A simple approach to calculate internal phosphorus loads in shallow lakes

Av Olav Grøterud and Ståle Haaland

Olav Grøterud (olav.groterud@umb.no) is professor emeritus at Norwegian University of Life Sciences, Department of Plant and Environmental Sciences. *Ståle Haaland* is a research scientist at Bioforsk, and associated professor at Norwegian University of Life Sciences, Department of Plant and Environmental Sciences.

Sammendrag

En enkel fremgangsmåte for å anslå intern fosforbelastning i grunne innsjøer. Fosforkonsentrasjon i en grunn innsjø gjennom to somre har blitt estimert ved å bruke tilførselsdata for nedbørfeltet. Metoden er enkel og er ment å være illustrativ. Differansen mellom målte og simulerte fosforkonsentrasjoner ble antatt å skyldes intern fosforbelastning. Metoden kan være anvendbar for å angi et grovt estimat for grunne innsjøer, særlig om man har få data og direkte målinger av intern fosforbelastning ikke er tilgjengelig. Artikkelen er basert på et foredrag holdt på den 31. kongress til den Internasjonale Forening for Limnologi, Cape Town 2010.

Summary

Phosphorus concentrations in a shallow lake during two summers were estimated by using catchment input data. The approach is straightforward and simple. The difference between measured and simulated phosphorus concentrations was assumed to be due to internal phosphorus loading. The method may be applicable to give a rough estimate in shallow lakes, especially where few data are available and direct measurements of internal phosphorus loading are lacking. The paper is based on an oral presentation given at the 31st Congress of the International Society of Limnology, Cape Town 2010.

Introduction

The classic explanatory model for internal phosphorus loading is phosphorus release from lake sediments (Einsele, 1936; Mortimer, 1942). Stratified lakes with anoxic sediments, and possibly anoxic hypolimnetic waters, tend to conform to that, with diffusion considered to be the most important mechanism for sediment-water exchange (Håkanson and Jansson, 1983; Bostrøm et al., 1988). In shallow lakes, however, factors like high pH, anaerobic conditions, bioturbation and wind turbulence with resuspension, can affect the internal phosphorus loading (Boström at al., 1988; Koski-Vähälä and Hartikainen, 2001; Grøterud and Haaland, 2007).

The objective of this paper has been to show the application of a simple method for estimating internal phosphorus loading in shallow lakes during summer. This might for many be a relevant task along the process of implementing the European Water Framework Directive in Norway (EC, 2000). The phosphorus concentrations in the lake were predicted based solely on catchment data, even if the latter data are somewhat uncertain (as often might be the case). The discrepancy between measured data (in the lake) versus the simulated data (based on catchment input), provides a simple approach for estimating the internal phosphorus loadings.

Materials and methods

Study site

Lake Østensjøvannet is used as an example. The lake has been previously described by Grøterud and Haaland (2007) and is situated in a rural area, approximately 30 km south of Oslo, Norway. Arable land comprises about 50 % of the catchment. The main sources of phosphorus loads to the lake are point sources from urban areas and diffuse sources from agricultural activities. The lake is shallow and is generally well mixed during the ice-free season, with high levels of nutrients. The water quality is characterised by high pH (up to above 10 in June) and high primary productivity (up to 6 g C m^{-2} day^{-1}).

Field and laboratory work

Precipitation data were taken from the local meteorological station at Ås. Annual total water inflow ($Q_ø$) and summer water inflow ($dQ_ø$) to the lake, were estimated due to the lack of direct measurements:

I) Inflow measurements to Lake Årungen, given by Grøterud and Rosland (1981), together with the ratio between the catchment area of Østensjøvannet and Årungen (0.28). Årungen is situated downstream close to Østensjøvannet. These were used to calculate the inflow to Østensjøvannet ($Q_ø$) in 1977 and 1978.

II) Runoff measurements from a research field in the vicinity of Østensjøvannet

A_c (km^2)	A_l (Mm^2)	V (Mm^3)	z_{max} (m)	z_{mean} (m)	z_r (%)	Q_N (Mm^3)	T_w (years)
14	0.34	1.31	7.1	3.9	1.08	6.62	0.2

A_c = catchment area, A_l = lake area, V = lake volume, z_{max} = maximum depth, z_{mean} = mean depth, z_r = relative depth ($88.6\ z_{max} / \sqrt{A_l}$), Q_N = normal inflow per year, T_w = hydraulic retention time (V/Q_N).

Table 1. Morphometric and hydrologic values for Lake Østensjøvannet. (Grøterud and Haaland 2007).

catchment during 1984-2004. Measurements for May, June, July and August (dQ_t), together with precipitation data (dPr_t), provided the following regression equation (H. Lundekvam, pers. comm.):

$$\mathbf{dQ_t = 0.598dPr_t - 112.9}$$

$r^2 = 0.77$, $p < 0.0001$, n = 21, units = mm

This equation, along with precipitation data, was used to estimate the water inflow to Østensjøvannet during the two summer periods 13th June – 31st August (1977) and 6th June – 29th August (1978).

III) Direct measurements from RF during 1987 ($Q_ø$) for testing the relevance of the estimations.

The relevance of using both Årungen and measurements from a research field to estimate the inflow to Østensjøvannet 1977, 1978 and 1987, was indicated by the ratio between precipitation and inflow values these years. The mean ratio for Årungen in 1977-1978 ($Q_Å/Pr$) and RF in 1987 ($Q_ø/Pr$) were equal (0.72).

Mean annual total phosphorus concentrations in the inflows to Østensjøvannet in 1977 and 1978 (TP_t) were estimated by using the total phosphorus loading on the lake (TP_L) according to Erlandsen et al. (1980), $TP_t = TP_L/Q_t$. TP_L are point sources from the urban areas and the agricultural activities, and the diffuse sources from the scattered dwellings and Q_t is the annual runoff. We had to use a constant concentration (TP_t) during the research periods, due to the lack of systematic measurements. Other scattered measurements, however, indicated relatively small deviations during summer.

Concentrations of total phosphorus, oxygen, pH and temperature in Østensjøvannet were measured with standard methods in five depths and seven times during June, July and August as described by Grøterud and Haaland (2007).

Results and discussion

Phosphorus concentrations in the lake during summer

The development of total phosphorus concentrations at 3 m depth in Lake Østensjøvannet, during the two summer periods, is shown in table 2. The concentrations from 3 m depth have been chosen to be representative for the whole water body, but also with respect to the effect from the sediments. The variations in temperature in the vertical strata (from top to bottom) was small, and ranged between 15 - 17° C throughout both summers (Grøterud and Haaland 2007).

Year	P in the inflow	P at the start	P at the end	Duration
1977	464	155	781	79
1978	498	226	873	84

Table 2. Total phosphorus concentrations (μgL^{-1}) in the inflow and in the lake at the start and the end of the research periods; 13th June – 31st August (1977), and 6th .June – 29st August (1978). Duration is given in days.

Estimates of internal phosphorous loading

If the lake behaves like a mixed reactor, with no transformation of a constituent, a first order differential equation according to Rainy (1967) or Welch (1993) could be used to estimate the change in concentration of the constituent with time as a result of a change in the input value. This equation was applied to our lake and is given below:

$$dC/dt = q * C_i / V - q * C/V$$

And, in its integrated form:

$$C_t = C_i + (C_o - C_i)\, e^{-q*t/V}$$

C_i = concentration in the inflow
C = concentration in the lake
C_o at start, C_t at time t
q = discharge from the lake
V = lake volum

where C_t is the TP concentration after time t in summer (after 79 days in 1977 and 84 days in 1978; table 2). Note: TP should not be transformed since it can be regarded as a somewhat "conservative" substance representing all fractions of P. C_o is the TP concentration in the lake at the start of the two summer periods, 13th June – 31st August and 6th June – 29th August (155 µg P L^{-1} and 226 µg P L^{-1} in 1977 and 1978, respectively; table 2). C_i is the TP input to the lake (464 µg P L^{-1} and 498 µg P L^{-1} in 1977 and 1978, respectively; table 2). q is the discharge from the lake (6200 m^3 day $^{-1}$ in 1977 and 4100 m^3 day $^{-1}$ in 1978, respectively) and V is the lake volume (1310000 m^3; table 1). Internal loading can be calculated as:

$$C_{t\ int.load} = C_{t\ meas.} - C_t$$

where $C_{t\ meas.}$ represents the measured concentration after time t (781 µg P L^{-1} in 1977 and 873 µg P L^{-1} in 1978, respectively; table 2). Expressed as an areal internal loading (mg P m^{-2} day^{-1}) the equation is:

$$C_{t\ int.areal\ load} = (C_{t\ meas.} - C_t)\ V/(A_1 * t)$$

where A_1 represents the lake area (340000 m^2, table 1).

For the given summer values for 1977 and 1978 for Lake Østensjøvannet, an estimate is derived for the total phosphorus concentration in the lake at the end of summer (C_t) based on external loading (251 µg P L^{-1} for 1977 and 226 µg P L^{-1} for 1978). Thus the contribution of internal loading to the concentration in the lake ($C_{t\ int.load}$) is 530 µg P L^{-1} for 1977 and 647 µg P L^{-1} for 1978, with respective areal loads ($C_{t\ int.\ areal\ load}$) of 26 and 30 mg P m^{-2} day $^{-1}$.

Some few sensitivity calculations for 1977 have been done:
A reduction of 10 and 25 % of both q and C_i, gives respective areal loads of 27 and 28 mg P m^{-2} day $^{-1}$. An increase of 25% of both q and C_i gives an areal loads of 23 mg P m^{-2} day $^{-1}$. An increase of q by 10% with an additional reduction by 10 % of C_i, would give an estimated areal load of 26 mg P m^{-2} day^{-1}. An increase of q by 25 %, and an additional reduction of 25 % of C_i, would give an estimated areal load of 27 mg P m-2 day-1.

Conclusion

We have focused on a simple, unpretentious and easy accessible method for calculations of internal phosphorus loadings in shallow lakes. The method is projected where direct measurements of internal phosphorus loading are absent. We acknowledge its uncertainties, but the method seems to estimate the level of internal phosphorus loading quite well. The calculated values were in the same range compared to studies from other shallow eutrophic lakes (Jensen and Andersen, 1992).

Acknowledgement

Sincere thanks are due to the late Associate Professor Helge Lundekvam for helping us with runoff data.

References

Boström, B., Andersen, J.M., Fleischer, S., and Jansson, M., 1988. Exchange of phosphorus across the sediment-water interface. Hydrobiologia 170, 229-244.

EC, 2000. Directive 2000/60/EC of the European Parliament and the Councli of 23. October 2000 of establishing a framework for community action in the field of water policy.

Einsele, W. 1936. Über die Beziehungen des Eisenkreislaufs zum Phosphorkreislauf im Eutrophen See. Arch. Hydrobiol. 29: 664-686.

Erlandsen, A.H., Grøterud, O., and Skogheim, O.K., 1980. Intern tilførsel av fosfor i innsjøer ved høy pH. Research report. Department of hydrotechnics, Agricultural University of Norway. p.27.

Grøterud, O., and Rosland F., 1981. Vannbalanse og stofftransport i Årungens nedbørfelt 1977-79. Research report. Department og hydrotechnics, Agricultural University of Norway, 54 p.

Grøterud, O., and Haaland, S., 2007. Østensjøvannet – a shallow hypertrophic lake in Norway with significant internal phosphorus loading during summer. Vatten 63: 313–320.

Håkanson, L. and Jansson, M., 1983. Principles of lake sedimentology. Springer-Verlag Berlin Heidelberg, 316 p.

Jensen, H.S. and Andersen, F.Ø., 1992. Importance of temperature, nitrate and pH for phosphate release from aerobic sediments of four shallow, eutrophic lakes. Limnol. Oceanogr. 37, 57-589.

Koski-Vähälä, J. and Hartikainen, H., 2001. Assessment of risk of phosphorus loading due to resuspended sediment. J. Environ. Qual. 30, 960-966.

Mortimer, C. H., 1942. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29: 280-329, 30: 147-201.

Rainy, R.H., 1967. Natural displacement of pollution from the Great Lakes. Science 155, 1242-1243.

Welch, E.B. 1993. Diluting and flushing, pp. 129 – 148. In: Cook, G.D., Welch, E.B., Peterson, S.A. and Newroth, P.R. (eds). *Restoration and management of lakes and reservoirs*. 2nd edition. 548 p. Lewis publishers.