Internal Phosphorus Loading Estimates for Lake Macatawa

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1. Analyses:

Internal loading calculations followed the procedures outlined in Steinman et al. (2004), with the following modifications. Flux calculations were based on the change in water column concentrations of SRP and TP. Calculations were based on two different time periods to bracket a range of potential internal loading rates. Time periods were based on visual estimates of high and low release periods. This range of release rates allows for a better understanding of the possible uncertainties in estimating internal loading in Spring Lake, as opposed to simply measuring maximum (i.e. linear) release rates. Phosphorus flux was calculated using the following equation:

$$P_{\mathrm{flux}} = (C_t - C_0) * V/A, \qquad [1]$$

where, P_{flux} is the net P flux or retention per unit surface area of sediments (mg P m^{-2} d^{-1}), C_t is the P concentration in the water column at time t, C_0 is the P concentration in the water column at time 0, V is the volume of water in the water column, and A is the area of the sediment surface.

Internal load for the lake was calculated by scaling up the mean P flux from the anaerobic and aerobic treatment condition as calculated in equation [1] to the entire lake area. Because data were not available for the percent of time during the year that Lake Macatawa experiences anaerobic conditions (i.e. DO concentrations < 1 mg L^{-1}), internal loads were estimated for the extreme conditions of year-round anoxia, as well as anoxia for 20% of the year, which was the percentage measured in Spring Lake, MI (Steinman et al. 2004).

2. Results

SRP: As expected, SRP release rates were generally greater under anaerobic than aerobic conditions (Fig. 1). Exceptions included Site EE in experiments 2 and 3, and Site BB in experiment 3 (Fig. 1). Under aerobic conditions, SRP flux rates were negative at all sites during experiments 1 and 2, with the exception of site EE (high release conditions; Table 1). However, SRP flux rates were positive during experiment 3. This may be related to temperature, as experiments 1 and 2 were conducted at $15^{O}C$, whereas experiment 3 was conducted at $25^{O}C$. These data suggest that 1) sediments in Lake Macatawa have the potential to serve as a sink for SRP when the sediment surface layer is oxygenated; and 2) there may be a temperature threshold, above which the sediments switch from serving as a P sink to a P source under aerobic conditions.

Under anaerobic conditions, SRP release rates ranged between 0.16 and 0.41 mg $P/m^2/d$ during experiment 1, between 0.05 and 0.23 mg $P/m^2/d$ during experiment 2, and between -0.30 and 1.86 mg $P/m^2/d$ during experiment 3 (Table 1). There were no striking differences in SRP release rates among Sites EE, PC, and WE, but Site BB has relatively low release rates (data for experiment 3 only; Fig. 3). Similar to the aerobic SRP data, higher release rates were observed in experiment 3 compared to experiments 1 and 2. These data again strongly suggest that phosphorus release rates are influenced by temperature.

If Lake Macatawa was anaerobic year-round, which is highly unlikely in reality but a useful assumption for setting upper limit boundary conditions, the observed diffusive flux rates would translate into average internal SRP loads of approximately 0.75, 0.40, and 3.3 tons/yr for experiments 1, 2, and 3, respectively (Table 1). If the lake was anaerobic 20% of the year, the SRP load estimates would be proportionately lower: <¼ to ~ 1 ton/yr (Table 1). Under aerobic conditions, the sediments are capable of assimilating a very small amount of SRP (experiments 1 and 2) or releasing up to ~ 2 tons/yr (Table 1).

TP: Total phosphorus release rates were greater under anaerobic than aerobic conditions at all sites in all experiments with the single exception of Site BB in experiment 3 (Figs. 1-3). This pattern is very similar to what was observed for SRP. Under anaerobic conditions, TP release rates ranged from 0.13 to 0.49 mg $P/m^2/d$ during experiment 1, between 0.08 to 0.28 mg $P/m^2/d$ during experiment 2, and between 0.33 and 8.23 mg $P/m^2/d$ during experiment 3 (Table 2). TP release rate was somewhat higher at site PC than the other sites in experiments 1 and 2, but release rates were much higher at Site WE in experiment 3 compared to other sites (Table 2). Total phosphorus release rates were negative at all sites under aerobic conditions in experiments 1 and 2, and were either negative or slightly positive at the sites in experiment 3 (Table 2), results generally similar to the SRP data. TP release appears to show the same pattern as SRP with respect to increasing flux with temperature.

If anaerobic conditions were present year-round, these release rates would translate into an internal TP load of between 0.4-1.4 tons/yr for experiment 1, between 0.2 and 0.8 tons/yr for experiment 2, and between 0.3 and 23.8 tons/yr for experiment 3 (Table 2). Assuming anaerobic conditions for 20% of the year, the overall internal TP load would be quite small in experiments 1 and 2: <¼ ton per year, and ~ 1 ton/yr at Sites PC, WE, and BB in experiment 3. Site EE was an anomaly, with release rates exceeding 4 tons/yr (Table 2).

3. Discussion

The phosphorus release rates measured in Lake Macatawa sediments were low compared to other lake systems (Table 3; Nürnberg 1988). Indeed, based on the relationship between TP release rate and lake trophic state developed from 91 small lakes, Lake Macatawa would be classified as mesotrophic given the measured TP release rates (Fig. 3; Nürnberg and LaZerte

2004). However, based on the lake's water column phosphorus concentrations, it is much more reasonable to classify the lake as eutrophic. Internal TP loading estimates from Spring Lake, another drowned river mouth lake just north of Lake Macatawa, were 1-2 orders of magnitude greater (1.64-29.54 mg TP/m^2/d) than the current estimates at most sites in Lake Macatawa (Steinman et al. 2004).

It is unclear if the low release rates from Lake Macatawa represent actual fluxes or are tempered by experimental conditions related to conducting the aerobic and anaerobic exposures in succession on the same cores. The higher release rates during experiment 3 suggest that temperature strongly influence the release rates. If the data are representative, they strongly suggest that internal P loading may not be a major source of phosphorus in Lake Macatawa, and management strategies that focus on controlling external inputs will be effective at reducing lower water column P concentrations. However, if these data underestimate the true internal P loading rates, control of external inputs alone will not result in short-term reductions of TP concentration in the water column (Sas 1999). Under these circumstances, the internal P loading will also need to be addressed. The spatial heterogeneity in internal P loading is also noteworthy; the relatively low rates at Site BB and the high rates at Site EE (experiment 3 only) suggest that strategies to remediate internal P loading in Lake Macatawa should recognize this heterogeneity, and use a targeted approach to optimize resources.

4. References

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Nürnberg, G.K., and B.D. LaZerte. 2004. Modeling the effect of development on internal phosphorus load in nutrient-poor lakes. Water Res. Research 40: W01105, doi:10.1029/2003WR002410, 2004.

Sas, H. 1989. Lake restoration by reduction of nutrient loading: expectations, experiences and extrapolation. Academia-Verlag, Richarz, St. Augustine, Germany.

Steinman, A.D., R. Rediske, and K.R. Reddy. 2004. The reduction of internal phosphorus loading using alum in Spring Lake, Michigan. J. Environ. Qual. 33: 2040-2048.

Table 1. Range of flux rates of SRP release and estimates of annual internal loading from sediments to Lake Macatawa water column under year-round anaerobic conditions and anaerobic conditions for 20% of the year. See text for more detail.

Treatment	**Site**	**Flux (mg P/ m^2/day)**	**Annual Load (100% anaerobic) (tons/yr)**	**Annual Load (20% anaerobic) (tons/yr)**
Experiment 1				
Anaerobic	EE	0.23-0.41	0.66-1.18	0.13-0.24
Anaerobic	PC	0.16-0.24	0.47-0.71	0.09-0.14
Anaerobic	WE	0.23-0.24	0.66-0.71	0.13-0.14
Aerobic	EE	-(0.07-0.15)	N/A	N/A
Aerobic	PC	-(0.09-0.18)	N/A	N/A
Aerobic	WE	-(0.05-0.10)	N/A	N/A
Experiment 2				
Anaerobic	EE	0.05-0.07	0.13-0.19	0.03-0.04
Anaerobic	PC	0.05-0.23	0.14-0.65	0.03-0.13
Anaerobic	WE	0.07-0.19	0.19-0.55	0.04-0.11
Aerobic	EE	-0.04-0.05	N/A	N/A
Aerobic	PC	-(0.01-0.06)	N/A	N/A
Aerobic	WE	-(0.01-0.07)	N/A	N/A
Experiment 3				
Anaerobic	EE	0.11-1.30	0.33-3.77	0.07-0.76
Anaerobic	PC	-0.03-1.28	-0.10-3.70	-0.02-0.74
Anaerobic	WE	0.44-1.86	1.29-5.38	0.26-1.08

Anaerobic	BB	-0.30-0.39	-0.86-1.13	-0.17-0.23
Aerobic	EE	0.16-0.24	N/A	N/A
Aerobic	PC	0.54-0.68	N/A	N/A
Aerobic	WE	0.31-0.49	N/A	N/A
Aerobic	BB	0.07-0.33	N/A	N/A

Table 2 Range of flux rates of TP release and estimates of annual internal loading from sediments to Lake Macatawa water column under year-round anaerobic conditions and anaerobic conditions for 20% of the year. See text for more detail.

Treatment	**Site**	**Flux (mg P/ m^2/day)**	**Annual Load (100% anaerobic) (tons/yr)**	**Annual Load (20% anaerobic) (tons/yr)**
Experiment 1				
Anaerobic	EE	0.26-0.33	0.76-0.94	0.15-0.19
Anaerobic	PC	0.33-0.49	0.94-1.42	0.19-0.28
Anaerobic	WE	0.13-0.33	0.38-0.94	0.08-0.19
Aerobic	EE	-(0.61-1.33)	N/A	N/A
Aerobic	PC	-(0.75-1.03)	N/A	N/A
Aerobic	WE	-(0.23-0.34)	N/A	N/A
Experiment 2				
Anaerobic	EE	0.08-0.11	0.24-0.32	0.05-0.07
Anaerobic	PC	0.16-0.28	0.47-0.81	0.09-0.16
Anaerobic	WE	0.08-0.23	0.24-0.65	0.05-0.13
Aerobic	EE	-(0.20-0.39)	N/A	N/A
Aerobic	PC	-(0.20-0.39)	N/A	N/A
Aerobic	WE	-(0.27-0.52)	N/A	N/A
Experiment 3				
Anaerobic	EE	7.22-8.23	20.9-23.82	4.18-4.76
Anaerobic	PC	0.96-1.55	2.77-4.48	0.55-0.90
Anaerobic	WE	1.66-2.16	4.80-6.25	0.96-1.25

Anaerobic	BB	0.33-0.39	0.94-1.14	0.19-0.23
Aerobic	EE	-(0.12-0.67)	N/A	N/A
Aerobic	PC	-0.21-0.24	N/A	N/A
Aerobic	WE	-0.50-0.08	N/A	N/A
Aerobic	BB	0.07-0.33	N/A	N/A

Table 3. Mean depth and TP release rates from selected lakes around the world.

Lake	Mean Depth (m)	TP Release rate (mg P/m^2/d)
Arresø (Denmark)	2.9	40
Neagh (UK)	8.9	4.4
Alderfen Broad (UK)	0.6	3.5
Klamath (OR)	2.4	6
Long (WA)	2.0	2.6
Spring Lake	6.0	1.6-29.5
Mendota (WI)	12.2	31.4
Mona (MI)	4.1	2-14
Macatawa (MI)	?	-0.30 – 8.23

Figure 1. Diffusive flux rates of TP and SRP from the three Lake Macatawa sediment core experiments. Values represent means when there was more than one replicate core per site.

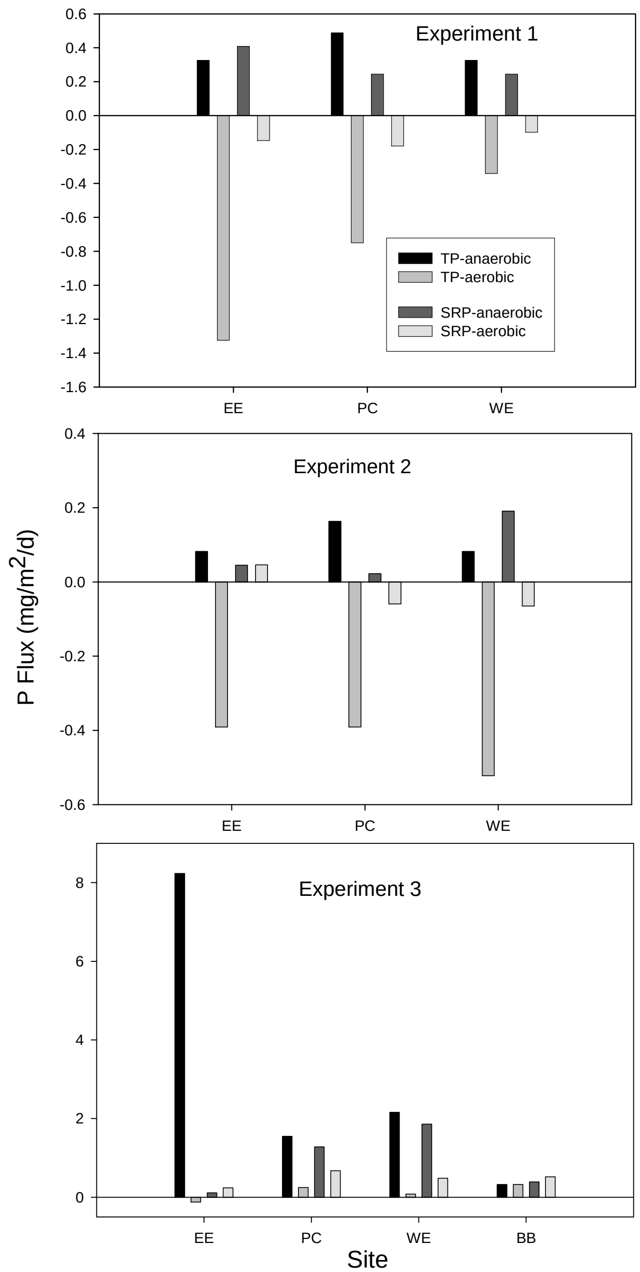


Figure 2. TP release rates from Lake Macatawa cores sampled during June-July, 2005 (Experiment 2).

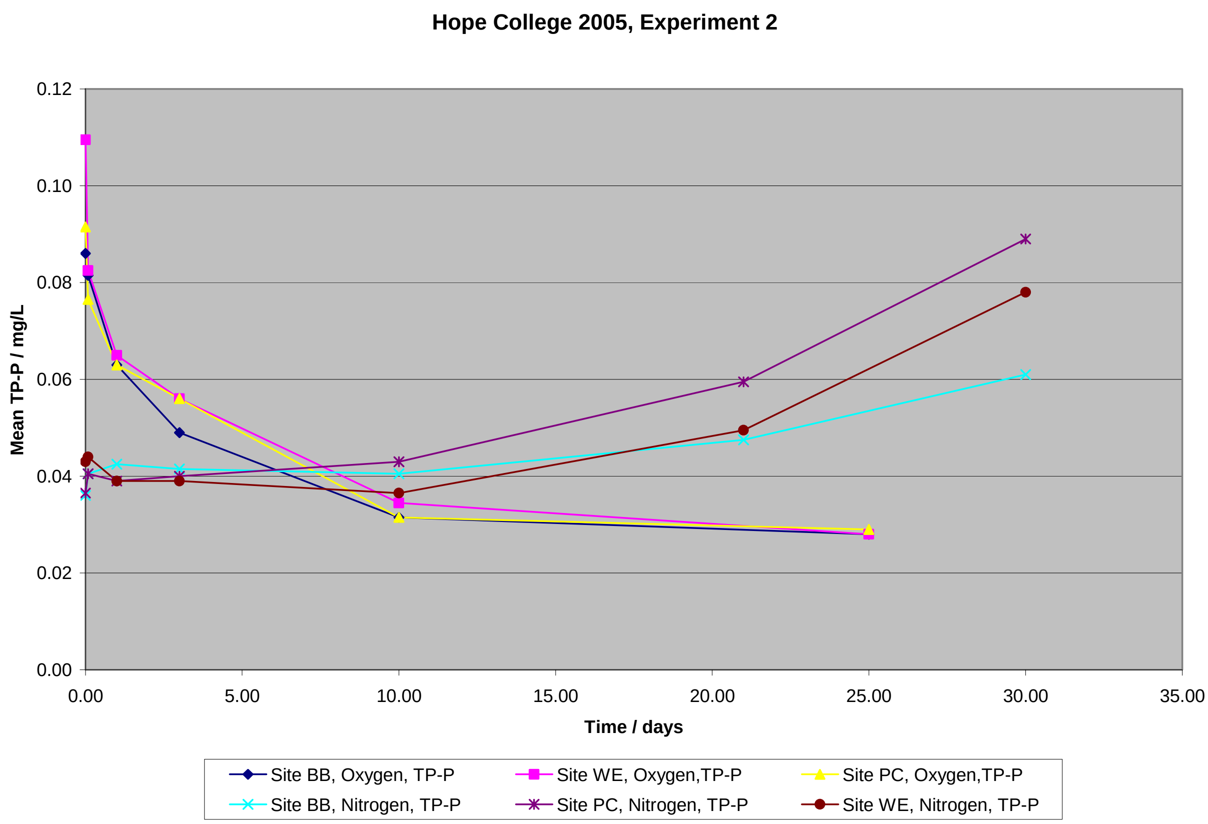
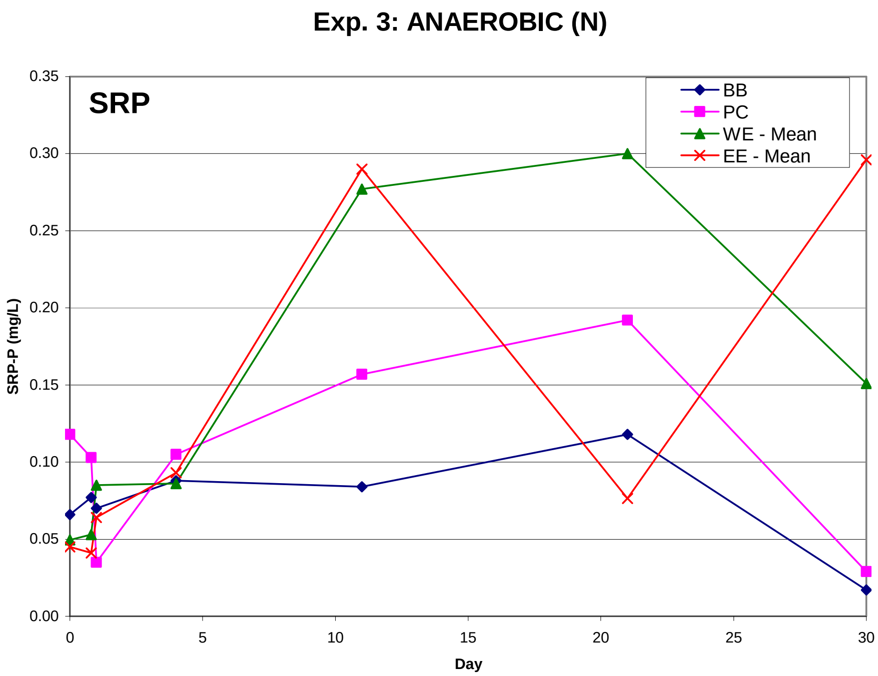


Figure 3. TP release rates from Lake Macatawa cores sampled during August, 2005 (Experiment 3).



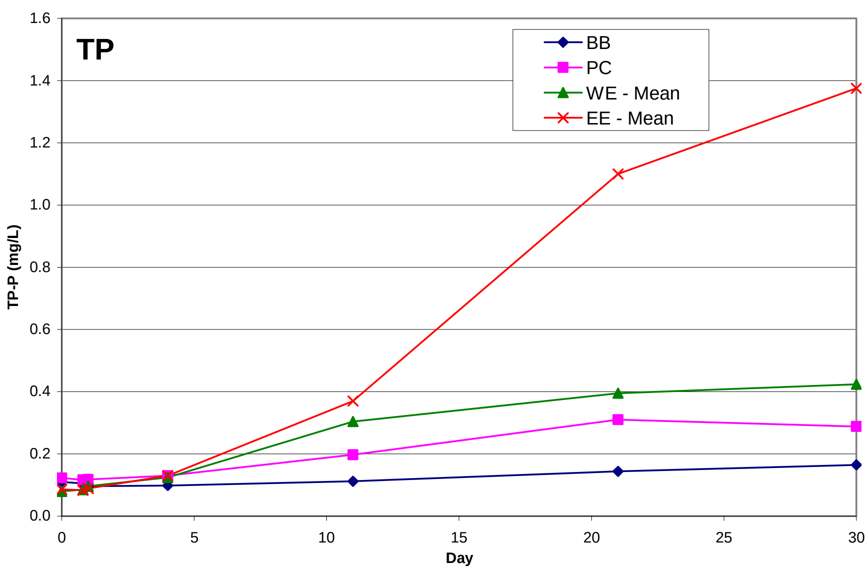


Figure 3. Classification of lakes based on diffusive flux rates. Original data from Nürnberg (1988), modified to include data from west Michigan lakes.