



Role of sediment and internal loading of phosphorus in shallow lakes

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Abstract

The sediment plays an important role in the overall nutrient dynamics of shallow lakes. In lakes where the external loading has been reduced, internal phosphorus loading may prevent improvements in lake water quality. At high internal loading, particularly summer concentrations rise, and phosphorus retention can be negative during most of the summer. Internal P loading originates from a pool accumulated in the sediment at high external loading, and significant amounts of phosphorus in lake sediments may be bound to redox-sensitive iron compounds or fixed in more or less labile organic forms. These forms are potentially mobile and may eventually be released to the lake water. Many factors are involved in the release of phosphorus. Particularly the redox sensitive mobilization from the anoxic zone a few millimetres or centimetres below the sediment surface and microbial processes are considered important, but the phosphorus release mechanisms are to a certain extent lake specific. The importance of internal phosphorus loading is highly influenced by the biological structure in the pelagic, and lakes shifting from a turbid to a clearwater state as a result of, for example, biomanipulation may have improved retention considerably. However, internal loading may increase again if the turbid state returns. The recovery period following a phosphorus loading reduction depends on the loading history and the accumulation of phosphorus in the sediment, but in some lakes a negative phosphorus retention continues for decades. Phosphorus can be released from sediment depths as low as 20 cm. The internal loading can be reduced significantly by various restoration methods, such as removal of phosphorus-rich surface layers or by the addition of iron or alum to increase the sediment's sorption capacity.

Introduction

Phosphorus availability is regarded as the most important factor for determining the water quality of lakes. Numerous studies have shown that high loading of phosphorus leads to high phytoplankton biomass, turbid water and often undesired biological changes. The latter includes loss of biodiversity, disappearance of submerged macrophytes, fish stock changes, and decreasing top-down control by zooplankton on phytoplankton.

In order to reverse the eutrophication of lakes, much effort has been made to reduce the external loading of phosphorus. Some lakes respond rapidly to such reductions (Sas, 1989), but a delay in lake recovery is often seen (Marsden, 1989; Jeppesen et al., 1991; van der Molen & Boers, 1994), one of the reasons being that phosphorus accumulated in the sediment during

the period of high loading needs time to equilibrate with the new loading level. Phosphorus release from the sediment into the lake water may be so intense and persistent that it prevents any improvement of water quality for a considerable period after the loading reduction (Granéli, 1999; Scharf, 1999).

Compared to deep lakes where a redox dependent accumulation of phosphorus occurs in the anoxic hypolimnion during stratification, shallow lakes are usually well mixed and oxidized throughout the water column. Nonetheless, the sediment of shallow lakes has often been demonstrated to release phosphorus to oxic lake water (Lee et al., 1977; Boström et al., 1982; Jensen & Andersen, 1992), suggesting that other factors than redox conditions at the sediment–water interface are involved. The importance of sediment–water interactions in shallow lakes is furthermore enhanced by the high sediment sur-

face:water column ratio, which means that the potential influence on lake water concentrations is stronger than in deeper lakes. The direct contact with the photic zone throughout the year and the regular mixing regime guarantee stable and near optimum conditions for primary production (Nixdorf & Deneke, 1995). Often the phosphorus pool in the sediment is more than 100 times higher than the pool present in the lake water, and lake water concentrations therefore depend highly on the sediment–water interactions.

In this paper we give a short review of the phosphorus retention in lake sediments and the mechanisms and factors suggested to be vital to phosphorus release from lake sediments. Our aim is to show that the sediment of shallow lakes is the domicile of numerous highly dynamic processes that may have very substantial effects on the total phosphorus budget and lake water quality.

Retention and phosphorus in the sediment

Retention of phosphorus

During steady state conditions a certain amount of the phosphorus entering a lake is retained in the sediment (Fig. 1). The retention percentage depends on the hydraulic retention time, as demonstrated through different simple, empirically established models of the Vollenweider type: $P_{\text{lake}} = P_{\text{in}} / (1 + tw^{0.5})$, relating in-lake phosphorus (P_{lake}) to inlet concentrations (P_{in}) and hydraulic residence time (tw) (Vollenweider, 1976; OECD, 1982). These models cannot, however, adequately describe the transient phase after reduced loading when the system is not in equilibrium and strongly influenced by the internal loading of phosphorus. The net retention of phosphorus is the difference between two processes with large opposite directed flux rates: (i) the downward flux caused mainly by sedimentation of particles continuously entering the lake or produced in the water column (algae, detritus etc.) and (ii) the upwards flux or gross release of phosphorus driven by the decomposition of organic matter and the phosphorus gradients and transport mechanisms established in the sediment. Phosphorus sedimentation from the lake water can be enhanced in productive lakes via co-precipitation with calcium carbonate (House et al., 1986; Driscoll et al., 1993; Golterman, 1995; Hartley et al., 1997).

The importance of internal loading of phosphorus during lake recovery is demonstrated by the finding

that phosphorus concentrations often increase during summer in shallow eutrophic lakes (Sas, 1989; Phillips et al., 1994; Welch & Cooke, 1995; Ekholm et al., 1997). In most cases this increase can only be the result of increased sediment loading, implying that summer phosphorus concentrations are largely controlled by internal processes (Jeppesen et al., 1997; Ramm & Scheps, 1997; Kozerski & Kleeberg, 1998). The most pronounced impact is often found in the most eutrophic lakes in which summer concentrations typically exceed winter concentrations by 200–300% from June until October (Søndergaard et al., 1999).

Mass balance calculations have shown that phosphorus retention exhibits a seasonal pattern mimicking the seasonal variation in lake water phosphorus. In a study of 16 Danish lakes, Søndergaard et al. (1999) showed that the retention was positive during winter irrespective of the eutrophication level, while it was negative during part of the summer. Even lakes with a phosphorus concentration below 0.1 mg P l^{-1} had a 2-month negative retention in mid-summer, but the duration of negative retention increased to 5 months in lakes with a mean summer phosphorus concentration above 0.2 mg P l^{-1} . In the most eutrophic lakes, a strongly negative retention occurred in May, suggesting that the onset of the increasing biological activity in spring triggered the release of some of the phosphorus retained during winter. In early summer retention was found to be less negative owing to the occurrence of a clearwater phase following late-spring development of a high zooplankton biomass and its grazing on phytoplankton (Sommer et al., 1986; Luecke et al., 1990; Jeppesen et al., 1997; Blindow et al., 2000).

Forms of phosphorus in the sediment

When entering the sediment, phosphorus becomes a part of the numerous chemically and biologically mediated processes and is ultimately either permanently deposited in the sediment or released by various mechanisms and returned in dissolved form to the water column via the interstitial water. It should be emphasized, however, that lake sediments can be very different and highly variable regarding chemical composition. Parameters such as dry weight, organic content, and content of iron, aluminum, manganese, calcium, clay and other elements with the capacity to bind and release phosphorus may all influence sediment–water interactions (Søndergaard et al., 1996).

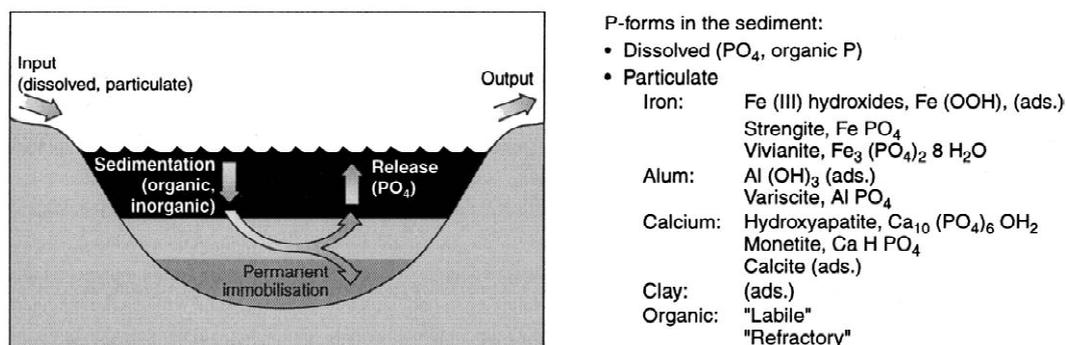


Figure 1. Schematic presentation of phosphorus pathways when entering a lake and some of the most important phosphorus compounds found in the sediment (from Søndergaard et al., 2001). Adsorbed phosphorus is indicated by ads.

Chemical sequential extractions have been widely used in order to describe the many different forms in which phosphorus occurs in the sediment (Williams et al., 1971; Hieltjes & Lijklema, 1980; Psenner et al., 1988; Golterman & Booman, 1988). The aim is often to give a more precise description of the potentials for phosphorus release from the sediment and to predict its future influence on lake water concentrations (Lijklema, 1993; Seo, 1999). By fractionation phosphorus is characterized as being bound to the variety of inorganic sediment components as described above (Stumm & Leckie, 1971; Boström et al., 1982) or in organic phosphorus compounds. Organically bound phosphorus occurs in more or less labile forms or in a refractory form that is not released during mineralization and which constitutes a fraction permanently buried in the sediment. Fractionation schemes usually yield operationally defined fractions, but it may be debated which type of sediment phosphorus the different fractionations actually measure (Pettersson et al., 1988; Jáugeui & Sánchez, 1993). Often, loosely sorbed organic and inorganic fractions as well as the iron-bound and redox-sensitive sorption of phosphorus are considered potentially mobile (Boström et al., 1982; Søndergaard, 1989; Søndergaard et al., 1993; Rydin, 2000). Petticrew et al. (2001) found a close connection between total phosphorus release rates and the iron-bound phosphorus components in the sediment, and during lake recovery, this fraction can constitute a majority of the phosphorus released (Fig. 2). While fractionation schemes may provide relevant information on the overall and long-term conditions for phosphorus sorption expected to prevail in the sediment, it has been difficult so far to establish general relationships between phosphorus forms and the intensity and duration of internal

loading. Knowledge coupling the mechanisms behind internal loading with sediment characteristics seems inadequate (Phillips et al., 1994; Welch & Cooke, 1995).

Importance of biological structure

The biological structure of a lake can significantly influence its phosphorus concentrations and retention (Beklioglu et al., 1999). For example, clearwater conditions resulting from increased top-down control on phytoplankton often ensure considerably lower in-lake nutrient concentrations (Søndergaard et al., 1990; Benndorf & Miersch, 1991; Nicholls et al., 1996). A positive relationship between clearwater conditions and increased phosphorus retention was documented by the changes recorded in Danish Lake Engelsholm after biomanipulation involving a 66% removal of the fish stock (Søndergaard et al., 2002a). Here, decreased turbidity led to significantly lower phosphorus concentrations and higher phosphorus retention. Furthermore, the period with negative retention during summer was reduced from 6 to 4 months. The annual net retention changed from -2.5 to $+3.3$ g phosphorus $\text{m}^{-2} \text{y}^{-1}$. These observations indicate that if a lake returns to a turbid state after being clear for some years, it has the risk of suffering from a high internal loading again. It also suggests that when biomanipulation is considered to improve lake water quality after a loading reduction it might be advantageous to wait for some years until the influence of internal phosphorus loading is reduced.

Several mechanisms are probably involved in the increased phosphorus retention when the clearwater state is achieved. These include the reduced sedimentation of organic matter, which again reduces oxygen

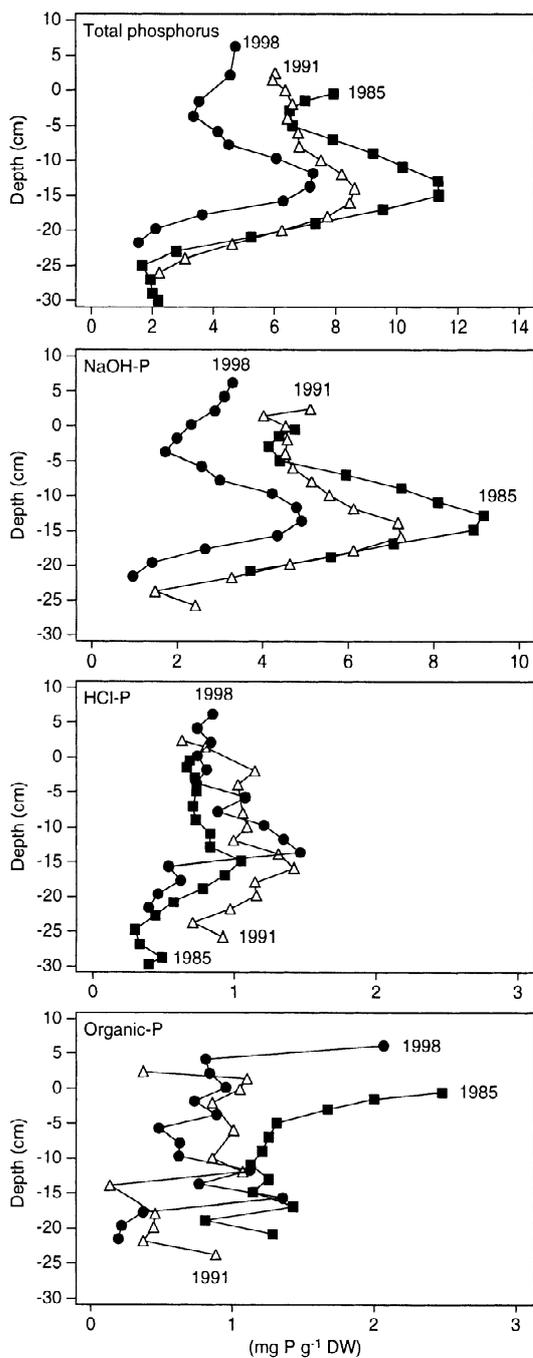


Figure 2. Changes in sediment phosphorus profiles of hypertrophic Lake Søbygaard, Denmark, during recovery (measured in 1985, 1991 and 1998). The external phosphorus loading to the lake was reduced by 80–90% in 1982. Fractionation was conducted according to Hieltjes & Lijklema (1980). Organic-P was calculated as Tot-P – (NH₄Cl-P+NaOH-P+HCl-P). After 20 years the annual retention of phosphorus is still negative, and the total recovery period is estimated to last more than 30 years after the loading reduction. The upper panel is from Søndergaard et al. (1999) and is reprinted with kind permission from Kluwer Academic Publishers.

consumption and prevents low redox conditions. In addition, the improved light conditions enhance benthic primary production and with it the phosphorus uptake and oxidation of the sediment surface (van Luijn et al., 1995; Woodruff et al., 1999). If submerged macrophytes become abundant they assimilate phosphorus, but may also effect the retention in other ways (see below). Benthivorous fish as for example bream (*Abramis brama*) have a significant impact on the re-suspension of sediment (Breukelaar et al., 1994) as well as on the concentration of phosphorus and its release from the sediment (Havens, 1991; Søndergaard et al., 1992). A reduction in their abundance may be a factor of particular importance in biomanipulated lakes formerly dominated by bream or other benthivorous species (Persson et al., 1993; Hansson et al., 1998). Fish-mediated phosphorus release from the sediment is sometimes believed to be stronger and more important for lake water quality than that achieved through reduced planktivory and top-down control on phytoplankton (Havens, 1993; Horppila et al., 1998).

Duration of internal loading

The duration and importance of internal loading relate mainly to the flushing rate, loading history and chemical characteristics of the sediment (Marsden, 1989). Some lakes respond rapidly to an external loading reduction by an immediate or only shortly delayed decline in lake concentrations following the changes in loading (Edmonson & Lehman, 1981; Sas, 1989; Welch & Cooke, 1995; Beklioglu et al., 1999). A fast response may be ensured by a high flushing rate provided that the period with high phosphorus loading was relatively short. On the other hand, a long loading history with a high loading rate is reflected in the size of the phosphorus pool accumulated in the sediment, and, if large, a rapid flushing rate may not suffice to ensure a fast return to low concentrations (Jeppesen et al., 1991).

The sediment depth interacting with the lake water is probably lake specific and highly dependent on lake morphology, sediment characteristics and wind exposure. Most often, phosphorus in the upper approximately 10 cm is considered to take part in the whole lake metabolism (Boström et al., 1982), but mobility of phosphorus from depths down to 20–25 cm has been seen (Fig. 2, Søndergaard et al., 1999). The internal phosphorus loading may be very persistent and endure at least 10 years after an external loading re-

duction has been effected (Welch & Cooke, 1999). In some lakes, phosphorus retention can remain negative even for 20 years or more after the nutrient loading reduction (Søndergaard et al., 1999).

Release mechanisms

Numerous mechanisms have been proposed to be responsible for the release of phosphorus from lake sediments. In the following we will give a short review of some of the most important bearing in mind, however, that one should be careful when generalising and that the phosphorus release can be governed by very different mechanisms in different lakes.

Resuspension

In shallow lakes, wind-induced resuspension is a mechanism that frequently causes increased concentrations of suspended solids in the lake water. Particulate bound forms of phosphorus settling to the bottom may be resuspended several times before permanent sedimentation (Ekholm et al., 1997). In very shallow lakes, resuspension events increase, more or less continuously, the contact between sediment and water (Kristensen et al., 1992; Hamilton & Mitchell, 1997). An example is shown in Figure 3 from a shallow Danish lake in which suspended solids and total phosphorus increased by a factor 5–10 within a few days during two events of increasing wind. In some shallow lakes, year-to-year variation in internal phosphorus loading has been shown to be largely controlled by wind mixing (Jones & Welch, 1990).

Resuspension increases turbidity, but does not necessarily lead to increased release of phosphorus. This is because the overall process depends on the actual equilibrium conditions between sediment and water and on the capability of phytoplankton to take up phosphorus (Søndergaard et al., 1992; Ekholm et al., 1997; Hansen et al., 1997). In the example from Lake Vest Stadil Fjord (Fig. 3), there was no or only a very slight persistent increase in total phosphorus concentrations after the wind events. In other lakes it has been shown that resuspension increases release rates (Fan et al., 2001), or at least during some parts of the season may cause a release, while there may be no effect later in the season due to changed concentrations in the lake water (Søndergaard et al., 1992). From measurements in a shallow Finnish lake, Horppila & Nurminen (2001) concluded that in early summer, the

concentration of suspended solids had a highly significant positive effect on soluble reactive phosphorus concentrations in the water, whereas in late summer no effect was found.

Temperature

Temperature reflects many of the biologically mediated processes in the lake. The pronounced seasonality in internal loading and retention capacity strongly indicates that the release mechanisms are linked to temperature and biological activity (Jensen & Andersen, 1992; Boers et al., 1998; Søndergaard et al., 1999). These include stimulation of the mineralization of organic matter, the release of inorganic phosphate with increasing temperatures (Boström et al., 1982; Jeppesen et al., 1997; Gomez et al., 1998), and increased sedimentation of organic material related to the seasonal variation in phytoplankton productivity (Ryding, 1981; Istvánovics & Pettersson, 1998).

As organic loading increases during spring and mineralization processes are strengthened, the penetration depth of oxygen and nitrate into the sediment declines (Tessenow, 1972; Jensen & Andersen, 1992). Jensen and Andersen (1992) observed that the temperature effect on phosphorus release was strongest in lakes with a large proportion of iron-bound phosphorus. They also noticed a decrease in the thickness of the oxidised surface layer with increasing temperatures, suggesting a redox-sensitive release. The thickness of the top oxic sediment can thereby influence the concentration of phosphorus in the whole water body (Gonsiorczyk et al., 2001).

Redox

Redox conditions in the surface sediment are the classical explanation of sediment water interactions. Einsele (1936) and Mortimer (1941) very early described how the phosphorus release was determined by redox-sensitive iron dynamics. In oxidised conditions, phosphorus is sorbed to iron (III) compounds, while in anoxia iron (III) is reduced to iron (II) and subsequently both iron and sorbed phosphate returned into solution. In shallow lakes the whole water column is usually oxic, which also establishes an oxic surface layer of the sediment with a high capacity to bind phosphorus. In agreement herewith, Penn et al. (2000) suggested that an oxidized microlayer at the sediment–water interface partially inhibits sediment phosphorus release under well-mixed conditions in spring and au-

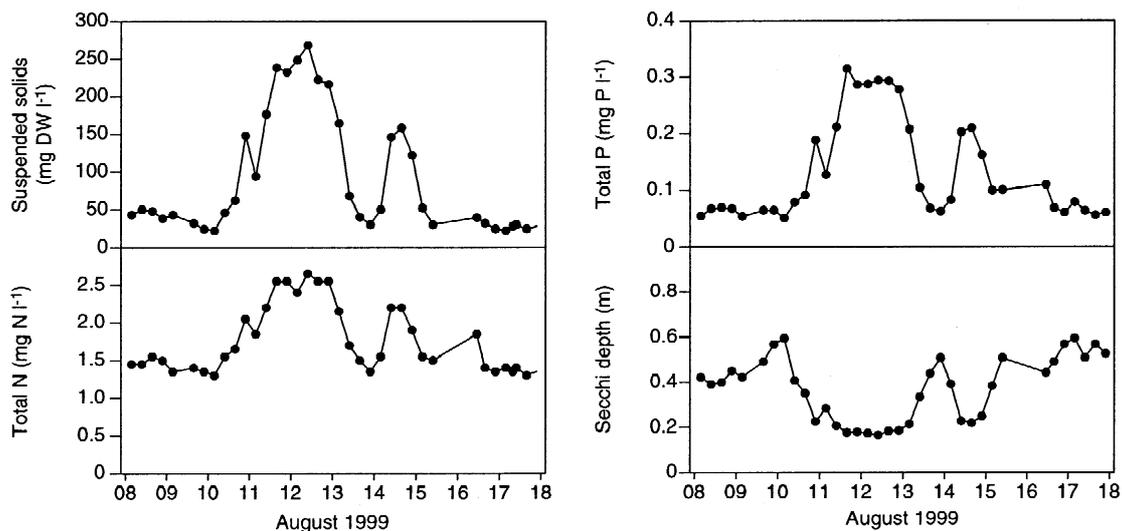


Figure 3. Lake water changes in Lake Vest Stadil Fjord, Denmark, during 10 days of varying wind speed (from 0–2 to 5–7 to 2–3 m s^{-1}). Lake area is 450 ha and mean depth 0.8 m.

tumn. On the other hand, phosphorus trapped in the oxic microlayer can be freed when the microlayer is chemically reduced at the onset of anoxia. Then, high phosphorus release rates are observed. In this way, the oxidized microlayer may serve to regulate seasonality in rates of sediment phosphorus release, but does not influence long-term sediment–water exchange. If the oxic surface layer becomes saturated with phosphorus, phosphorus transported upwards from deeper sediment layers may simply pass through the oxic layers into the water column.

The presence of nitrate, which normally penetrates deeper into the sediment than oxygen and, like oxygen, has the capability to keep iron in its oxidised form, can also be important for the redox sensitive sorption of phosphorus (McAuliffe et al., 1998; Duras & Hejzlar, 2001). For example Kozerski et al. (1999) found that high summer phosphorus release rates were related to low nitrate input to Lake Müggelsee. In contrast, Jensen et al. (1992) showed that the presence of nitrate during winter and early summer diminished the release rates, whereas nitrate addition in late summer enhanced the phosphorus release in the same lakes, probably by stimulating the mineralization process.

pH

pH is particularly important in lake sediments where the capacity to retain phosphorus depends on iron, because the phosphorus binding capacity of the oxy-

genated sediment layer decreases with increasing pH as hydroxyl ions compete with phosphorus ions (Lijklema, 1976). The impact of pH on release has been illustrated by Koski-Vahala and Hartikainen (2001), who demonstrated that high pH, which is common in eutrophic lakes during summer, may markedly increase the internal phosphorus loading risk when linked with intensive resuspension. In the sediment of eutrophic lakes, photosynthetically elevated pH can establish more phosphorus, which is loosely sorbed to iron, and thus increase release rates (Lijklema, 1976; Søndergaard, 1988; Welch & Cooke, 1995; Istvánovics & Pettersson, 1998).

Iron:phosphorus ratio

The combined ferric oxides and hydroxides available in the sediment may bind phosphate very effectively. The involvement of iron in the dynamic equilibrium between the sediment and water has led to the suggestion that an iron dependent threshold exists for the sediment's ability to bind P. Jensen et al. (1992) showed that the retention capacity was high as long as the Fe:P ratio exceeds 15 (by weight), and when above this ratio internal phosphorus loading may be prevented by keeping the surface sediment oxidised. Caraco et al. (1993) suggested that the Fe:P ratio should exceed 10 if it was to regulate phosphorus release. The presence of a threshold is supported by the strong positive relationship between the concentra-

tions of phosphorus and iron in the surface sediment of shallow lakes (Søndergaard et al., 2001). In hardwater lakes, iron may be less important for the phosphorus release compared to the solubilisation of apatite due to decreased pH during mineralization (Golterman, 2001). Yet, it has been suggested that even in calcareous systems, iron and aluminium, when present in high concentrations, are involved in regulating the phosphorus cycling (Olila & Reddy, 1997).

Chemical diffusion and bioturbation

The interstitial water of the sediment, which normally contains less than 1% of the sediment's total phosphorus pool, is important for the phosphorus transport between sediment and water as interstitial phosphate constitutes the direct link to the water phase above and the solid-liquid phase boundary between water and sediment (Boström et al., 1982; Löfgren & Ryding, 1985). An upward transport of phosphorus is created via a diffusion-mediated concentration gradient, normally appearing just below the sediment surface.

Bioturbation from benthic invertebrates or through gas bubbles produced in deeper sediment layers during the microbial decomposition of organic matter may significantly enhance the process (Ohle, 1958, 1978; Fukuhara & Sakamoto, 1987). There is some evidence that bioturbation from benthic chironomids can enhance phosphorus release rates, particularly in sediments low in total iron (Phillips et al., 1994). Benthic invertebrates can also inhibit phosphorus release by supplying oxic water into the sediment and increasing the oxidised surface layer of the sediment (Boström et al., 1982). Similarly, low phosphorus flux rates can be recorded despite a steep interstitial water gradient, provided that the top centimetres of the sediment either have a high phosphorus sorption capacity (Moore et al., 1998), or its chemical processes are controlled by a photosynthetically active biofilm (Woodruff et al., 1999).

Mineralization and microbial processes

In shallow and eutrophic lakes, the sediment continuously receives high amounts of freshly produced organic material that is not decomposed before reaching the sediment. Thus, sediment bacteria may have a significant role in the uptake, storage and release of phosphorus (Pettersson, 1998). High organic input creates the potential for a high mineralization rate, provided that the supply of oxidizers such as oxygen or

nitrate is sufficient. Subsequently, the typical sediment profile will have oxygen penetrating a few millimetres into the sediment, followed by nitrate which can be found several centimetres into the sediment depending on the decomposition rate and the nitrate input.

If nitrate concentrations are low, but sulphate levels and the supply of biodegradable organic matter high, desulphurication and sulphur cycling may become important parts of the sediment processes (Holmer & Storkholm, 2001). Hydrogen sulphide formed from sulphate reduction induces the formation of iron sulphide and decreases the potential of phosphorus sorption and thereby the potential phosphorus release from the sediment (Ripl, 1986; Phillips et al., 1994; Kleeberg & Schubert, 2000; Perkins & Underwood, 2001). The internal, dynamic P-release from lake sediments may thereby be determined by the ligand exchange of phosphate against sulphide with iron. During winter, low sedimentation rates and sufficient supply of oxygen or nitrate to the sediments establish a high redox potential, maintaining the sedimentary iron in its oxidized form.

Submerged macrophytes

In shallow lakes, submerged macrophytes have the potential of being very abundant with a high plant-filled volume. Macrophytes may, however, influence the phosphorus cycle both negatively and positively. Decreased release is seen when oxygen released from the roots increases the redox-sensitive phosphorus sorption to iron-compounds (Andersen & Olsen, 1994; Christensen et al., 1997), and when high abundance of macrophytes diminishes the resuspension rate and reduces the phosphorus release from the sediment (Granéli & Solander, 1988; Van den Berg et al., 1997). Increased phosphorus release may be recorded in dense macrophyte beds and beneath macrophyte canopies due to low oxygen concentrations (Frodge et al., 1991; Stephen et al., 1997), or due to increased pH (James et al., 1996). From experiments and measurements in the Broads in U.K., Stephen et al. (1997) concluded that if rooted macrophytes have a significant effect on phosphorus release they increase it. Barko & James (1997) have given a comprehensive review of the effects of submerged aquatic macrophytes on nutrient dynamics, sedimentation and resuspension.

Concluding remarks

Because of their strong impact on lake water concentrations, it is clear that knowledge of sediment–water interactions and the processes behind retention and release of phosphorus is fundamental for understanding the function of shallow lakes. Many different mechanisms may be involved in the sediment release, but two types are often of particular importance: (i) redox-dependent release of phosphorus bound to iron and (ii) microbial processes. The redox-dependent release mechanism is also relevant in well-mixed eutrophic lakes with an organic-rich sediment. Here, the oxic surface layer is often too thin to prevent a release from deeper parts of the sediment. Microbial processes being fuelled by degradable matter accumulated in the sediment or sediment settling from the lake water, together with the supply of oxidizers (oxygen, nitrate and sulphate), are important for the cycling of phosphorus.

Presently, we do not have sufficient knowledge to develop general models for the release mechanisms of shallow lakes, descriptions that could be used as a predictive tool in lake management following a nutrient loading reduction. More clear relationships between easily measurable sediment characteristics and net release rates of phosphorus have to be established. It should also be noted that phosphorus release mechanisms to some extent are lake specific: resuspension being important particularly in very shallow and wind-exposed lakes, redox-sensitive release in iron-rich systems, etc.

In order to combat internal phosphorus loading and accelerate lake recovery after decreased external loading, numerous lake restoration techniques have been developed and tested (Dunst et al., 1974; Born, 1979; Cooke et al., 1993; Phillips et al., 1999; Welch & Cooke, 1999; Søndergaard et al., 2000; Perkins & Underwood, 2001). They comprise both physical measures, such as sediment dredging by which nutrient rich sediment is removed, as well as chemical methods. The chemical methods aim to influence the redox-dependent phosphorus fixation by either improving the sorption capacity of the elements already present in the lake/sediment or by adding new sorption capacity, as for example iron, alum or calcium (Søndergaard et al., 2002b). For all types of restoration measures, an important prerequisite for obtaining success and long-term effects is elimination of the underlying reasons for the impoverished water quality, i.e. a sufficient reduction of the external phosphorus loading (Benndorf,

1990; Jeppesen et al., 1990; Hansson et al., 1998; Søndergaard et al., 2000).

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