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Whole-system phosphorus balances as a practical tool for lake management

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ARTICLE INFO

Article history:

Received 14 June 2006

Received in revised form

23 September 2006

Accepted 24 September 2006

Keywords:

Phosphorus

Watershed

Lake management

Phosphorus accumulation

Phosphorus retention

ABSTRACT

Controlling phosphorus (P) inputs to lakes remains a priority of lake management. This study develops watershed P balances for 11 recreational lakes in Minnesota. Areal P input rates to the watersheds ranged from 0.32 to 6.0 kg P ha⁻¹ year⁻¹ and was linearly related to the percentage of watershed in agriculture. Watershed P retention ranged from 10% to 89% of input P. Although many best management practices work to increase P retention (by trapping P in basins; reducing erosion; filtration), P retention is not sustainable indefinitely, particularly in “hot spots” such as septic leach fields and heavily manured fields. The watershed P balance tool is a framework that can allow watershed managers to develop novel strategies for managing P. P management strategies should be developed to keep P inputs and exports in balance so that P does not accumulate; long-term P accumulation is not sustainable and can eventually lead to lake eutrophication.

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1. Introduction

Watershed development often increases nutrient inputs to lakes, leading to cultural eutrophication. In Minnesota, as in many areas, phosphorus (P) is often the limiting nutrient (Heiskary and Wilson, 2005). Efforts to limit eutrophication therefore often focus on reducing P inputs to lakes. Currently, the main approach for reducing P inputs to lakes is to reduce P in the landscape from entering lakes with “barrier” type best management practices (BMPs). These include installation of properly designed septic systems, stormwater detention ponds, constructed wetlands and buffer strips. These systems can be expensive to build (particularly if land acquisition is required) and have extensive operations and maintenance requirements. They also may not be sustainable over long periods; “barrier” type BMPs reduce direct P inputs to lakes,

but they act as P retention sites in watersheds, allowing P to accumulate over time.

The development of more holistic, whole-system P management strategies has been limited to date by methodology. Although the concepts of ecosystem nutrient balances and nutrient flow networks have been widely used for many years, they have been infrequently used for ecosystems with substantial human influence, and then primarily for large watersheds or regions (e.g. Correll et al., 1992; Jaworski et al., 1992; Boggess et al., 1995; Bennett et al., 1999; Baker et al., 2001; Hishock et al., 2003; Stuewe, 2006). One difficulty until recently has been the fact that most data needed to develop P balances for human systems is compiled by governmental units (e.g., county and state). Because watersheds invariably transect government entities, it has been difficult to acquire data within watershed boundaries, particularly for smaller

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doi:10.1016/j.ecoleng.2006.09.009

watersheds (<1000 km²). The widespread availability of satellite imagery, the increasing power of geographic information systems (GIS) and the steady accumulation of water quality data now make it possible to develop the spatially discrete datasets needed to develop whole-watershed P balances at reasonable cost and effort.

This paper develops whole-system P balances for the watersheds of 11 case study lakes in Minnesota. Total P inputs to these watersheds – in the form of human and livestock food, fertilizers, sewage piped in from other watersheds and atmospheric deposition – varied by a full order of magnitude on an areal basis. Input P was partitioned into watershed retention, deliberate exports (agricultural products, sewage and sewage sludge), and stream P. These terms also varied widely, reflecting differences in watershed activities and management. We propose that whole watershed P balances will enable watershed managers to better understand the dynamics of P in an entire watershed and thus be able to develop sustainable P management strategies that can be tailored to individual watersheds. Additional details regarding the development of watershed P balances are presented in [Schussler \(2005\)](#). In a related paper, [Baker et al. \(2006b\)](#) describes drivers of change in Secchi Depth Transparency (SDT), with a focus on watershed P dynamics.

2. Methods

2.1. Lake selection

We selected case study lakes that had undergone substantial development since 1980. The Minnesota Department of Natural Resources' (DNR) lake morphometry database was the starting point for lake selection. The database included 6131 lakes. Minimum and maximum lake surface area criteria were set at 80 and 800 ha, respectively, to focus on recreationally important lakes.

The U.S. Forest Service's "Changing Midwest Assessment" ([Potts, 2004](#)) was used to identify counties that had experienced significant growth in "urban" areas between 1980 and 2000. U.S. Census data was then used to identify lakes in those high growth counties that had experienced a population increase of more than 25% in at least one U.S. Census partial block adjacent to the shoreline ([Hammer et al., 2004](#); [Radeloff et al., 2005](#)). Because historical P data is unavailable for many lakes in Minnesota, we selected study lakes with more-or-less continuous SDT data from the 1980 to 2000. SDT is closely related to lake P concentrations in Minnesota lakes ([Heiskary and Wilson, 2005](#)), so SDT can be used as a proxy for lake P. Discussions with local water planners were able to further reduce the pool to eleven study lakes in three counties ([Fig. 1](#) and [Table 1](#)).

2.2. P balance equation

The watershed P balance approach used in this study is based on the following equation:

$$\begin{aligned} \text{input P} = & \text{deliberately exported P} + \text{stream P} \\ & + \text{P retained in watershed} \end{aligned} \quad (1)$$

Input P comes into a watershed from an external source, such as food imported for human or animal consumption, fertilizer, or sewage transported from another watershed via sewers. Examples of deliberately exported P include agricultural crops exported from the watershed for sale or sewage piped to a water treatment plant outside the watershed. P is also exported from the watershed via streams. Finally, retained P accumulates within the watersheds, stored primarily in soils. (A diagram of the preceding processes is provided in [Fig. 2](#).) The upstream system boundary is the topographic watershed boundary and the downstream boundary is the point at which the stream enters the lake. In this definition, the lake is not part of the watershed. Because we infer stream P from hindcast modeling (discussed below), "stream P" includes any groundwater that directly enters the lake ([Fig. 3](#)).

The P balance was constructed for circa 2000. In reality, because various types of data needed for this analysis are not all available for 2000, the range for most data inputs is 2000 ± 5 years. Data on cultivated land for some watersheds was based on 1990 air photo interpretation (see "P from cropland", below).

2.3. Watershed boundary delineation

Each study lake's watershed boundary was defined using the digital watershed boundary database from the Minnesota DNR Division of Waters. Watersheds for the case study lakes were constructed by aggregating all hydrologic units that flowed to the study lake.

2.4. Household P inputs

Study watershed population was calculated based on census block population data from 2000 obtained from the University of Wisconsin, Madison ([Hammer et al., 2004](#); [Radeloff et al., 2005](#)). A GIS was used to clip census block data with each study lake's watershed boundary. Per capita P input was based on a state-wide P balance ([Barr, 2004](#)), with the excretion component modified using a national food consumption database ([USDA, 2005](#)) to estimate per-capita P consumption ([Baker et al., 2006a](#)). Because nearly all P consumed is excreted, we based P excretion on food consumption, yielding a population-weighted P excretion rate of 0.39 kg P capita⁻¹ year⁻¹. Combining this with the non-excretion sources (garbage disposal wastes, automatic dishwasher detergents and dentrifices; from [Barr, 2004](#)) yields an annual per capita input of 0.72 kg capita⁻¹ year⁻¹.

P inputs to households are routed to septic systems or sewers. For sewer areas, P leaving households is exported to sewage treatment plants (STP). The Alexandria Lakes Area Sanitary District (ALASD) serves portions of Darling, Le Homme Dieu, Lobster, and Victoria watersheds in Douglas County. Sewage P from the sewer areas of these watersheds, determined from the ALASD service area map, is conveyed to the ALASD wastewater treatment plant (WWTP) located in the Le Homme Dieu watershed. This represents an export of P from the watersheds of Darling, Victoria and Lobster. The treatment plant employs tertiary P removal, which removes about 90% of the P from sewage. The P in sewage sludge is then exported to a landfill outside the Le Homme Dieu watershed. The P that remains in the treatment plant's effluent

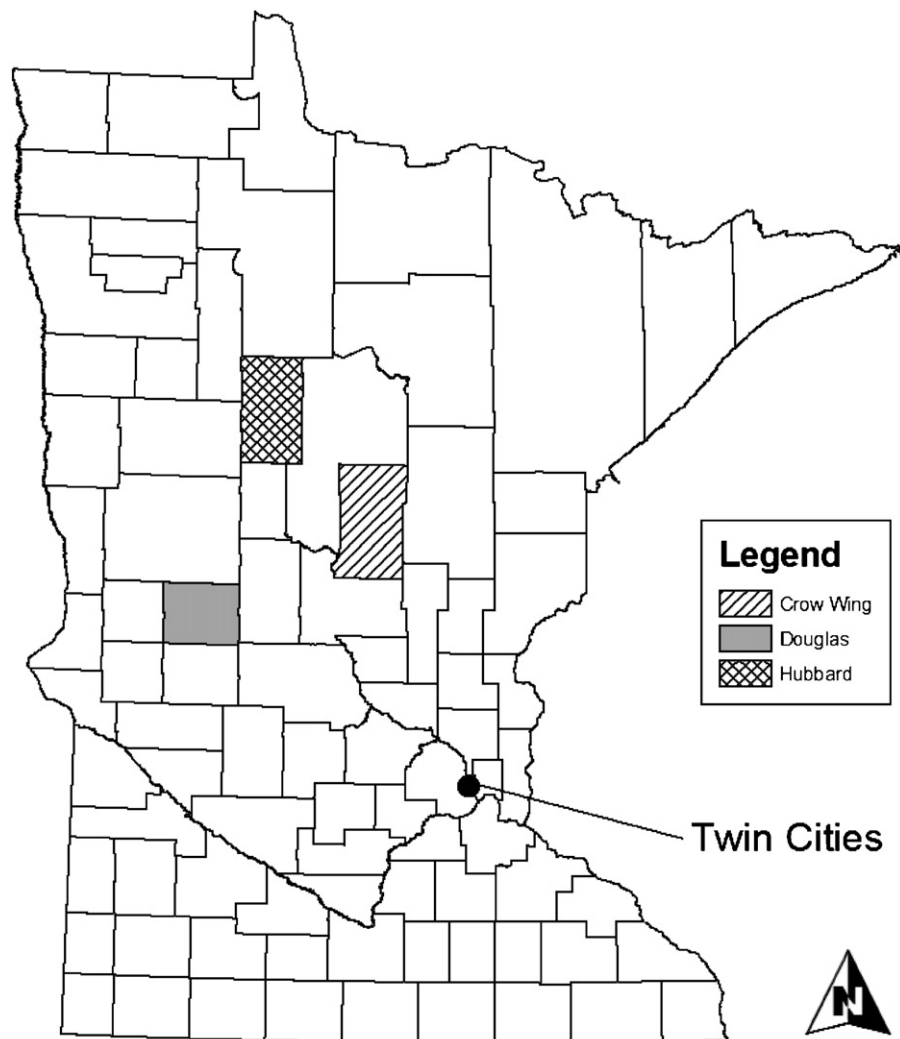


Fig. 1 – Case study counties.

Table 1 – Characteristics of the 11 case study lakes

County and lake name	Lake ID	Lake area (LA) (ha)	Watershed area (WSA) (ha)	WSA:LA	Maximum depth (m)	HRT ^a (year)	Shoreline development index ^b
Crow wing							
Big Trout	18031500	570	3,500	6	39	11.8	1.7
Gilbert	18032000	145	2,300	16	14	1.7	2.8
Hubert	18037500	525	1,600	3	25	14.3	1.4
Sibley	18040400	160	13,900	86	12	0.3	2.8
Douglas							
Darling	21008000	405	47,500	117	19	0.3	1.6
Le Homme Dieu	21005600	770	13,700	18	26	5.2	1.6
Victoria	21005400	160	6,600	41	18	1.6	2.5
Lobster	21014400	485	14,100	29	20	2.4	3.7
Hubbard							
Belle Taine	29014600	585	29,100	50	17	0.7	4.3
Fish Hook	29024200	670	63,000	94	23	0.5	1.3
Long	29016100	810	6,400	8	41	9.9	3.0

Source. MPCA and MN DNR water quality databases.

^a HRT = lake volume/outflow.^b Shoreline development index = shoreline length/(2 × (π × area))^{0.5}, also from Wetzel.

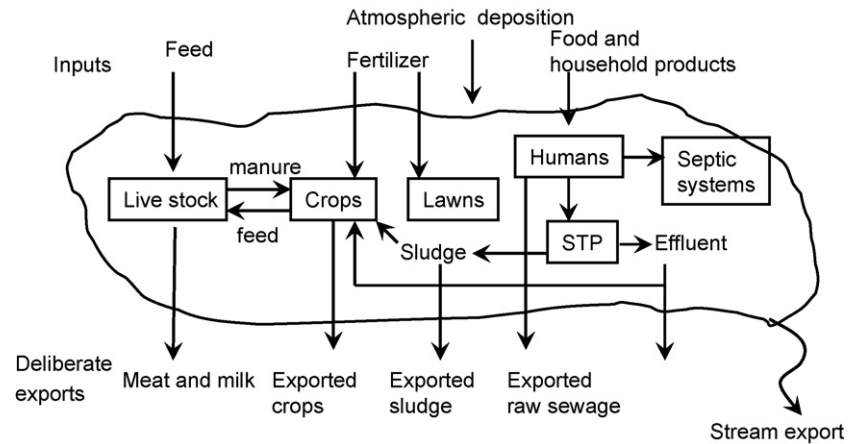


Fig. 2 – Watershed P balance diagram.

is discharged to a pond and from there moves to Lake Le Homme Dieu. Sibley Lake also has a WWTP within its watershed boundary. Pequot Lakes WWTP discharges outside of Sibley Lake's watershed; therefore, P from the sewered population is exported from the watershed. P in wastewater from unsewered populations in each watershed is presumably discharged to onsite sewage treatment systems.

2.5. Municipal and industrial discharges

National Pollution Discharge Elimination System (NPDES) permits obtained from the Minnesota Pollution Control Agency (MPCA) or the U.S. Environmental Protection Agency provided information on wastewater discharged by municipalities and industries in the study counties. Location data was imported into ArcView to determine NPDES facilities' positions within the case study watersheds. Only two NPDES facilities discharged significant amounts of P to surface waters within the case study watersheds. The Garfield wastewater treatment plant discharged 75 kg P year⁻¹ within the Lake Darling watershed and the ALASD treatment plant discharged 1210 kg P year⁻¹ within the Le Homme Dieu watershed. The

few industrial dischargers discharged very small volumes of water that were unlikely to be significant sources of P.

2.6. P from cropland

Identification of agricultural land in the watersheds was performed using the most current digital land cover data publicly available from the Minnesota DNR Data Deli (<http://deli.dnr.state.mn.us/>) for the study areas at the time. We used classified Landsat Thematic Mapper images taken from June 1995 to June 1996 where available (all four of the watersheds of Crow Wing County lakes, plus the watersheds of Belle Taine and Long Lakes in Hubbard County). For the four lakes in Douglas County and parts of the Fish Hook Lake watershed in Hubbard County we used International Coalition land classification data derived from 1990 aerial photography. For both datasets, overlays of "cultivated land" were digitally clipped to watershed boundaries to calculate cultivated land within each watershed.

Total cropland area and harvested acreage were obtained for each county from the National Agricultural Statistics Service (NASS, 2002, 2004). The ratio of harvested cropland to total

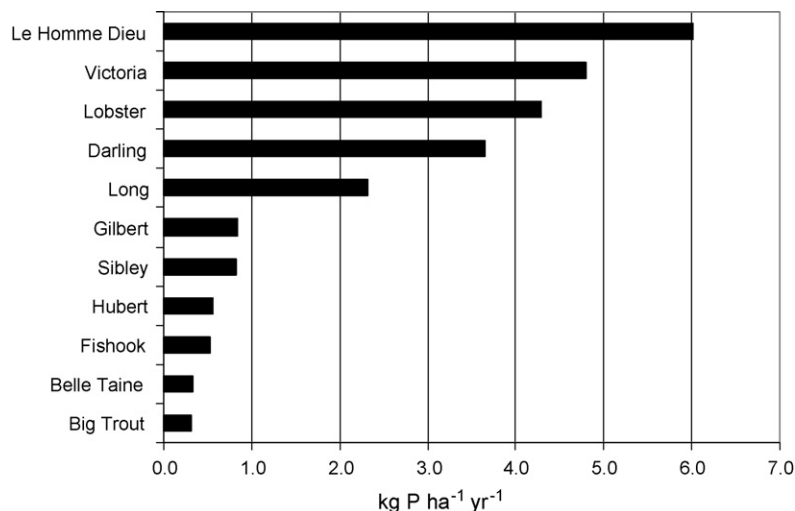


Fig. 3 – Areal P loads to the case study watersheds.

Table 2 – Agricultural P fertilizer applied and crop removal, by watershed

Watershed	Fertilizer applied	Corn P removal	Wheat P removal	Soybean P removal	Alfalfa P removal	Total crop P removal
Belle Taine	2,503	2,559	46	253	536	3,394
Big Trout	73	50	0	0	27	76
Darling	144,497	107,896	17,313	85,597	23,792	234,598
Fish Hook	17,318	6,495	6069	10,863	4928	28,354
Gilbert	116	79	0	0	43	122
Hubert	17	12	0	0	6	18
Le Homme Dieu	43,133	32,235	4953	26,963	6711	70,863
Lobster	41,372	30,919	4751	25,862	6437	67,970
Long	3,648	2,863	51	283	790	3,987
Sibley	792	622	0	0	499	1,121
Victoria	26,512	19,814	3044	16,573	4125	43,557

All units are kgP year⁻¹.

cropland for each county was then used to estimate harvested cropland from total cropland in each watershed within that county. The NASS census also provides the number of harvested acres in each county by crop type; we assumed this relative distribution of crop types in our case study watersheds was the same as the distribution within the county. Only regionally important crop types were used in the P budget calculations: corn (grain and silage), wheat, soybeans, and alfalfa. In Minnesota between 1999 and 2002, P fertilizer was applied to 89% of corn and 11% of soybeans. Data for 2000 and 2002 show that P fertilizer was applied to 84% of wheat (NASS, 2002). The percentage of alfalfa to which P fertilizer was applied was assumed to be the same as the percentage for soybeans (11%). Padgitt et al. (2000) reported application rates of 28, 27 and 16 kgP ha⁻¹ for corn, soybeans and wheat, respectively. We used an application rate for alfalfa fields of 27 kgP ha⁻¹ (Russelle, 1999). Total fertilizer P was calculated by summing applications to major crops (Table 2).

2.7. P removal by crops

County data on crop production for corn, wheat, soybeans and alfalfa (NASS, 2002) were used in conjunction with crop P removal rates per harvested unit (e.g., kgP/m³ of corn; from MAS, 2001). We assumed that crops grown in the watershed were fed to livestock in that watershed. If the harvested crop P exceeded livestock P requirements, we assumed that the excess crop P was exported from the watershed. If livestock P requirements exceeded the amount of P in crops grown, we assumed that livestock feed was imported into the watershed. This calculation results in a net import or export of crop P.

2.8. Livestock P conversion efficiencies

P inputs to livestock herds were estimated based on information on manure production and production of animal products. From conservation of mass:

$$I = M + P \quad (2)$$

where I is the P input in feed (kg year⁻¹), M the P in manure (kg year⁻¹) and P is the P in animal products (kg year⁻¹).

We then define P transfer efficiency (E) as:

$$E = \frac{P}{I} \quad (3)$$

Combining Eqs. (2) and (3) and rearranging:

$$I = \frac{M}{1 - E} \quad (4)$$

Because we have no direct information on total feed rates (I), we calculated E using data on animal products exported (meat and milk) and manure production (Eq. (3)). Food input (I) was then calculated using Eq. (4).

E values were calculated for each major animal system (hogs, dairy and beef). County level statistics on overall numbers of animals were used in conjunction with expert knowledge on the population dynamics of livestock operations in the case study counties.¹ The population structure of livestock operations was used to estimate manure P production (M) using tables from Lorimer et al. (2004). Output of animal products (P) was estimated as the product of animal product output and the P content of these outputs. Values of P content were: total body P content, cows = 0.7% (Tilden, 1995) and hogs = 1.0% (Powers and Van Horn, 2001); P content of milk = 911 mg kg⁻¹ (USDA, 1998). Additional details regarding the population structure of livestock operations and manure production are found in (Schussler, 2005).

2.8.1. Beef operations

In 2004 there were a total of 13,200 beef cows in the three case study counties. We assumed that 85% of these produced calves, with an equal distribution of males and females. Of these calves, 1720 became replacement heifers. The rest of the females and most males were exported at the end of their first year at a weight of 200 kg. In these counties it is common to retain about 10% of male calves to become “beef on feed”, grown to market size (450 kg), and an even smaller number (about 7% of males) are grown to be bulls. Total feed P was computed by summing manure P (233,087 kg year⁻¹) plus ani-

¹ We would like to thank the staff of the U of MN Southern Research and Outreach Center for their help in providing information on local livestock operations.

mal export (20,195 kg P year⁻¹), to yield 253,282 kg year⁻¹ and an efficiency (*E* in Eq. (3)) value of 0.08 (8%). This value is much lower than values reported for beef on feed operations (14–34%; Van Horn et al., 1994; Erickson et al., 1998; Powers and Van Horn, 2001). The reason for this is that these operations mainly export only heifers. They must maintain a large breeding stock, which requires a large input of food but results in little export (~1 heifer per year). By contrast, beef-on-feed operations start with heifers and grow them to maturity, with no reproductive costs.

Beef herds in the case study counties generally are pastured for 6 months a year, with little or no additional feed. Because pastures are not usually fertilized, pasturing animals recycles P from manure, comprising an internal cycle. During the other 6 months of the year, the animals are confined and fed harvested crops (grain and hay). In our calculations for individual watersheds, we therefore assumed that only half of the feed P was derived from harvested crops or imported feed.

2.8.2. Dairy operations

There were 10,300 milk cows and 2040 dairy beef calves (male calves born to dairy cows that are raised for beef) in the three case study counties. We assumed an average lifespan of 4.5 years for a dairy cow, with first calving at 24 months. Calves were assumed to reach 230 kg in 6 months. Male calves other than those grown for dairy beef were assumed to be exported within 3 days of birth. A state-wide feedlot database showed that 10% of milk cows are “small” (<455 kg) and 90% are “large” (>635 kg). Milk output from the dairy herd was based on state-wide milk production rates and concentrations of P in milk (0.09%)

Output of animal products resulted in export of 102,900 kg P year⁻¹. About 85% of this was milk and 15% was exported animals. Manure production was 367,900 kg P year⁻¹. Total feed input was therefore 470,800 kg, yielding an *E* value of 0.22 (22%). This value is slightly lower than the range of *E* values reported for other dairy operations (26–34%; Van Horn et al., 1994; Powers and Van Horn, 2001; Spears et al., 2003), probably reflecting the fact that dairy farms in our case study counties are often small and therefore more likely to be inefficient.

2.8.3. Hog operations

The total number of pigs, number of farrowings per year, and total pig crop were obtained from Minnesota Agricultural Statistics. The number of sows was estimated from the number of farrowings, assuming two farrowings per year. The number of boars was estimated as 5% of sows. The replacement rate for both sows and boars was assumed to be 40% per year. Based on these figures, P export in animals was 46,445 kg year⁻¹. Manure production was 52,700 kg year⁻¹, yielding an *E* value of 0.47 (47%). This is nearly identical to the P conversion efficiency computed for a hog life cycle by (Powers, 2004).

2.9. P Dynamics of livestock operations in case study watersheds

The locations and number of animals for each livestock operation in the case study watersheds were obtained from

Table 3 – P fluxes through animal operations

Watershed	Manure production	Imported feed	Exported animal products
Belle Taine	2,752	0	239
Darling	137,938	0	48,792
Fish Hook	9,006	0	2,284
Le Homme Dieu	27,176	0	6,026
Lobster	62,841	10,266	26,488
Long	9,456	7912	2,954
Sibley	7,228	5946	1,458
Victoria	24,815	0	5,464

Only watersheds with livestock are listed. All units are kg P year⁻¹.

a state-wide GIS feedlot database obtained from the Minnesota Department of Agriculture (MDA). Feedlot locations were mapped onto the digital watershed layers for each case study watershed to identify feedlots within each watershed. The MDA databases contain information on the number and type of animal units present at each feedlot in each of five categories: dairy, beef, swine, chickens, and turkeys. Chickens and turkeys are not present in significant numbers in any of the study watershed feedlots, so they were not included in the P calculations. Big Trout, Gilbert, and Hubert watersheds in Crow Wing County do not have feedlots included in the database, and after visiting these watersheds, it appears likely that they do not have feedlots. The MDA databases report animal population in animal units (one AU = one 455 kg dairy cow). Animal units were converted to number of animals using the multipliers provided by the Minnesota Pollution Control Agency (Statutes, 2003).

Estimates of the amount of phosphate (P₂O₅) produced in the manure of livestock animals based on size and type of animal (Lorimer et al., 2004), MDA livestock categories and expert knowledge of livestock operations were used to calculate total livestock manure production (Table 3).

P transfer efficiencies (*E* values, calculated above) were used in conjunction with manure production to estimate the amount of P in feed by using Eq. (4). Animal P output was then computed using Eq. (2) (Table 3). Within a given watershed, when feed P required by livestock was greater than harvested crop P, we assumed that supplemental P was imported to fulfill the feed requirement. When the P input required by livestock was less than the P in harvested crops, we assumed that the additional crop P was exported.

2.10. P from lawn fertilizer

To estimate the amount of P entering the study watersheds in the form of P lawn fertilizer, the amount of land in urban/industrial and rural residential land use classifications was calculated for each of the study watersheds using the digital International Coalition and LandSat land cover data. It was assumed that 50% of urban and residential lands are fertilized. This value was derived by two assumptions: pervious surfaces comprise 80% of urban/residential land, and about one-third of lawns are not fertilized in a given year. The latter estimate is based on lawn surveys in the Twin Cities metropolitan area

Table 4 – Estimated watershed lawn fertilizer application, kg P year⁻¹

Watershed	Watershed lawn fertilizer application
Belle Taine	1436
Big Trout	358
Darling	7157
Fish Hook	3984
Gilbert	446
Hubert	394
Le Homme Dieu	8893
Lobster	2172
Long	594
Sibley	1494
Victoria	1309

(Baker et al., 2006a). P application rates were based on recommendations (Rosen et al., 2004) for medium fertility soils for established lawns (Table 4). The recommended application for medium soil P (0.001 kg P m⁻²) was used to estimate fertilizer application to the area.

2.11. P from atmospheric deposition

The Minnesota Lake Eutrophication Analysis Procedure (MINLEAP) is a “box type” eutrophication model that provides average areal atmospheric P deposition estimates for each ecoregion in Minnesota (Wilson and Walker, 1989). The eleven study watersheds are in either the Northern Lakes and Forests ecoregion (NLF) or the Central Hardwood Forests ecoregion (CHF). Estimated atmospheric deposition rates from MINLEAP are 15 kg ha⁻¹ year⁻¹ for the NLF ecoregion and 30 kg ha⁻¹ year⁻¹ for the CHF ecoregion. These values are consistent with values estimated by Barr (2004). These estimates were multiplied by each lake’s watershed area and lake surface area to determine the average annual amount of P contributed both to the watershed and directly to the lake by atmospheric deposition.

2.12. Stream P export

We also used MINLEAP to estimate stream P concentrations. MINLEAP includes ecoregion-specific default values for watershed runoff, evaporation, atmospheric deposition and stream P (for reference conditions). The model is normally used to estimate changes in SDT as a function of varying stream P concentrations. There was little stream P data but a wealth of SDT data for the case study lakes. We therefore used the model in hindcast mode, starting with average SDT values for 2000–2003. Default values were used for hydrologic variables and atmospheric deposition, and stream P concentration was adjusted until the predicted SDT value matched the measured value. Stream P export was then calculated from modeled concentration and runoff.

2.13. Net retention

Net watershed P retention was computed by difference from estimated inputs, deliberate exports, and stream P using Eq. (1).

3. Results

3.1. P inputs to watersheds

Estimated total P inputs to the eleven study watersheds ranged from about 950 kg year⁻¹ in Lake Hubert’s watershed to more than 170,000 kg year⁻¹ in Darling Lake’s watershed (Table 5). On an areal basis, watershed P loadings (kg ha⁻¹ of watershed) ranged by a factor of 20, from 0.32 to 6.0 kg ha⁻¹ year⁻¹ (Fig. 2).

Watersheds with little agricultural activity (Belle Taine, Big Trout, Gilbert, Hubert) had areal P inputs rates <1 kg ha⁻¹ year⁻¹. For these watersheds, agricultural land was ≤30% of the total watershed area and agricultural P inputs (fertilizer and animal feed) comprised <26% of total P input. The main inputs to these watersheds were atmospheric deposition, lawn fertilizer and household inputs (Table 5). For the four watersheds with highest areal P inputs (>3 kg ha⁻¹ year⁻¹), agricultural land was >60% of watershed area and agricultural P inputs (fertilizer + feed) comprised 53–86% of total P inputs. The watershed with the highest areal P input (6.0 kg ha⁻¹ year⁻¹) had both high agricultural inputs and a high input of sewage, imported from the watersheds of Darling and Victoria. The percentage of watershed in agricultural land was an excellent predictor of areal watershed P input (Fig. 4).

3.2. Deliberate P exports from watersheds

Deliberate P exports included crops, sewage, animal products and sewage sludge (Table 6). Overall, there is a good correlation between total P input and deliberate output ($r^2 = 0.86$) but the relationship is bifurcated: watersheds with a high percentage of agriculture exported 38–63% of P input in the form of animal products and crops, whereas watersheds with little or no agriculture exported <10% of total P inputs. For these watersheds, most P input was retained (discussed below). The watershed with highest percentage of P export was Le Homme Dieu, which exported both agricultural products (68% of total P input) and sewage sludge (18% of total P input).

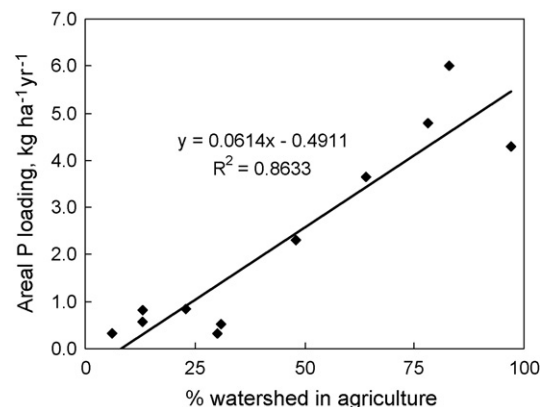


Fig. 4 – Percentage of watershed in agricultural vs. areal P input.

Table 5 – P inputs to the case study watersheds, as % of total

Watershed	% of total P input								Total input (kg P year ⁻¹)
	Atm. dep.	Animal feed	Households	Crop fertilizer	Industrial (NPDES)	Imported sewage	Lawn fertilizer	Total (%)	
Darling	8	0	3	84	0	0	4	100	171,398
Le Homme Dieu	5	0	13	53	1	17	11	100	81,769
Lobster	7	17	3	69	0	0	4	100	59,546
Fishhook	28	0	8	52	0	0	12	100	33,563
Victoria	6	0	4	86	0	0	4	100	31,007
Long	6	56	7	26	0	0	4	100	14,089
Sibley	18	51	11	7	0	0	13	100	11,641
Belle Taine	45	0	14	26	0	0	15	100	9,712
Gilbert	18	0	51	6	0	0	24	100	1,835
Big Trout	47	0	11	7	0	0	34	100	1,044
Hubert	27	0	31	2	0	0	41	100	965

3.3. Watershed P retention

Watershed P retention as a percent of total P inputs was highly variable, ranging from 10% to 89%. Agricultural watersheds generally had low P retention, reflecting the fact that a large fraction of input P was exported as agricultural products. At the other end of the spectrum, watersheds where the dominant P inputs were lawn fertilizer and household sewage, watershed retention was generally well over 50%. Gilbert lake watershed retained nearly 90% of input P, and Belle Taine and Long lakes' watersheds retained over 70% of input P (Fig. 5).

3.4. Stream P export

For 8 of the 11 study lakes, stream export comprised <10% of watershed P input. The watersheds with the highest percentage of stream export were Big Trout (29% of input) and Hubert (39% of input). For Hubert Lake, which has a small watershed: lake ratio and is completely surrounded by homes mostly older than 20 years, we postulate that watershed retention in septic leach fields may have reached saturation, resulting in P export from the watershed to the lake.

There is no significant correlation between areal P input to the watersheds and stream P export when both are normalized to watershed area (Fig. 6). The lack of correlation highlights the point that stream P export is not simply a function of how

much P enters a watershed, but how that P is processed, both by humans and natural processes.

3.5. Sensitivity analysis

A sensitivity analysis was performed for two case study watersheds. Big Trout was selected to represent non-agricultural watersheds. Most P input to the watershed of Big Trout Lake was human food, lawn fertilizer and atmospheric deposition. Lobster Lake's watershed was selected to represent agricultural watersheds because it has a high percentage of P input from both supplemental feed and from fertilizer applied to agriculture. The sensitivity analysis was performed by increasing and decreasing each input component (crop fertilizer, atmospheric deposition, etc.) by 25%, and then using those new values in place of the original values in the P balance model. Measured outputs were total P input, and retention, export and stream loading as input percentages.

3.5.1. Big trout lake

The total P input to the Big Trout watershed was particularly sensitive to changes in the value of atmospheric deposition. Raising or lowering the atmospheric deposition term resulted in an 11% increase or 12% decrease in P input to the watershed. Calculated P input was also sensitive to lawn fertilizer application rates. A 25% change in this value resulted in about a 9% increase or decrease in P input. That these two variables

Table 6 – Deliberate export of P from the case study watersheds

Watershed	% of P export				Deliberate exports, as % of P input
	Crops	Sewage	Animal products	Sewage sludge	
Le Homme Dieu	60	14	8	18	88
Victoria	75	3	22	0	81
Darling	58	2	40	0	71
Fish Hook	89	0	11	0	60
Lobster	0	2	98	0	46
Belle Taine	89	0	11	0	22
Long	0	0	100	0	21
Sibley	0	32	68	0	19
Big Trout	100	0	0	0	7
Gilbert	100	0	0	0	7
Hubert	100	0	0	0	2

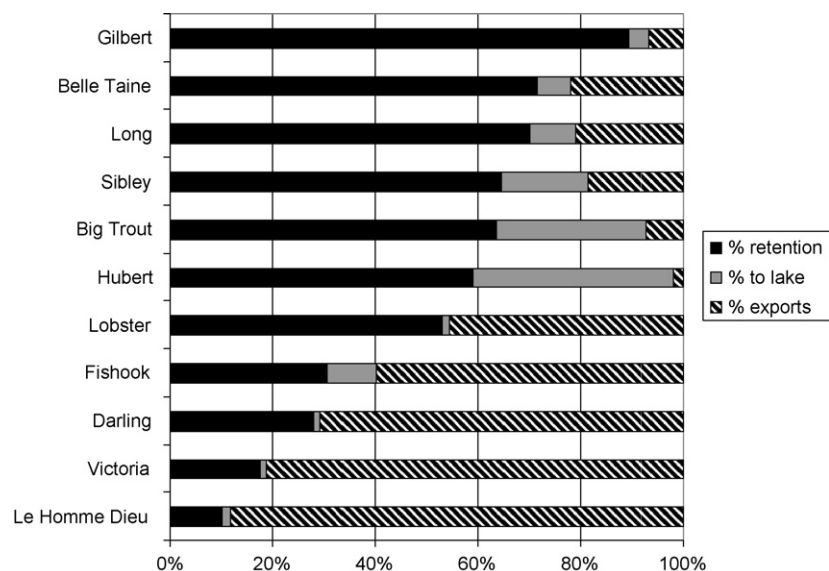


Fig. 5 – Fate of P: retention, deliberate export and stream loading.

were the most important to the model's results for Big Trout watershed is not surprising given that 82% of the watershed's overall P comes from these two sources.

Changing the input variables also resulted in changes to the percentages of input P that is retained, exported, or entering the lake. A 25% increase in atmospheric loading resulted in a 6% increase in the percentage of P input that is retained, a 10% decrease in the percentage of P input that is exported, and a 10% decrease in the percentage of P input that goes to the lake. Lowering the atmospheric deposition by 25% resulted in an 8% decrease in P retention, a 13% increase in the percentage of P input that is exported, and a 13% increase in the percentage of P input that goes to the lake.

3.6. Lobster lake

Calculated P input to this watershed was most sensitive to the selected swine P efficiency value (E). Raising the swine P efficiency value by 25% resulted in a 16% increase in P input, as well as a 14% decrease in the percentage of input P retained,

an 18% increase in the percentage of input P exported, and a 15% decrease in the percentage of P inputs that reach the lake. Lowering the swine P efficiency value by 25% resulted in a 12% increase in the percentage of input P reaching the lake.

In general, model calculations are less reliable for non-agricultural watersheds because atmospheric deposition and lawn fertilizer become major input terms, and these are the least reliably known terms. For agricultural watersheds, inputs of animal feed and crop export are sensitive to the E values used in calculations.

4. Discussion

Whole watershed P balances could be an important tool for watershed managers to develop more effective strategies for reducing P inputs to lakes. Many watersheds accumulate P, apparently over long periods of time. For example, 82% of total P input was stored in the upland landscape of the Lake Okechobee watershed (Boggess et al., 1995) and 42% was stored in the watershed of L. Mendota (Bennett et al., 1999). P accumulation may not be sustainable indefinitely with high P inputs because soils will become saturated with P. Further addition of P will then lead to leaching or surface runoff of soluble P. P leaching has been documented under septic systems (Robertson et al., 1998), a Cape Cod sewage pond (McCobb et al., 2003), dairy farms in Florida (Campbell et al., 1995), and a potato field receiving wastewater irrigation (Zvomuya et al., 2005), with total P concentrations in groundwater often reaching several mg/L. Several studies have demonstrated a direct relationship between soil test P and P concentrations in runoff in lab studies (summarized by Vadas et al., 2005). Klatt et al. (2003) showed a direct relationship between average soil test P and P concentrations in runoff from five watersheds in Iowa. Some P exiting upland parts of the watershed may be trapped in wetlands, lakes and other depressions, but unless these are very large, retention is <100%, meaning that watershed P export is likely to increase after P saturation occurs.

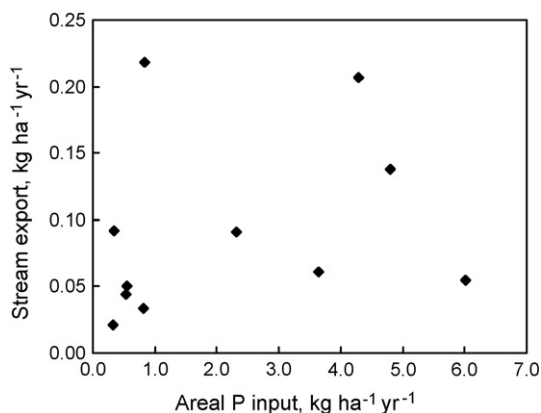


Fig. 6 – Areal P input vs. areal stream export for the case study watersheds. Both terms are in $\text{kg P ha}^{-1} \text{ year}^{-1}$.

Current watershed management focuses largely on increasing P retention, for example, by compelling homeowners to install and maintain septic systems, reducing erosion, and installing buffers and sediment-trapping structures. With high P loadings, these measures may not be sustainable over long periods of time.

We suggest that watershed managers seek to develop long-term strategies that eventually result in a balance of inputs and outputs or even an imbalance (inputs < outputs) that would eventually lead to declining P storage in watersheds. Accomplishing this requires reducing P inputs or increasing deliberate exports. In this paper we have demonstrated that whole-watershed P balances are a practical tool that can be used to achieve this goal.

In rural watersheds, reductions of P inputs may occur by improving the efficiency of animal feed, with potentially large savings (Wu et al., 2001). Bundy (1998) showed that improved cropping practices has increased crop P export from Wisconsin cropland and reduced the rate of accumulation of soil P from 1975 to 1995. In urban watersheds, a restriction of lawn P fertilizers, as enacted in Minnesota in 2004, may decrease P inputs to residential neighborhoods by 90% (Baker, unpublished data). An earlier ban in the suburb of Plymouth appears to have reduced stormwater P export by ~30% (James Johnson, Three Rivers Park District, personal communication).

The modeling approach outlined in this paper needs refinement. For lakes with low overall P input, model calculations are sensitive to estimates of atmospheric deposition, which are poorly known. There is also little published information regarding fertilization practices of lawns in rural areas. For agricultural systems, better understanding of the P dynamics of whole-farm livestock operations is needed.

5. Conclusions

This paper presents a conceptually simple modeling and analysis tool by which watershed managers could increase their understanding of the P dynamics of watersheds. Further research is needed to refine the approach, but the conceptual basis is sound and warrants further refinement. Although the concept of watershed P balances is not new, new technologies such as satellite imagery and digital GIS along with rapidly expanding environmental databases mean that the approach is now viable for application to watersheds. The approach could lead to novel methods of managing P in watersheds, resulting in less reliance upon retention-based strategies and greater emphasis on reducing P inputs or increasing P outputs.

Acknowledgements

This study was supported by the U.S. Forest Service, with additional support from NSF Biocomplexity Project EAR-0322065. We thank Stephanie Snyder, the USFS project manager, for her support throughout this project and her thoughtful review of this paper and Sue Leitz (USFS) for GIS support. We also thank the many state agency staff and people in the case study counties who provided insights regarding these lakes and their watersheds (see Schussler, 2005).

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