Exchange of phosphorus across the sediment–water interface

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Key words: phosphorus, sediments, retention, release, microbial processes

Abstract

In this article, principles of phosphorus retention and phosphorus release at the sediment–water interface in lakes are reviewed. New results and hypotheses are discussed in relation to older models of phosphorus exchange between sediments and water. The fractional composition of sedimentary phosphorus is discussed as a tool for interpretation of different retention mechanisms. Special emphasis is given to the impact of biological, particularly microbial, processes on phosphorus exchange across the sediment–water interface and to the significance of biologically induced CaCO₃ precipitation to phosphorus retention in calcareous lakes.

Introduction

Sediments play an important role in the overall phosphorus metabolism of lakes, acting both as a sink and a source of phosphorus. In most lakes, there is a net deposit of phosphorus in the sediments. However, in lakes of higher trophic levels, phosphorus release may exceed phosphorus sedimentation for periods of weeks or months and at certain conditions also on an annual level.

The twofold role of the sediments in phosphorus turnover in lakes has been known for a long time. Already Einsele (1936, 1938) and Mortimer (1941, 1942) demonstrated that oxygenated sediments retain phosphorus by fixation to iron (III) while reduced sediments release phosphorus by reduction of iron and subsequent dissolution of iron-phosphorus complexes. In a way these results were too convincing. Although it was known that calcareous sediments, for example, behaved differently, the Einsele/Mortimer model created a widespread opinion that phosphorus sedimentology was more or less entirely linked to iron chemistry.

Vollenweider (1968) demonstrated and formalized the nutrient loading–trophic level relationship. Vollenweider's model paved the way for political decisions on sewage water diversion and building of sewage treatment plants and, as a consequence, external phosphorus loading on many recipients was reduced dramatically. However, many lakes did not respond as was expected from common nutrient loading–trophic level relationships and existing theory on sediment–water interactions. Nutrient levels did not decrease or decreased only slightly. Phosphorus concentrations remained high because of phosphorus release from the sediments. Substantial release occurred from anoxic sediment surfaces as well as from sediments superimposed by well oxygenated water.

The problems caused by high internal phospho-
Loading increased the interest and research efforts in the mechanisms that govern the exchange of phosphorus between sediments and lake water. It has become evident that phosphorus exchange between sediment and water is a highly complex phenomenon and includes interrelated chemical, biological and physical processes. It has also become evident that phosphorus retention is highly variable between lakes, not only due to differing morphometry and water renewal rates, but also due to differences in background history regarding external phosphorus loading and differences in the edaphic characteristics of the drainage basin (reflected in varying occurrences of potential phosphorus binding particulates). In this article we shall summarize the general principles of phosphorus exchange between sediment and lake water, and concentrate on a treatment of the possible impact of biological, particularly microbial processes on phosphorus exchange across the sediment-water interface. One reason for doing so is that much of the work in this field is not included to any great extent in existing reviews. Secondly and more important, it has become increasingly evident that interactions between biological and abiotic processes are of great importance to phosphorus cycling between sediments and lake water.

Retention processes and distribution of phosphorus forms in lake sediments

Six major transfer mechanisms can be distinguished as regards the deposition of phosphorus in lake sediments. (i) Sedimentation of detrital phosphorus minerals derived from the watershed. A large proportion of this fraction consists of rapidly settling material and deposition thus occurs mainly in nearshore areas. (ii) Adsorption or precipitation of phosphorus with inorganic compounds. Williams & Mayer (1972) subdivide this mechanism into (a) phosphorus coprecipitated with iron and manganese, (b) adsorption (to clays, amorphous oxyhydroxides etc.) and (c) phosphorus associated with carbonates. (iii) Sedimentation of phosphorus with allochthonous organic matter. It should be emphasized, though, that metal (primarily iron) mediation might be highly significant for the association of phosphorus with allochthonous organic matter (cf. Young & Comstock, 1986). (iv) Sedimentation of phosphorus with autochthonous organic matter. (v) Direct uptake by assimilation of phosphorus from the water column by periphyton and other biota in surficial sediments. (Carignan, 1982; Carignan & Kalff, 1982; Riber, 1984). (vi) Direct adsorption of lake water dissolved phosphorus onto particles in the sediments. This mechanism might analytically be hard to distinguish from (ii) and from diagenetic and transfer processes within surface sediments.

Phosphorus retention in a lake is dependent on the sedimentation characteristics of particulate phosphorus carriers which depend on factors like lake morphometry, hydrological conditions such as water residence time, and the size and density of particles. For a more thorough review of these aspects we refer to Håkanson & Jansson (1983) who treat physical sedimentation processes in general, and to Sonzogni et al. (1982) who discuss the significance of different sedimentation rates of various particulate phosphorus carriers for actual phosphorus retention.

Differences between lakes in phosphorus retention patterns are reflected in the composition of sedimentary phosphorus. The fractional composition of sedimentary phosphorus is normally characterized using sequential chemical extractions and the fractions are normally operationally defined (Logan, 1982; Pettersson et al., 1988). The fractions obtained correspond neither to specific retention mechanisms nor to bindings to well defined sedimentary compounds. Yet, differences within and between lakes regarding dominant sedimentary phosphorus compounds and dominant retention processes can be demonstrated and indicated, respectively.

Pettersson (1986) demonstrated large variations in the fractional composition of phosphorus in different Swedish lake sediments in different edaphic regions and with different backgrounds regarding phosphorus loading from anthropogenic sources. The sediments investigated could