

Whole Watershed Balances

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Whole Watershed Phosphorus Balances as a Lake Management Tool

Introduction

Since the 1970s, when phosphorus (P) was recognized as a limiting nutrient controlling algae growth, management strategies for reversing lake eutrophication have generally focused on reducing P inputs to lakes. Two P reduction approaches in particular resulted in several early examples of improved water quality. The first was to reduce inputs of phosphorus entering lakes from municipal sewage treatment. Lake Washington, in Seattle, was the classic example of sewage diversion and demonstrated the potential impact of reducing phosphorus inputs to lakes. From the mid-1960s, when diversion began, to the mid-1970s, total P levels in Lake Washington declined by two-thirds and Secchi disk clarity tripled.

A second major strategy for reducing surface water P levels was the elimination of P from laundry detergents. Detergent P bans were first introduced in the early 1970s; by 1999, 27 states had enacted detergent phosphorus bans (Litke 1999). Detergent P bans reduced the P concentration of raw wastewater by nearly one-half. Combined with modern tertiary treatment, many sewage treatment plants now discharge effluents with P concentrations less than 0.5 mg/L, a mere 10 percent of typical effluent P concentrations from three decades ago (Figure 1).

Sewage diversion and the detergent P ban both addressed point sources of phosphorus to surface waters. Achieving further reductions in lake P inputs will require greater focus on nonpoint sources

(NPS), such as agricultural runoff, urban stormwater, and septic systems. Two new policies developed under the Federal Clean Water Act are driving renewed interest in the NPS problem. The first is the “total maximum daily load” (TMDL) process that requires demonstrable loading reductions to impaired surface waters. The second is the urban stormwater program, which is compelling cities to reduce pollutant loadings from urban areas.

To date, most efforts to reduce NPS pollution are similar to those used to deal with point sources of pollution in that they remove the pollutant after it is produced by using end-of-pipe “best management practices” (BMPs). These include septic systems, stormwater detention ponds, infiltration basins, constructed wetlands, and buffer strips.

Reliance solely upon end-of-pipe approaches for NPS control is unwise

for several reasons. First, unlike modern municipal or industrial wastewater systems that can attain high and consistent P removal efficiencies, BMPs for NPS control generally have lower removal efficiencies, more variable performance, and lower reliability. Second, operations and maintenance requirements have often been far higher than projected for urban BMPs.

Finally, and perhaps most importantly for lake managers, P is not actually “removed” by most structural BMPs, it simply accumulates and is stored in the watershed. For BMPs based on P adsorption on soils (erosion control measures, infiltration basins, rain gardens, and septic leach fields), the amount of adsorbed P accumulates year after year. Although it was once thought that soil adsorption of P was permanent, there is now a wealth of research to show soils’ capacity to adsorb P is limited and

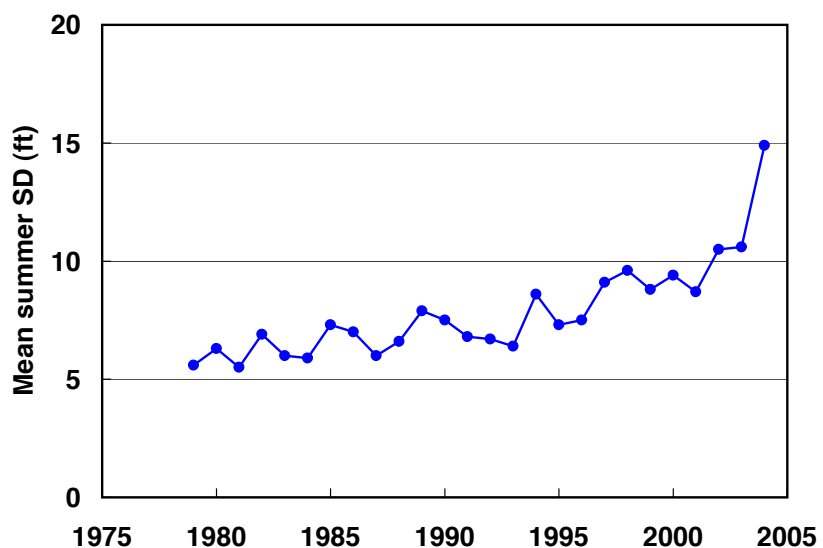


Figure 1. Secchi disk trend in Shagawa Lake, Minnesota following implementation of tertiary treatment of sewage entering the lake in 1973.

that P “breaks through”, resulting in contamination of surface and ground waters. Here are four convincing studies that are changing the P retention paradigm:

- A study of soils and water in the Clear Lake watershed in Iowa (Klatt et al. 2003) showed that there was a linear relationship between the average “Bray P” (a measure of adsorbed P readily available to plants) in the soils of five watersheds and P concentrations in streams draining these watersheds.
- Robertson et al. (1998) studied the groundwater plumes below ten septic systems in Ontario. For those located on calcareous sands, distinct plumes of P in groundwater, with concentrations exceeding 1 mg/L, were observed tens of meters beyond the edge of the leach fields.
- A study of an abandoned sewage lagoon on Cape Cod conducted by the U.S. Geological Survey revealed a phosphate plume that traveled a quarter-mile, entering Ashumet Pond (McCobb et al. 2003).
- Using experimental data from dozens of studies (Vadas et al. 2005) determined a single, overall relationship between adsorbed P on soils and P in runoff.

Conceptual Development of Whole-Watershed P Balances

Clearly, P-retention BMPs cannot be relied upon entirely to alleviate P input to lakes. In this paper, we propose a more holistic approach for P management, one based on whole-watershed P mass balances. Although the concept of using whole-watershed mass balances for management of pollutants is not new, new technology – geographic information systems (GIS), satellite imagery, and large-scale, readily accessible data on everything from household demographic characteristics to digitized feedlot locations make the use of whole-watershed balances a practical tool for lake management.

Figure 2 shows a generalized watershed P balance for a typical recreational lake. Written as an equation, the watershed P balance is:

$$P \text{ Accumulation} = P \text{ Inputs} - \text{Deliberate P Exports} - \text{Stream P Export} \quad \text{equation 1}$$

Input P comes into a watershed from an external source, such as imported human and animal food or fertilizer. Deliberately exported P is contained in products exported from the watershed such as crops, animal products, or waste. Stream export is the mass of P leaving the watershed via streamflow. Accumulated P is phosphorus stored in a watershed’s plants, soils, and sediments.

Case Study of 11 Minnesota Lake Watersheds

Whole-watershed P balances were recently developed for watersheds of 11 recreational lakes in Minnesota (Schussler et al. 2007) with the goal of better understanding how changing land use, shoreline development, and economic activities affect lake clarity. Lakes were selected to be typical of lakes in three lake-rich, rapidly developing counties (Crow Wing, Douglas and Hubbard) in Minnesota.

To develop the watershed P mass balances and define the terms in equation 1, major P inputs and exports were first identified. For the study lakes, major P

inputs included human food, fertilizer, animal feeds, and atmospheric deposition. Deliberate exports included P in exported crops and animal products (milk, meat, eggs). Sewage and sewage sludge can be transported across watershed boundaries and were included as an export in some watersheds and an import in others.

Data to fill in the terms in equation 1 were obtained from readily available, existing sources of data. Watershed population was determined from U.S. Census data and per capita input of P were estimated using information from a statewide P study. Counties in which case study lakes were located provided the sewered population of each watershed; areas outside the sewershed were assumed to have septic systems. Watershed land cover databases were obtained from the Minnesota Department of Natural Resources. Watershed crop production was estimated from mapped agricultural land and county-wide crop production data. Fertilizer application rates for each major crop were determined using statewide data. County-level data were used to estimate the number of feedlots

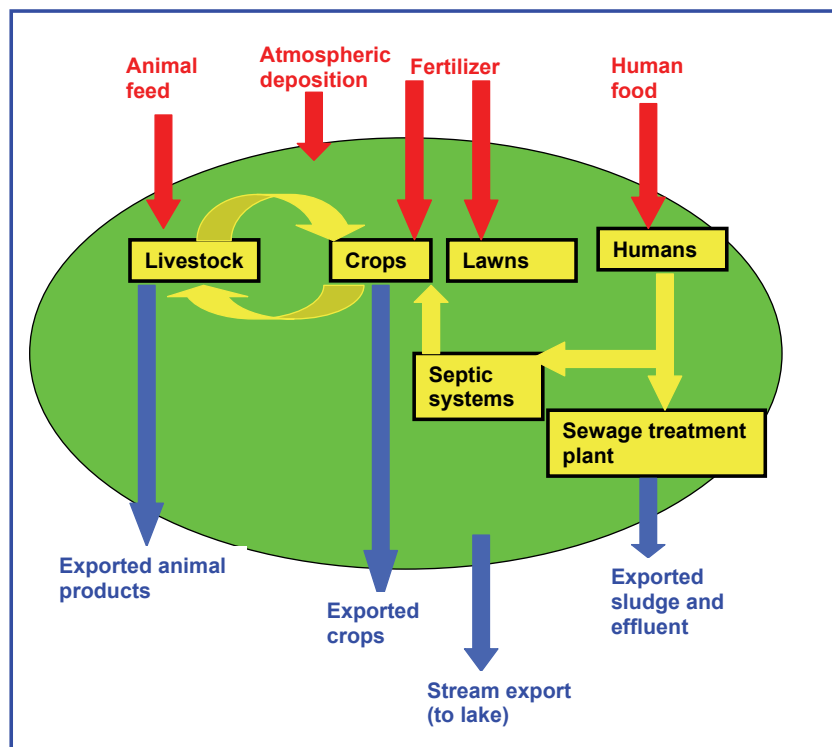


Figure 2. Schematic of a watershed P balance. Inputs are shown by red arrows, outputs by blue arrows, and internal cycling by yellow arrows.

and the number and types of animals in these feedlots. Permitted point source discharges were determined using data from the National Pollution Discharge Elimination Program (NPDES) and interviews with local officials regarding sewage treatment and sludge disposal. Finally, since we did not have estimates of P loadings from streams, we hindcast stream P loading using measured Secchi disk clarity to infer lake P concentrations using the MINLEAP model (Wilson and Walker 1989). With all other terms defined, watershed P accumulation was determined by difference (see equation 1).

We found that areal P inputs to the 11 case study watersheds varied by one full order of magnitude, from 0.3 kg P/ha-yr to 6.0 kg P/ha-yr. The percentage of watershed in agriculture correlated directly with areal P inputs rates (Figure 3). This does not mean that agricultural P is the main source of P to all watersheds. When the watershed was less than 30 percent agricultural, human food, lawn fertilizer, and atmospheric deposition were the dominant P inputs.

Although agricultural watersheds had higher areal P inputs, they also had higher deliberate exports – P in the form of crops, milk and meat (Figure 4). In the watersheds dominated by agriculture, agricultural exports accounted for 38 to 63 percent of total P inputs. The highest P export occurred in the watershed of Le Homme Dieu Lake, located near Alexandria, Minnesota. This watershed exported agricultural products and sewage sludge, the latter from a tertiary treatment plant. These exports combined account for 86 percent of P inputs to the watershed.

All 11 watersheds accumulated P. For watersheds with little deliberate P exports, P accumulation was up to 90 percent of P input. Watersheds with high P accumulation typically had little export of agricultural products and a high fraction of homes on septic systems. Watersheds with high agricultural activity generally had lower P accumulation rates.

Stream P export is affected not only by P inputs but also by deliberate exports and accumulation. Hence we found virtually no relationship between areal P inputs and areal stream export rates, and only a weak relationship between watershed P input rates and Secchi disk transparency.

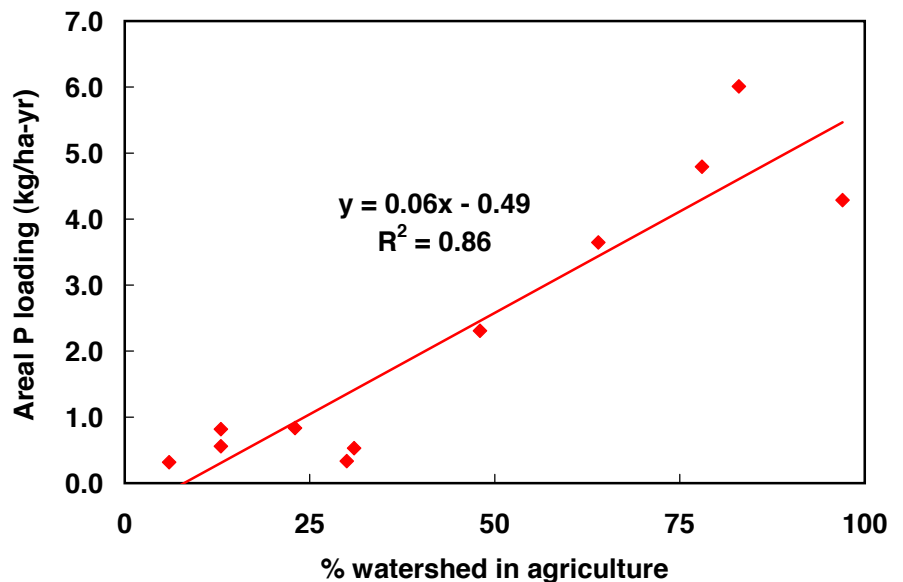


Figure 3. Relationship between percentage of watershed in agriculture and areal watershed P input rate.

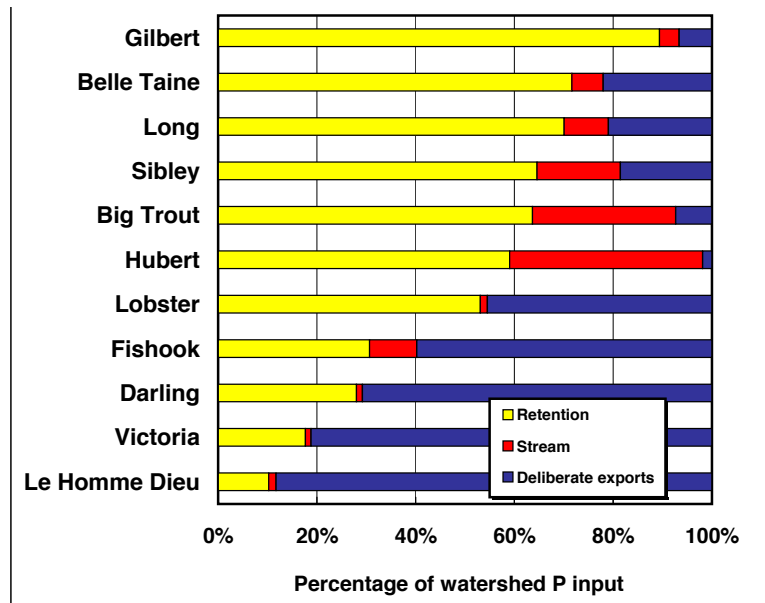


Figure 4. Deliberate P exports, stream P exports, and watershed P accumulation, each as percentage of watershed P input.

Refocusing P Management

Results from our study, taken together with several other studies such as a P balances for the watersheds of Lake Mendota (Bennett et al., 1999) and Lake Okeechobee (Boggess et al., 1995) and a long-term P balance for Wisconsin’s cropland (Bundy, 1998), suggest that long-term P accumulation may be the rule, rather than the exception for watersheds with substantial human activity. This should be of concern to lake managers, because long-term P accumulation

will eventually lead to P breakthrough, followed by accelerated eutrophication.

We suggest that a minimal long-term goal of watershed P management should be to create a balance between P inputs and deliberate exports. For watersheds with long histories of high P input, a long-term goal should be to keep P inputs less than deliberate P exports to reduce P accumulation. This can be done by either decreasing inputs or by increasing deliberate exports. In a long-term experiment conducted by Giles Randall

and his colleagues at the University of Minnesota's Southern Experiment Station, reducing P fertilization rates by one-half following 20 years of sustained high P inputs reduced soil accumulation by nearly 50 percent in six years (Randall et al. 1997). For residential areas, laws restricting lawn P fertilizer have been enacted in Minnesota and in several counties and cities in Wisconsin, Michigan, and Florida. Preliminary results from an ongoing study of paired watersheds near the Twin Cities being conducted by John Barten and his colleagues at the Three Rivers Park District (see Barten article following) shows that the watershed that had a lawn P fertilizer restriction had one-third less soluble P export than the watershed with no such law. P inputs to animal herds can also be reduced. A study by Wu et al. (2001) showed that reducing mineral P feed supplements to dairy cows can reduce the P excretion in manure with no loss of milk production or harm to the cows. Moreover, farmers would benefit economically, through reduced costs for mineral supplements.

On the output side, farmers have steadily increased crop production efficiency. Bundy's study of Wisconsin cropland showed farmers were adding about the same amount of P fertilizer in 1970 as they added in 1995 (Table 1), but the amount of P removed by crops increased by 54 percent. During the same period, percentage of input P that accumulated in soils declined from 50 percent in 1975 to only 16 percent in 1995. (Table 1).

For areas with community sewage treatment, converting secondary treatment systems to tertiary treatment with P removal, accompanied by export of sludge, would increase P export. For areas on septic systems, sewerage the area and exporting the sewage from the watershed

| Table 1. P balance for Wisconsin cropland (from Bundy 1998). Units are millions of pounds of P per year. | | |
|--|------|------|
| | 1970 | 1995 |
| Fertilizer + manure P used | 214 | 194 |
| Crop harvest (exported) | 104 | 150 |
| Runoff | 2.9 | 3.0 |
| P accumulation | 107 | 31 |

could be an effective approach to reverse P accumulation.

Summary

As point sources of P pollution come under control, most future reductions in P inputs to surface waters will occur by managing NPS pollution. Simply trapping P in structural BMPs or by reducing erosion is useful, but not sufficient, particularly over the long run. We suggest that lake managers turn to a more holistic approach, using whole-watershed P balances as a tool to manage P, with a long-term goal of achieving a net balance between P inputs and P outputs.

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Ph.D., is a Senior Fellow in the water resources science program at the University of Minnesota and an independent environmental consultant. His current research focuses on the biogeochemistry of human ecosystems and the application of this knowledge to practical environmental problems. He has published more than 100 journal articles and technical papers and is currently editing a new book, *The Water Environment of Cities*, to be published in 2008.



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completed her M.S. degree in water resources science at the University of Minnesota in 2005. The research reported here is based on her thesis, "A comparison of phosphorus sources and fate in eleven Minnesota watersheds". Johanna is now the Citizen Volunteer Monitoring Coordinator for the Minnesota Pollution Control Agency. 🐾

