activities, including application of excess fertilizer and manure to crop fields, are considered to be a major source of nonpoint P input to lakes (EPA 1990b, 1996; NRC 1992, 1993; Daniel and others 1994). In addition to degrading lakes, fertilizer lost as runoff represents a financial and energy loss both to society and to farmers.

Although the importance of studying nutrient cycling at the watershed scale has long been recognized (Bormann and Likens 1967; Likens 1974), the growing problem of nonpoint P loading has increased the need for studies on this scale. Calculation of lake P budgets has advanced our understanding of in-lake P dynamics, such as P retention and recycling [for example, those summarized in Vollen-

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*Corresponding author; e-mail: embenne1@students.wisc.edu

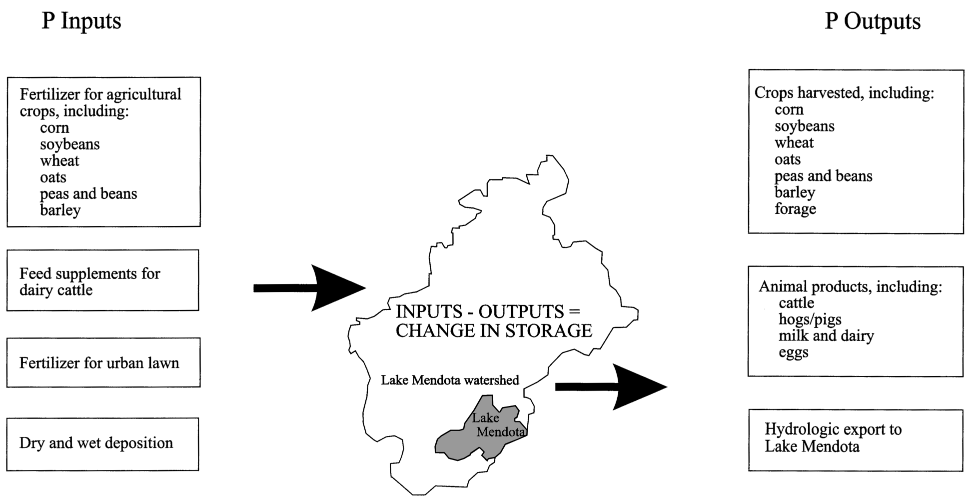

Figure 1. Schematic diagram of inputs and outputs used to calculate a phosphorus (P) budget for the Lake Mendota watershed for 1995.

weider (1968), Dillon (1975), Schindler and others (1976), and Campbell (1994)]. These studies contribute to lake restoration efforts that emphasize reduction of P inputs, but they do not focus on the question of the magnitude of P runoff relative to the P budget of the entire watershed. Lowrance and colleagues (1985) showed that, in four subwatersheds of the Little River in the Georgia Coastal Plain, imports of P exceeded exports by 3.7–11.3 kg ha^{-1} $year^{-1}$. They concluded that a large percentage of the P imported each year was being stored somewhere in the watershed. Similarly, in a nitrogen and P budget of the upper Potomac River Basin, Jaworski and coworkers (1992) found that over 60% of the imported P was retained within the watershed.

If P inputs to a watershed exceed outputs, the excess P likely will be stored in the soil due to the propensity of phosphates to bind to soil particles. To our knowledge, however, there has been no attempt to link a watershed P budget to the P content of the soil to examine this hypothesis. In Wisconsin, soil P budgets have shown that while P additions from commercial fertilizer have decreased since 1985, as much as 10 kg ha^{-1} excess P is still added to the soil every year (Bundy 1994). Sharpley and others (1994) also found that inputs of P in fertilizer and manure in excess of crop requirements have increased P in the soil.

We calculated a P budget for the watershed of a eutrophic lake for which detailed P budgets are known (Lathrop 1992; Soranno and others 1997; Lathrop and others 1998). We asked whether the P runoff to the lake was a significant component of the terrestrial P budget. Budget estimates of P accretion in the watershed were compared with estimates of P accretion in soils.

Study Area

The 686 km^2 watershed of Lake Mendota is almost entirely contained within Dane County, Wisconsin, with a small portion in Columbia County. The upland soils are well-drained silt loams, whereas the lowlands are poorly drained silts (Cline 1965). In 1995, the watershed land use was approximately 86% agricultural, 9% urban, 4% wetlands, and 1% forest (Soranno and others 1996). The proportion of agricultural land had reached its current level by about 1870 (Lathrop 1992). Land use is currently changing through the conversion of agricultural land to urban uses (Dane County Regional Planning Commission 1992).

Methods

A mass-balance approach was used to calculate inputs, outputs, and change in storage (amount retained or lost by the watershed) of P in the Lake Mendota watershed for 1995. Jaworski and colleagues (1992) used a similar approach to evaluate the change in storage of nitrogen and P for the Upper Potomac River Basin in Maryland, USA. Inputs of P to the Mendota watershed are in the form of fertilizer for agricultural crops and urban lawns, feed supplements for dairy cattle, dry and wet deposition, groundwater flow, and weathering. P leaves the watershed in corn and other crops, livestock and livestock products, and hydrologic export to Lake Mendota (Figure 1).

Inputs and outputs of P were calculated based on values for 1995 from various published and unpublished sources (Table 1). The distribution of crops

Table 1. Sources of Data Used to Calculate 1995 Phosphorus (P) Budget for the Lake Mendota Watershed

Component	Subcomponent	Source
Inputs		
Fertilizer for agricultural crops	Recommended fertilization rates	Kelling and others 1991
	Typical rates of fertilization	Nowak and others 1996
	Typical manure application rates	P. Nowak, Rural Sociology, University of Wisconsin, personal communication
	Amount of land planted in each crop	DATCP[a] 1996
Feed supplements for dairy cattle	Recommended feed supplements for dairy cattle	NRC[b] 1988
	Typical feed supplements for dairy cattle	D. Undersander, Agronomy, University of Wisconsin, personal communication
	Number of cattle in Dane County	DATCP 1996
Fertilizer for urban lawn	Turf fertilization rates by homeowners	Pennsylvania Agricultural Statistics Service
	Turf fertilization rates by lawn care companies	Pennsylvania Agricultural Statistics Service
	Acreage of turf in the watershed	Bannerman and others 1993
	Percentage of homeowners using lawn care services	W. Kussow, Soil Science, University of Wisconsin, personal communication
Atmospheric deposition	Dry deposition	Lathrop 1979
	Wet deposition	Lathrop 1979
Outputs		
Crops harvested	Amount of each crop harvested in Dane County	DATCP 1996
	%P in each crop	NRC 1982
Animal products	Number of cattle and hogs in Wisconsin and Dane County	DATCP 1996
	Number of cattle and hogs slaughtered in Wisconsin	DATCP 1996
	%P in cattle and hogs	Georgievskii and others 1982
	Milk and eggs produced in Dane County	DATCP 1996
	%P in milk and eggs	NRC 1982
Hydrologic export to Lake Mendota	Hydrologic export to Lake Mendota	Lathrop and others 1998

[a]*DATCP, Department of Agriculture, Trade, and Consumer Protection.*
[b]*NRC, National Research Council.*

and livestock within the watershed was assumed to be proportional to the distribution in the county. Where numbers could not be obtained for the watershed, they were scaled down based on the ratio of watershed area to county area. Values for recommended fertilization rates (Kelling and others 1991), typical fertilization rates (Nowak and others 1996), and manure application rates (P. Nowak, Department of Rural Sociology, University of Wisconsin, personal communication), as well as the amount of land planted in each crop [Department of Agriculture, Trade, and Consumer Protection (DATCP) 1996] were used to calculate the amount of P imported as fertilizer for agriculture. Estimates of the amount of fertilizer applied by homeowners and professional lawn-care providers (Pennsylvania Agricultural Statistics Service n.d.), as well as an estimated percentage of homeowners who use professional lawn-care services (W. Kussow, personal communication) and the amount of turf in the urban part of the Lake Mendota watershed (Bannerman and others 1993), were used to calculate fertilizer imported for lawn care. All commercial fertilizer was considered to have been produced outside the watershed and imported. No P is mined within the watershed. All manure was considered to originate within the watershed. Information on feed supplement recommendations (NRC 1988), typical feed supplement use in Dane County (D. Undersander, Department of Agronomy, University of

Wisconsin, personal communication), and number of cattle in the watershed (DATCP 1996) were used to calculate P imported in feed supplements for dairy cattle. Values for dry and wet deposition in the Madison area had been developed previously (Lathrop 1979).

Outputs were calculated in a manner similar to inputs. All products sold for human consumption were considered exports because they were either sold outside the watershed or the P they contained was removed through the sewage system. Since all sewage is released outside the watershed, all food produced for human consumption, including that consumed within the watershed, can be considered a single output. Amount and %P of each product were used to determine P exported in agricultural crops, milk, and eggs (NRC 1982; DATCP 1996). The number of cattle and hogs were available for Dane County and were scaled down to the watershed (DATCP 1996). Rates of slaughter, available for the state and assumed to be similar to those for the county, were used to calculate the amount of P lost from the watershed through beef production (DATCP 1996). Percent P in cattle and hogs was available from Georgievskii and colleagues (1982). Hydrologic export to Lake Mendota was based on 21 years of P-loading estimates for Lake Mendota (Lathrop and others 1998).

Retention of P was then calculated based on the formula

$$\text{INPUTS} - \text{OUTPUTS} = \text{CHANGE-IN-STORAGE}.$$

Uncertainties in the P budget were described by bracketing the most likely estimate with the minimum and maximum plausible values for each item. For inputs, uncertainties involved different assumptions about the amount of fertilizer applied to agricultural crops. The minimum calculation was based on the postulation that farmers apply commercial fertilizer in the amount recommended by the University of Wisconsin Extension (Kelling and others 1991). However, Nowak and coworkers (1996) showed that, in Dane County, farmers apply an average of 100 kg P ha^{-1} (91 lb P $acre^{-1}$) to fields planted in corn, whereas the amount recommended is only 50 kg P ha^{-1} (45 lb P $acre^{-1}$). The maximum calculation was based on the postulation that farmers apply approximately double the recommended rate of fertilizer to all crops. In the maximum estimate, all fertilizer used is commercial; that is, farmers do not credit manure application toward the amount of commercial fertilizer that they need to reach their intended level of fertilization. The most likely estimate is based on the assumption that farmers are crediting manure application and are therefore applying less commercial fertilizer (P. Nowak personal communication). Bracketing for outputs was based on differences in the amount of forage exported versus that used or stored for future use within the watershed. The maximum output is based on export of 10% of all forage produced in the watershed. The most likely and minimum estimates are based on 5% and 0% export of all forage produced, respectively (D. Undersander personal communication).

Accumulation of P in the soil from 1974 to 1994 was based on available soil test P data for Dane County averaged over 4-year periods (Combs and others 1996). These data were converted to kg P $year^{-1}$ accumulation in the soil based on the average P-buffering capacity of soils in much of the United States: 3.632 kg P $acre^{-1}$ for every 1 μg g^{-1} increase in the Bray P-1 soil test (Leikam 1992).

Results

Estimates of total input of P to the Lake Mendota watershed ranged from a minimum of 851,000 kg P $year^{-1}$ to a maximum of 1,717,000 kg P $year^{-1}$. The most likely estimate was 1,307,000 kg P $year^{-1}$ (Table 2A). Fertilizer for corn was the largest single source of P, accounting for 54.3% of all P entering the watershed (most likely estimate). The second-largest input of P to the watershed was feed supplements for dairy cattle, accounting for 18.2% of inputs. P input as corn fertilizer were the least precise components of the budget, with a range that was nearly 75% of the nominal estimate. Natural movement of P into the watershed, through dry and wet deposition, makes up only a small percentage (4.7%) of the total inputs in this budget. Human-induced movement of P, through the import of fertilizer and feed supplements, comprises the majority of the budget (95.3%).

Estimates of P lost from the watershed range from a minimum of 729,000 kg P $year^{-1}$ to a maximum of 735,000 kg P $year^{-1}$. The most likely estimate is an output of 732,000 kg P $year^{-1}$ (Table 2B). Corn exported was the largest source of P lost from the watershed, accounting for 55.3% of all outputs. The second-largest output item was dairy products, which accounted for 10.5% of the total output. The only item that differed in the minimum and maximum estimates was forage, which ranged from 0 to 6200 kg P $year^{-1}$ exported. Natural export of P, through hydrologic export to Lake Mendota, made up only 4.6% of the total outputs. Human-caused

Table 2A. Most Likely, Minimum, and Maximum Estimates of Phosphorus (P) Inputs to the Lake Mendota Watershed in kg P year^{-1} [a]

Item	Minimum	Most Likely	Maximum
Fertilizer for corn	396,000	710,000	901,000
Feed supplements	238,000	238,000	357,000
Fertilizer for soybeans	81,000	146,000	185,000
Fertilizer for urban lawn	37,000	86,000	128,000
Dry deposition	43,000	43,000	43,000
Fertilizer for wheat	20,000	35,000	44,000
Fertilizer for oats	13,000	22,000	28,000
Wet deposition	18,000	18,000	18,000
Fertilizer for peas and beans	3,000	6,000	8,000
Fertilizer for tobacco	1,000	2,000	3,000
Fertilizer for barley	1,000	1,000	2,000
Total	851,000	**1,307,000**	1,717,000

[a] *Items in bold indicate those minimum and maximum estimates that differ from the most likely.*

Table 2B. Most Likely, Minimum, and Maximum Estimates of P Outputs from the Lake Mendota Watershed in kg P year^{-1}

Item	Minimum	Most Likely	Maximum
Corn	405,000	405,000	405,000
Dairy products	77,000	77,000	77,000
Eggs	73,000	73,000	73,000
Soybeans	70,000	70,000	70,000
Cattle	42,000	42,000	42,000
Export to Lake Mendota	34,000	34,000	34,000
Wheat	10,000	10,000	10,000
Peas and beans	8,000	8,000	8,000
Oats	5,000	5,000	5,000
Hogs and pigs	4,000	4,000	4,000
Forage	0	3,000	6,000
Barley and tobacco	1,000	1,000	1,000
Total	729,000	732,000	735,000

[a] *Items in bold indicate those minimum and maximum estimates that differ from the most likely.*

movement of P was responsible for 95.4% of all P leaving the watershed.

There was considerably more uncertainty in the inputs than in the outputs. Uncertainty associated with inputs is due to the difficulty of estimating how much commercial fertilizer and manure is applied by farmers. Variability in fertilization practices is high, and average farmer behavior may be misleading (Nowak and others 1996). Variation in P output reflects uncertainty in the amount of forage exported from the watershed versus that consumed by animals or stored for future use within the watershed.

The most likely estimates of P budget for the Lake Mendota watershed clearly show that the amount of P entering the watershed (1,307,000 kg P year^{-1}) exceeds the amount of P lost from the watershed (732,000 kg P year^{-1}). Nearly half the P entering the watershed is retained.

Changes in the soil P levels in Dane County over the past 20 years corroborate this result (Figure 2). Soil tests in Dane County indicate that P in the soil has increased annually by approximately 450,000 kg P year^{-1} (Combs and others 1996), which agrees reasonably with the retention of 575,000 kg P year^{-1}, as determined by excess input in the P budget for 1995.

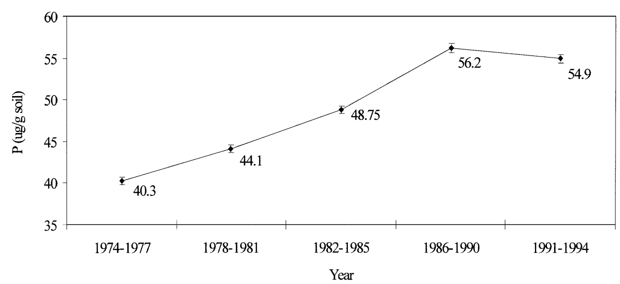

Figure 2. Soil test phosphorus (P) data for Dane County (1974–94), with 95% confidence intervals (Combs and others 1996).

Discussion

The 1995 P budget for the Lake Mendota watershed clearly shows that the amount of P that enters the watershed exceeds the output, indicating that P is being retained in the watershed. Changes in soil test P levels in Dane County confirm this excess and indicate that the surplus P is being stored in the soil. Correspondence of these results indicates that the general argument is unlikely to be changed qualitatively by quantitative refinements. Excess imports of P, derived from fertilizers and feed, are accumulating in the soils of the Lake Mendota watershed.

Allowing soil P levels in the Lake Mendota watershed to drop could take many years. If we were to stop overfertilizing immediately and apply only as much P as leaves the watershed in agricultural products each year (assuming that agricultural production, and therefore export of P, will not decrease with reduced fertilization), it would take over 260 years for P in the soil to drop to 1974 levels. Calculations based on the additional movement of P through the watershed that is caused by human actions show that even if we were to cease importing P to the watershed completely, it would still take at least 12 years for the P in the soil to drop to 1974 levels.

In the absence of a reduction in P fertilizer usage, the P accumulating in the watershed will wash downhill and contribute to eutrophication of the lake. Chemicals such as P that appear to be sequestered in the soil may later be mobilized by a geologic, hydrologic, chemical, or climatic event such acid precipitation or heavy summer thunderstorms. P could also be mobilized by changes in land-management practices or some unpredictable mechanism. In this sense, P accumulation in the watershed can be viewed as what Stigliani and others (1991) term a "chemical time bomb" in the soil. Future management programs designed to reduce P input to Lake Mendota will have to take into account the excess P being stored in the watershed soil. Although not all of the accumulated P will reach Lake Mendota, not very much of it has to in order to maintain the eutrophic state of the lake (Lathrop and others 1998). Our results indicate that the eutrophication of Lake Mendota is caused by only a small percentage of the P moving through the watershed.

The general pattern of P accumulation seen in the Lake Mendota watershed is not an issue restricted to this watershed. Global P cycle data show that, on average, P is building up in the world's soil (Carpenter and others 1998). P inputs to the world's oceans are also increasing (Howarth and others 1995). Howarth and colleagues (1995) attribute 70% of this increase to increased erosion and the remaining 30% to increased P stored in the world's soils. P accretion in agricultural soil has been documented at a national scale. In the United States and Europe, only about 30% of P input in fertilizers is exported in agricultural products (Isermann 1991; NRC 1993). This pattern has also been documented at the watershed scale [for example, see Lowrance and others (1985) and Jaworski and others (1992)]. Fluck and others (1992) found that less than 20% of the P input to the Lake Okeechobee watershed is output in agricultural and other products. At many scales, including global, national, regional, and local, P has been shown to be accumulating in agricultural soils.

Accumulation of P in the soils of the world's agricultural watersheds could lead to an increase in the number of eutrophied lakes worldwide and a decrease in the social, economic, and ecological value of these lakes (Postel and Carpenter 1997). Decreases in water quality reduce the amount of water available for human use, or increase the costs of purifying water, and thereby contribute to problems of dwindling water supplies (Postel 1997). Management efforts to reduce P inputs to lakes worldwide will be compelled to cope with increased amounts of P stored in watershed soils.

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