



When large lakes respond fast: A parsimonious model for phosphorus dynamics

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ABSTRACT

This article illustrates how the time scale of lake responses to external inputs of limiting nutrients, such as phosphorus, can be evaluated with minimum calculation from a simple mass balance model that takes into account nutrient recycling in sediments. The characteristic transient time can be estimated from

$$\tau_{trans} \equiv [\tau^{-1} + \eta(1-k)]^{-1}$$

where τ (yr) is the hydrological residence time, η (yr^{-1}) characterizes the rate of nutrient removal by settling from the water column, and k (between 0 and 1) is the efficiency of nutrient recycling in sediment. At steady state, τ_{trans} is equivalent to the nutrient residence time with respect to inputs I^{st} , so that, for given inputs, the steady state nutrient level (W^{st}) can be calculated as

$$W^{st} = \tau_{trans} I^{st}$$

Application of the model to the Laurentian Great Lakes reproduces the historical data for total phosphorus levels and suggests changes in recent decades in the rate of P sequestration from the water column into sediments. The model demonstrates that lakes with sediment phosphorus recycling efficiencies of <50%, such as many oligotrophic and well-oxygenated large lakes of the world, can respond to external P inputs quickly even when the hydrological residence time of water is long. Higher recycling efficiencies lead to a dominance by internal loading and increased response times. When net sedimentation is positive ($k < 1$), however, lakes should respond to changes in external P inputs faster than their hydrological residence time even when their P budgets are dominated by internal loading.

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Introduction

The trophic status of lakes is commonly determined by the concentrations of productivity-limiting nutrients, such as phosphorus (Schindler et al., 2008). The time scale over which the nutrient concentrations adjust to changes in their external supply depends on the size of the lake and the rate at which the water is renewed by inflows, but also depends on processes within the lake (Katsev et al., 2006; Hupfer and Lewandowski, 2008). Whereas nutrients are supplied into the water column from catchments, a substantial portion of the lake nutrient pool can be stored in bottom sediments, from where nutrients can be recycled into the water column (Katsev, 2016). Such internal nutrient loading can sustain primary productivity for decades, even after the external inputs are curtailed, frustrating efforts to control the productivity by regulating external inputs (Sondergaard et al., 2001). Similarly,

changes to lake water geochemistry or changes in the composition of benthic animal communities may alter the rate at which the limiting nutrients are sequestered in sediments. In the Laurentian Great Lakes, for example, invasion by filter-feeding dreissenid mussels (zebra mussels and then quagga mussels) (Hecky et al., 2004; Dove and Chapra, 2015) in mid-1990s and early 2000s led to a near disappearance of native amphipod *Diporeia* bioturbators and has been suggested to affect the rates of phosphorus removal (Ozersky et al., 2015; Mosley and Bootsma, 2015; Kim et al., 2013). Ability to predict the time scales over which the effects of such disruptions become fully manifest, as well as the eventual nutrient concentrations, is an important aspect of understanding ecosystem dynamics and effective lake management.

When it comes to internal loading (e.g., Nürnberg, 1991, 1998), the data that are usually available on sediment geochemistry and sediment-water nutrient exchanges are often insufficient for detailed assessments, which calls for an approach that uses as few fitting parameters as possible. In this article, some of the previously suggested approaches are reformulated to obtain simple mass-balance

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relationships that can be used for quick assessments of the time scales on which lakes may respond to changes in external inputs. The approach is illustrated by applying the model to phosphorus dynamics in the Laurentian Great Lakes, and the time scales of lake responses are discussed for a range of sediment conditions and internal vs. external loading situations.

The model

The mass balance model (modified from Lorenzen et al., 1976; Chapra and Canale, 1991) that explicitly takes into consideration nutrient recycling in sediments can be written as

$$\frac{dW}{dt} = I(t) - O - F_{sed} + F_{out} \quad (1)$$

where W [g] is the nutrient amount in the water column, and the terms on the right [g yr⁻¹] represent external inputs (I), outputs (O), and fluxes of nutrient into the sediment with sedimentation (F_{sed}) and out of the sediment with the recycled fraction (F_{out}). To minimize the number of fitting parameters, the model relies on the following four simplifications. First, on the time scale of interest, the water body is considered well mixed, so that the nutrient amount in the water column can be represented by a single variable, W . The model thus does not attempt to resolve spatial variability (e.g., epilimnion vs. hypolimnion or nearshore vs. offshore) and effectively disregards summer stratification in lakes, considering only annual averages. For simplicity, the average whole lake concentrations (W/V , where V is the lake volume) of nutrient may be reasonably represented by the concentrations during spring overturn (though when internal loading is high these could underestimate the annual averages (Nürnberg, 1998)). Secondly, the average sedimentation of the nutrient, F_{sed} , is proportional to the nutrient's total amount in the water column:

$$F_{sed} = \eta W \quad (2)$$

where η [yr⁻¹] is a depth-averaged quantity. For a productivity-limiting nutrient like phosphorus, sedimentation occurs primarily with organic particles that originate in the photic zone, and η can be calculated as $\eta = v / z_{av}$, where v is the apparent settling velocity and z_{av} is average depth. In less frequent cases where sedimentation occurs with other particles, such as Ca-P precipitates in hardwater lakes, the corresponding settling velocity and depth parameters could be adjusted accordingly. Thirdly, the input flux I represents all external inputs, including with runoff and atmospheric deposition. The export flux O represents the loss of the nutrient from the lake. For phosphorus, it typically includes only the outflows and can be calculated as proportional to the nutrient amount in the lake:

$$O = \gamma W \quad (3)$$

where γ [yr⁻¹] is determined by the water outflow rate ($\gamma = \text{outflow [m}^3/\text{yr}] / V [\text{m}^3]$) and can be taken as the inverse of the hydrological residence time, τ [yr]. Fourth and last, the return flux of the nutrient from sediments, F_{out} , is assumed proportional to the sedimentation flux, F_{sed} :

$$F_{out} = k F_{sed} \quad (4)$$

The dimensionless coefficient k is the efficiency of nutrient recycling in the sediment. This simplification of the net effect of sediment processes deserves a separate justification. At steady state, one can define k as the ratio of the corresponding steady state fluxes: $k = F_{out}^{st} / F_{sed}^{st}$. For transient situations, this approximation requires that the ratio $F_{out}(t) / F_{sed}(t)$ remains approximately constant. While this is not always the case, this is a good approximation in systems where changes in organic sedimentation do not lead to significant shifts in the mechanisms of nutrient remobilization (e.g., for P mobilization in oligotrophic well-

oxygenated systems; Katsev et al., 2006; Li, 2011), and even in strongly impacted systems this ratio is unlikely to vary by >20% (estimated from Katsev and Dittrich, 2013; Hupfer and Lewandowski, 2008).

Using Eqs. (2)–(4), the mass balance Eq. (1) then becomes

$$\frac{dW}{dt} = I(t) - \gamma W - \eta W + k\eta W \quad (5)$$

At steady state, the left-hand-side is zero, and the amount of nutrient in the water column equals

$$W^{st} = \frac{I^{st}}{\gamma + \eta(1-k)} = \tau_{trans} I^{st} \quad (6)$$

The steady-state input I^{st} is thus linked to the steady state amount W^{st} through a time scale parameter τ_{trans} [yr]:

$$\tau_{trans} \equiv [\gamma + \eta(1-k)]^{-1} \quad (7)$$

which effectively represents (Eq. (6)) the residence time of the nutrient with respect to inputs (Vollenweider, 1976).

For non-steady state situations, it is convenient to rewrite Eq. (5) in terms of time-dependent deviations $\Delta I(t) = I(t) - I^{st}$ and $\Delta W(t) = W(t) - W^{st}$ from the corresponding steady state values:

$$\frac{d(\Delta W)}{dt} = \Delta I(t) - \Delta W(\gamma + \eta(1-k)) \quad (8)$$

If, after initial perturbation, external inputs remain constant in time ($\Delta I(t) = 0$), the nutrient amount in the water column approaches its steady state value exponentially on the time scale of τ_{trans} :

$$\Delta W(t) = \Delta W_{t=0} \exp(-t/\tau_{trans}) \quad (9)$$

The parameter τ_{trans} thus represents the characteristic time scale on which the nutrient amount in the water body responds to perturbations. As Eq. (7) shows, it depends not only on the hydrological residence time but also on the rates of sediment-water nutrient exchanges (k) and on the rate of nutrient removal from the water column (η). After initial perturbation, 90% of the steady state value is reached in time

$$\tau_{90} = -\ln(0.1)\tau_{trans} = 2.3026 \tau_{trans}$$

The steady state ratio of the internal to external loadings, F_{out}^{st} / I^{st} , can be calculated from Eqs. (2), (4) and (6) as

$$\frac{F_{out}^{st}}{I^{st}} = \frac{k\eta}{\gamma + \eta(1-k)} = k\eta\tau_{trans} \quad (10)$$

Results and discussion

Phosphorus dynamics in the Great Lakes

The described model is based on the conservation of mass and should be applicable to a wide range of situations where its underlying assumptions hold. It is illustrated here through an application to the phosphorus dynamics in the Laurentian Great Lakes. Phosphorus is commonly considered as a productivity-limiting nutrient in the Great Lakes, and its dynamics in the Laurentian Great Lakes has been recently reviewed (Dove and Chapra, 2015; Bunnell et al., 2014; Dolan and Chapra, 2012; Schelske et al. 2006). In particular, Chapra and Dolan (2012) used a mass-balance model that considered multiple horizontal segments with individually calibrated fitting parameters, to reproduce the multidecadal P monitoring data. The results below suggest that an adequate fit can be obtained with a simpler model for individual lakes, with parameters that are amenable to verification by measurements.

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