PHOSPHORUS RELEASE FROM ANOXIC SEDIMENTS: WHAT WE KNOW AND HOW WE CAN DEAL WITH IT

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ABSTRACT

An attempt is made to classify lakes that are especially prone to high internal phosphorus load derived from anoxic sediment surfaces. Morphometric, hydrological and geochemical characteristics of lakes with high internal P load are discussed. For example a lake with a mean depth between 5 and 12 m and an average flushing rate is a candidate for internal P load, especially if sediment P concentration is elevated due to eutrophication. Measures for remediation are presented like hypolimnetic withdrawal, aeration and chemical precipitation.

INTRODUCTION

Phosphorus (P) release from anoxic sediments or internal P load represents an additional P load to a water system. It enhances eutrophication and may create a shift from P to N limitation. Because it boosts production more detritus settles and the oxygen demand in water and sediment increases. Therefore the sediment area overlain by anoxic water is likely to increase as well. Because of increased sediment P concentration due to increased sedimentation also areal P release rates are likely to increase. Both these increases combined produce even higher internal loads. Internal P load is a self-enhancing process that fertilizes water systems (NURNBERG & PETERS, 1984).

Ail types of water systems are prone to exhibit internal load. It is clearest in stratified waters, where the build-up of anoxia and increased P concentrations in the bottom water layer can be witnessed. But even shallow, polymictic systems often have a microlayer of stagnant water above the sediment surface, e.g. in weedbeds, at certain times i.e. before dawn, and anoxic P release may occur. Internal load is especially known in round deep lakes, like kettle lakes, with only small water replenishing rates, but they can also be found in fastflushing lakes, that more resemble wide river sections. Internal load has been reported from many man-made impoundments and dams as well as from rather pristine lakes, although the quantity is usually much smaller in unspoiled lakes. Anoxic P release even has been detected in estuaries and fiords, as well as nearshore ocean sections and large embayments (e.g. the Baltic Sea). In this report l will concentrate on mono- and dimictic freshwater lakes, although many conclusions are readily applicable to other water systems as well.

Despite the wide spread of internal P load there are certain characteristics that are more common to lakes with anoxic P release. I will try to pinpoint these characteristics or their combinations, so that some statements about the probability and quantity of internal load can be made, even if only few limnological data are available. To achieve this, I will separate internal load into release rate and anoxia and present models to predict these components. Next, some more simple lake characteristics are examined and related to internal load. Finally the most promising restoration measure for high internal load will be presented.

THE COMPONENTS OF INTERNAL P LOAD

Areal internal P load (L,,,,, mg m^{-2} yr^{-1}) can be broken down into the release and the anoxic component.

L,,,, = RR x AF Eq. 1

with RR, areal release rate (mg m^{-2} d^{-1}) and AF, anoxic factor (d yr^{-1}). In fact, internal load estimated from increases of P in the anoxic hypolimnion compare well with the product of AF and RR for 34 years of eight North American lakes (Fig. 1, NÜRNBERG, 1987a).

P release rates are highly correlated to sediment total P (TP_{sed}) and reductant soluble P (CDB-P or BD-P). In a

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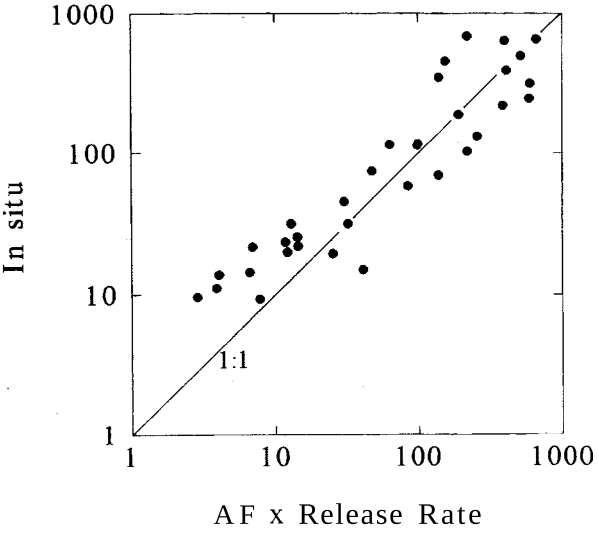


FIGURE 1. Internal P load (mg m^{-2} summer^{-1}) for 34 years of eight North American lakes. In situ- estimated from hypolimnetic increases during anoxic summer stratification after correction for external inputs, AF x Release Rate, determined according to Eq. I. The line of perfect agreement is also shown (1:1). (NÜRNBERG 1987a).

study involving 3 to 21 cores each from 14 sample sites of 8 North American lakes and 63 literature data from lakes worldwide, following regression equations were determined (NÜRNBERG, 1988):

North American study lakes:

n=14; $p<0.0001$: $RR= -4.3 + 3.88\ TP_{sed}$, $r^2= 0.59$;

$RR= -0.47 + 13.66$ BD-P; $r^2= 0.71$;

World-wide lakes:

n=63, $\log RR= 0.8 + 0.76 \log TP_{sed}$, $r^2= 0.21$, $p<0.001$;

n=25, $\log RR=1.31 + 0.79 \log$ CDB-P, $r^2=0.49$, $p<0.001$.

If sediment concentrations are not available, RR can be estimated from the mere observation of the degree of eutrophication or even of the population density of the watershed. Figure 2 relates the trophy of 82 lakes to RR, Figure 3 relates population density of the basins of the Laurentian Great Lakes to their trophy.

The anoxic factor (AF) is a measure of the oxygen state of a stratified lake. It represents the number of days per year (or season) that a sediment area equal to the lake surface area is overlain by anoxic water (days year-', e.g NURNBERG, 1987a). Following steps lead to the computation of the AF:

1. Determine the oxycline from oxygen profiles. Criteria of anoxia: ≤ 1 mg/l
2. Determine the period of a constant oxycline.

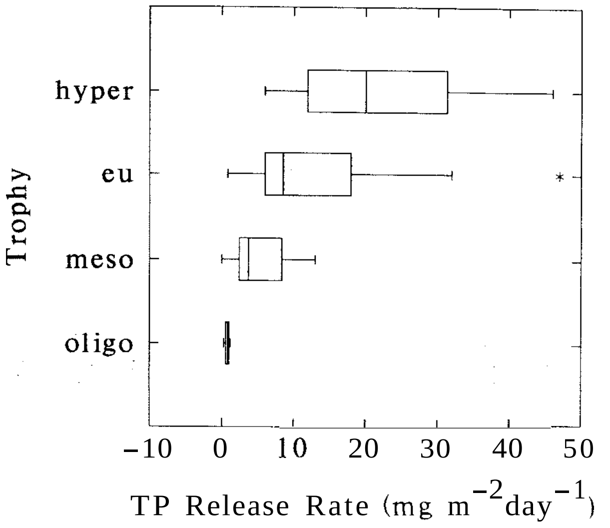
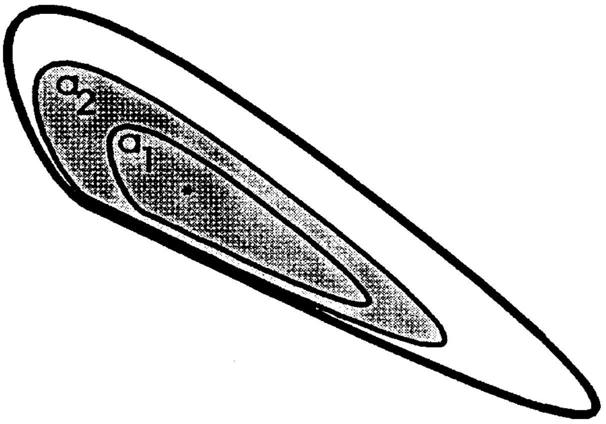


FIGURE 2. TP release rate and its relationship to lake trophy for X2 small North American lakes. L: n=3, 12, 38, 29, for oligo- to hypertrophic. Median and non-parametric confidence limits are shown.



3. Use morphometric information, i.e. hypolimnetic area below the oxycline.
4. Multiply the period of anoxia (t_i in days) by the corresponding hypolimnetic area (a, in m^2)
5. Add up all products:
$t_1*a_1+t_2*a_2+t_3*a_3+...+t_n*a_n= \sum t_i*a_i$
6. Divide the grand total by the lake surface area (A,,, m^2)

$$AF= \frac{\sum_{i=1}^{n} t_i * a_i}{A_0}$$

I found the AF to be highly significantly correlated to average annual total phosphorus concentrations. I used this relationship to tentatively set up limits for the trophic

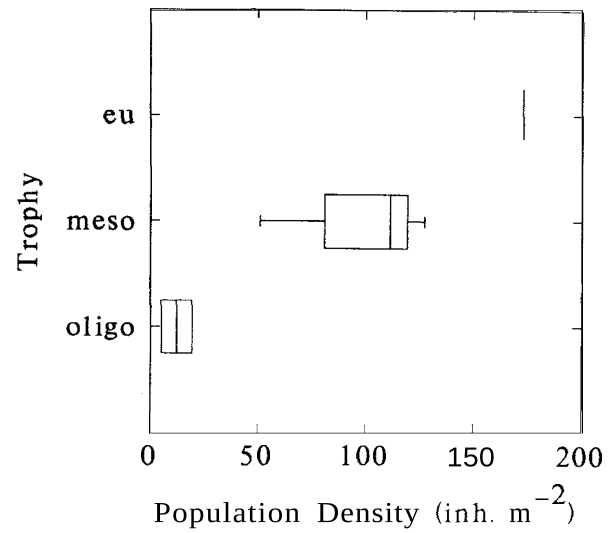


FIGURE 3. Population density of the Great Lake's Basins as they correspond to trophy. n= 2, 3, 1, for olig- to eutrophic. Median and nonparametric confidence limits are shown.

state of lakes based on oxygen concentrations: For an anoxic factor (days year^{-1}) of 0-25 the lake may be oligotrophic; 25-60, mesotrophic; 60-110, eutrophic; above 110, hypertrophic. For example Lake Erie has an anoxic factor of 20 days yr^{-1}, some meromictic lakes of 60 days yr^{-1}, and some of my Canadian study lakes of the Precambrian Shield anything between 0.5 to 50 days yr^{-1}.

AF is predictable from the correlation with average lake TP concentration and from the minimum redox potential of the bottom water sampled in the late summer before fall turnover (NURNBERG, in prep.).

LAKE CHARACTERISTICS OFTEN FOUND IN LAKES WITH INTERNAL P LOAD

From a large data file of ca 70 lakes with different amounts of internal P load cluster analysis and a non-parametric technique to separate subgroups distinguished lakes that release hydrogen sulfide (S-Lakes) from lakes that release iron (Fe-Lakes), once their sediment surfaces become anoxic. The S-Lakes typically have higher pH, conductivity and hardness than the Fe-Lakes. Their AF is larger and their hypolimnetic redox potential smaller than the Fe-Lakes. Furthermore they often have other signs of eutrophication as well, like higher total P and nitrogen

TABLE 1. Examples of lake characteristics. A_d/A_{lake}, ratio of the area of the watershed to the lake area; TP hypo/epi, ratio of hypolimnetic to epilimetic P concentration; TP fall/summer, ratio of fall turnover to summer surface concentration; L,,,, effect on internal load (+, positive or -, negative).

Characteristics	**Wara-maug**	**Chub**	**Magog**	**Harp**	**Wonon scop.**	**L_{INT}**
z, m	7.0	8.9	9.8	13.3	12.5	strat.
qs, m yr^{-1}	8.4	4.5	163	4.3	3.1	
AF, d yr^{-1}	83	19	NA	4	60	+
EH, mvolt	-38	38	-50	184	58	
Sed. TP, mg g^{-1}	2.9	2.0	NA	2	2.1	
RR, mg m^{-2} d^{-1}	9.2	1.4	14	NA	7.3	+
L_{ext}, mg m^{-2} yr^{-1}	NA	100	++	200	NA	+
A_d/A_{Lake}	14	8	NA	7	NA	+
Pop. Density	+	-	+	-	+	
Settlement	1700	1900	1800	1900	1700	early
pH	6.4	5.6	7.5	6.3	7.0	> 6
Color, Hazen U.	NA	33	NA	20	NA	clear
Fe vs. H_2S	Fe	Fe	Fe/S	Fe	S	S
Water TP, µg l^{-1}	35	10.7	43	7.5	27	
TP hypo/epi	24	13	20	1	15	+
TP fall/summer	NA	2.3	2.4	1	NA	+
L,,,,,mg m^{-2} yr^{-1}	457	26	486	3	595	+

concentration. The Fe-Lakes are often soft water lakes that could be humic, they also may be anoxic, sometimes because of morphometric reasons, but their P release rates can be small when the sediment P concentration is small.

Table 1 shows characteristics of five lakes. Even if not all the characteristics are known, some less quantitative ones might suffice to get an initial idea of the magnitude and importance of internal load. Just looking at historical information on early settlement in North America for example, or on population density and anoxia, internal load can be estimated.

HYPOLIMNETIC WITHDRAWAL AS A LAKE RESTORATION TECHNIQUE

In lakes with internal P load first external P load should be reduced. But often that measure is not enough because the internal P load still fertilizes the lake water. In that case hypolimnetic withdrawal seems to be a most promising technique (NÜRNBERG, 1987b). It does not alter the chemistry like additions of sedimenting chemicals do, and it does not only relieve the symptom like aeration does but it actually reduces the mass of hypolimnetic P.

To employ hypolimnetic withdrawal the major surface outflow of a lake is dammed and water is withdrawn from the hypolimnion instead, at times of maximum hypolimnetic P concentrations, i. e. during summer stratification. It therefore is especially applicable to manmade impoundments, where dams are already created. Sometimes treatment of the withdrawn water has to be employed before it can be discharged into the recipient stream. A study on several European and North American lakes (NURNBERG *et al.*, 1987) reveals that there is a good correlation between TP export via withdrawal and decrease in epilimnetic P ($n=8$, $r^2=0.75$, $p<0.005$). The success of withdrawal could usually be seen after 2 to 3 years and a tendency of the epilimnetic P concentration to decrease was still detectable after 9 years. The change of epilimnetic P was most pronounced when the initial P concentration had been very high.

CONCLUSION

Internal P load is a reality in many water systems. It is important to know the combination of lake characteristics that are often associated with high internal load. If more detailed information is available it can even be predicted from variables such as sediment P concentration and hypolimnctic redox potential. Hypolimnetic withdrawal appears to be a sound technique to restore natural and manmade lakes with high internal P load.

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