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PRIMARY RESEARCH PAPER

Sediment resuspension: rescue or downfall of a thermally stratified eutrophic lake?

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Abstract The aim of this study was to estimate the effect of sediment resuspension, a common phenomenon in many lakes, on the phosphorus budget of a eutrophicated lake. We used two different approaches, mass balance calculations and spatially comprehensive resuspension measurements, to determine the level of phosphorus loading from which rehabilitation action is started in a dimictic north temperate lake. The effect of resuspension was assumed to be significant, since it often is a governing process for cycling of material in lakes. Internal loading was multifold to that of external loading as determined by the budget calculation. Spatially comprehensive sedimentation and resuspension measurements were necessary, since deep site versus spatially comprehensive measurements had a marked difference in their results. Resuspension of P slightly exceeded the internal loading assessed by budget calculations and thereby proved its significance as a governing in-lake process that influences P cycling strongly. The shallow areas were of importance, since most of the total P load originated from there. The fate of P after resuspension depends on the retention capacity of resuspended particles in addition to prevailing biological and physico-chemical conditions. Therefore, sediment resuspension can either strengthen or diminish internal nutrient load and the processes of the shallow zones are of importance.

Keywords Sediment resuspension · Phosphorus budget · Internal phosphorus loading

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Introduction

Particles that settle at a lake bottom can originate from primary production, or resuspension of particles from the sediment and from an inflow of allochthonous material (Weyhenmeyer, 1996). These processes together with atmospheric precipitation, sedimentation, and outflow (OF) of particles in addition to sediment–water exchange of phosphorus determine the total phosphorus (TP) concentration of a water column. Therefore, they can be used for P-budget calculation for a lake. The extent of internal loading can be assessed by comparing the changes in the water column phosphorus storage to inputs and outputs (Ekholm et al., 1997). Therefore, nutrient budgets can provide important data on the large variety on lakes (Nõges et al., 1998). The mechanisms behind internal loading may be identified by observing the prevailing environmental conditions at the moment of nutrient release (Andersen, 1982). This is important, since the budgets alone give no insight into particular processes that may be significant for nutrient cycling. Combining the budget calculations with sedimentation measurements enables the quantification of both the downward and upward fluxes of nutrients (Nõges et al., 1998).

Sedimentation is one of the important processes that govern lake metabolism (Darnell, 1964; Bloesch et al., 1977; Bloesch & Uehlinger, 1986). Resuspension of the settled matter is often the main process that generates particles into a water column, and therefore resuspended material also represents most of the total settling flux in many lakes (Evans, 1994; Weyhenmeyer, 1998). The rates of sedimentation and sediment resuspension are usually not constant within a lake and may be characterized by large temporal and spatial variations (Rosa, 1985; Bloesch & Uehlinger, 1986). Gross sedimentation and resuspension rates are often higher in shallow areas than in deep water zones, due to sediment disturbance, which are caused by waves and water currents (Bloesch, 1982; Evans, 1994). Sediment resuspended in shallow areas is often transported into deeper water zones where it is deposited. This phenomenon is called sediment focusing (Ohle, 1962). In deep stratified areas, internal seiches can be the main factor behind resuspension (Horppila & Niemistö, 2008). Regardless of the mechanism behind the resuspension event that brings the sedimentary particles into a water column and transports them into different areas, the effect of resuspension on nutrient cycling can be significant (de Groot, 1981; Kristensen et al., 1992; Søndergaard et al., 1992; Koski-Vähälä et al., 2001; Das et al., 2009; Shinohara & Isobe, 2011). However, the significance is strongly case dependent and thus positive, negative, and also negligible effects of resuspension on P cycling have been reported (de Groot, 1981; Lennox, 1984; Peters & Cattaneo, 1984; Søndergaard et al., 1992, 2001; Vicente et al., 2010).

From the management point of view, it is important to know the magnitude and different sources of loadings. The budget calculations give information on the magnitude of external loading in relation to internal loading (Ekholm et al., 1997; Moosmann et al., 2006), whereas the sedimentation and resuspension measurements illuminate the role of the most important in-lake processes for the nutrient cycling in many lakes (Kristensen et al., 1992; Søndergaard et al., 1992; Evans, 1994). Therefore, in this study, the P-budget calculations and the resuspension calculations of a dimictic north temperate lake were compared. We quantified the internal phosphorus loading for a eutrophicated lake for these two different approaches which were conducted spatially comprehensively before the rehabilitation actions.

Materials and methods

Study area

The Enonselkä basin of Lake Vesijärvi in southern Finland (61°01′N, 25°35′E) is a fairly restricted basin with a surface area of 26 km^2 and a mean depth 6.8 m (Fig. 1). Due to the shallowness of the basin, most of its sediment is in direct contact with epilimnetic water (depth <10 m) during the stratification period (May–September) (Fig. 1). Originally, a clear water basin underwent eutrophication due to sewage effluent that emanated from the city of Lahti that surrounds the lake basin (Keto & Sammalkorpi, 1988). In the 1980s, massive cyanobacteria blooms degraded the water quality of the basin and therefore biomanipulation measures were implemented, along with diffuse load reduction, as restoration actions in the late 80s and early 90s (Kairesalo et al., 1999). Water quality improved, but within 10 years, cyanobacteria blooms had occurred again (Keto et al., 2005). Today, the TP concentration varies from the epilimnetic value of 20 up to 160 μg l^{-1} in the hypolimnion. The respective variation for soluble reactive phosphorus is from 2 to 55 μg l^{-1}. Strong blooms and high pH (8–9) of the water occur every summer, and hypolimnion is depleted in O_2 during stratification periods. In order to cut down the internal loading and accumulation of soluble P into hypolimnion, aeration was implemented at the beginning of 2010 and it was the main restoration action in the Enonselkä basin. In addition to hypolimnetic aeration, cyprinid fish removal (20 kg ha^{-1} a^{-1}) was also carried out as a P load reducing measure.

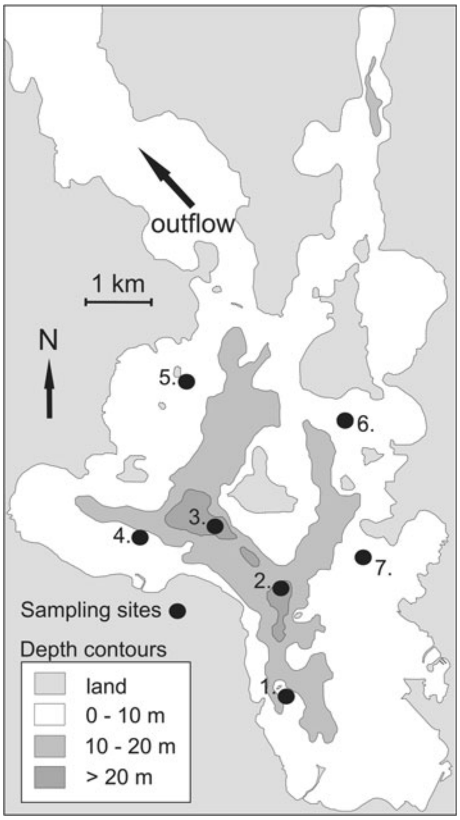

Fig. 1 Enonselkä basin of Lake Vesijärvi. Sampling sites 1–7 and depth contours

Sedimentation and resuspension

Gross sedimentation was measured at seven sites (Fig. 1) with four replicate cylindrical sediment traps (diameter = 5.4 cm, $h = 41$ cm) suitable to lake conditions (Bloesch & Burns, 1980) deployed at 2 m above the lake bottom. The shallow sites (depth <10 m) were 1, 4, 5, 6, and 7. In contrast, the respective depths of site 2 was 30 m and that of site 3 was 28 m. The traps were kept in the lake from 15 May to 4 November and emptied at 14–21 day intervals. The dry weight (dw) of entrapped material was measured after drying samples at 60°C for approximately 3 days and the organic fraction determined by loss on ignition at 550°C for 2 h.

Sediment resuspension was calculated according to the method by Weyhenmeyer (1997). The inflow of allochthonous particulate matter into Lake Vesijärvi is negligible (Liukkonen et al., 1997; Koski-Vähälä et al., 2000). Therefore the method of Weyhenmeyer (1997) is applicable for the determination of the amount of resuspended sediment in the settling flux. The method assumes that the main sources of settling particulate matter (SPM) are the sediment resuspension and new production. A linear regression between settling particulate organic matter (SPOM) and settling particulate inorganic matter (SPIM) value was established to quantify the amount of resuspended particulate matter in the sedimentation traps as follows:

$$\mathrm{SPOM} = k * \mathrm{SPIM} + \mathrm{intercept}\ \left(\mathrm{g\,dw\,m^{-2}\,day^{-1}}\right),$$

from where the rate of resuspension R is $R = \mathrm{SPM} - \mathrm{intercept}\ \left(\mathrm{g\,dw\,m^{-2}\,day^{-1}}\right)$, intercept of the SPOM/SPIM regression line and y-axis = the amount of newly produced suspended particulate organic matter, k = slope of the regression line

$$\mathrm{SPM} = \text{gross sedimentation}\ (= \mathrm{SPIM} + \mathrm{SPOM}) \times \left(\mathrm{g\,dw\,m^{-2}\,day^{-1}}\right)$$

The resuspension of phosphorus was calculated by multiplying the mean P concentration of surface sediment with the resuspension rate at each sampling location (Horppila & Nurminen, 2003).

Phosphorus budget calculations

The mean internal load (IL) of P for the ice-free period of year 2009 was calculated with the mass balance model as follows (Lappalainen & Matinvesi, 1990; Ekholm et al., 1997):

$$\mathrm{IL} = \mathrm{OF} + \mathrm{GS} + \mathrm{d}m/\mathrm{d}t - \mathrm{EL}\ \left(\mathrm{mg\,P\,m^{-2}\,day^{-1}}\right),$$

IL is the internal P load, EL the external P load, OF the outflow of P, GS the gross sedimentation of P, and dm/dt is the storage change of P in the water column.

Values for the external load (EL) (point source load sampled weekly, the diffuse load of different land use modeled, and the atmospheric precipitation taken into account) and the OF of P (fish removal included) were received from the Environmental Services of City of Lahti. The gross sedimentation of P was calculated by multiplying the mean GS rate and the mean P concentration of entrapped material at each sampling site.

The IL was calculated using the GS data only from the deepest site (no. 2) in addition to using the data from of all the seven sites (Fig. 1). The lake area was divided into shallow (depth <10 m, unstratified, aerobic water column) and deep areas (depth 10–30 m, stratified

June–September, suboxic/anoxic hypolimnion) when assessing the amount of loading that comes from the different areas. Shallow areas constituted 83% and deep areas 17% of the total lake area. The spatially comprehensive season average of GS was calculated as follows: average rate of shallow sites × coverage + average rate of deep sites × coverage.

Water samples were collected for determination of TP by a tube sampler (height 1 m, volume 7.5 l). In shallow stations (1, 4–7), samples from each meter of depth were combined before taking subsamples. In deep stations (2 and 3), the samples were combined to three separate layers; epilimnion (0–10 m), metalimnion (10–20 m), and hypolimnion (20 m–bottom). The concentration of TP was analyzed from each sample according to the method of Koroleff (1979) (Lachat QuickChem 8000 autoanalyzer).

Phosphorus and iron concentration of entrapped material and surface sediment

Surface sediment samples (topmost 0–1 cm) were collected with a HTH-gravity corer (diameter 90 mm) (Renberg & Hansson, 2008). The phosphorus concentration of entrapped material and surface sediment (samples dried at 60°C) was measured using inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo Scientific iCAP 6000) after wet digestion with nitric acid and hydrogen peroxide in the microwave digestion system (CEM Mars 5). The sample extract was moved into a 50 ml volumetric flask with purified water (Milli-Q). The quantitation was made by using external calibration curve fitted with five different concentrations. P was analyzed at wavelengths 177.4, 178.2, 178.7, and 213.6 nm, and iron (surface sediment) by wavelengths 238.2, 239.5, and 259.9 nm by the radial mode. The results were calculated as a mean. All determinations were made in duplicate. The correctness of the results was verified by using known in-house reference samples in determinations. Moreover, the sedimentary Fe/P ratios for each site were calculated, since it may indicate the P retention capacity of the sediment in aerobic conditions (Jensen et al., 1992).

Statistical analysis

The differences in the GS and R between the sampling sites, exposure periods, and depth areas were analyzed using analysis of variance for repeated measurements (ANOVAR) (SAS Institute Inc., 1990). Before the analyses, the normality of the datasets was verified with the Shapiro–Wilk test and the data were log-transformed when necessary.

Results

Gross sedimentation and resuspension

The gross sedimentation rates varied greatly in the Enonselkä basin during the open water season 2009. The rates varied between 2.8 and 65 g dw m^{-2} day^{-1} and the lowest rates were measured in spring and early July in the shallow stations ($p < 0.001$) and the highest rates in late June and autumn in the deep stations 2 and 3 ($p < 0.001$) (Fig. 2). Seasonal average rates for the different stations varied between 8 and 28 g dw m^{-2} day^{-1}. Spatially comprehensive (shallow areas coverage 83% and deep areas 17%) average was 13.8 g dw m^{-2} day^{-1}.

The regression between SPIM and SPOM was statistically significant ($p < 0.001$, $R^2 = 0.97$) (Fig. 3). The intercept of linear regression line and *y*-axis was 0.25 (g dw m^{-2} day^{-1}) when the data of all sampling periods were pooled. With the data of each trap exposure period (intercepts varied between 0.06 and 0.64 g dw m^{-2} day^{-1} being highest in May and August), we calculated the sediment resuspension rate that followed the seasonal pattern of the gross sedimentation constituting from 89.0 to 99.6% of that in all the sampling sites.

Gross sedimentation and resuspension of phosphorus

The P concentration of entrapped material varied between 1.79 and 2.57 mg g^{-1} and the highest values were measured in the deep stations (Table 1). Gross sedimentation rates of P (GS) varied from 5.0 to 160 mg m^{-2} day^{-1} (rates as dw multiplied by the concentration of P in each trap). The rates were highest in the deep sites in which both the P concentration of the entrapped material and the gross sedimentation rate as dw were at their highest.

In order to get a reliable value of the gross sedimentation rate of P (GS) for the budget calculation, the coverage of different depths was taken into account. Spatially comprehensive season average value of GS was

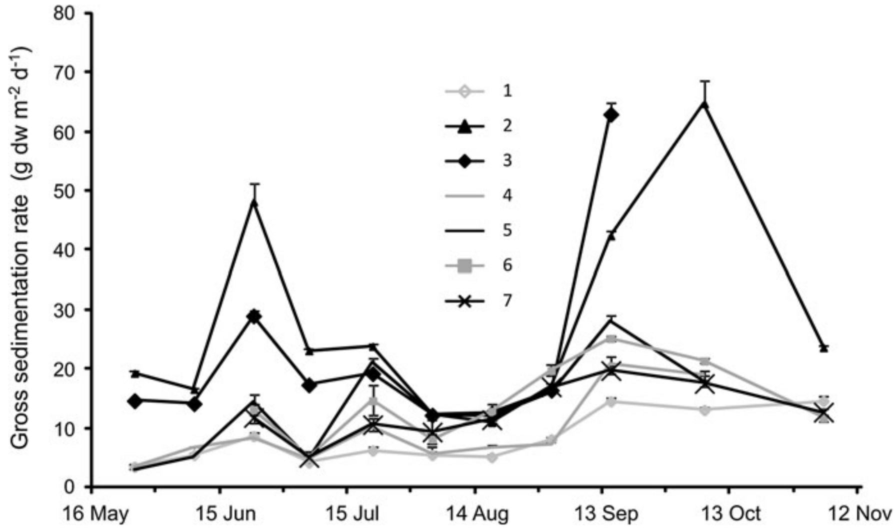

Fig. 2 Gross sedimentation rates during open water season 2009 at sites 1–7 in the Enonselkä basin (+95% conf. limits)

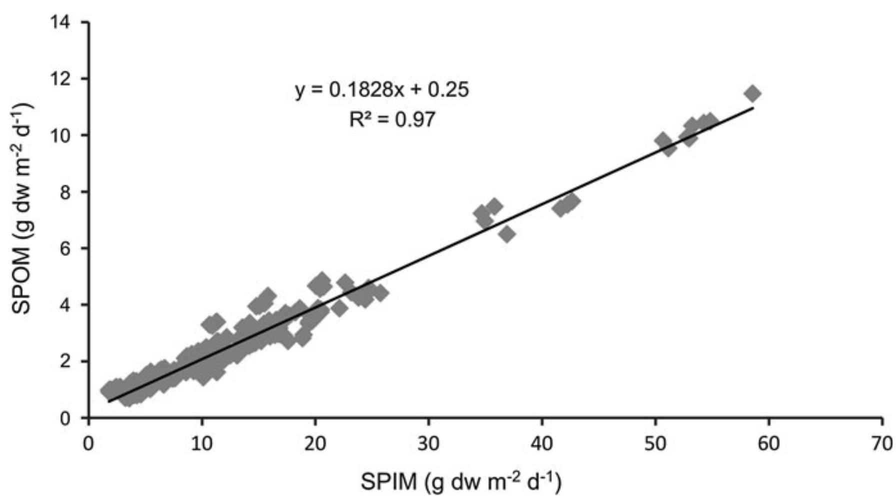

Fig. 3 The linear regression between settling particulate inorganic matter (SPIM) and settling particulate organic matter (SPOM)

27.99 mg P m^{-2} day^{-1} (Table 2). When only the data of the deepest site (no. 2) was used, the GS increased to the value 67.71 mg P m^{-2} day^{-1} (Table 2).

The P concentration of the surface sediment varied between 1.67 and 2.98 mg g^{-1}. The highest values were obtained in the shallow site seven and also in the deep sites (Table 1). The Fe/P ratios varied from 17 to 23. It was lowest in the deep sites and the shallow site seven. The resuspension rate of P (the rate of resuspension multiplied by the P concentration of the surface sediment measured at each site at each sampling time) varied between 3.8 and 168 mg P m^{-2} day^{-1}. The spatially comprehensive season average was 28.62 mg P m^{-2} day^{-1} (the sum of the rate in deep and shallow areas in Table 3) (Fig. 4). Scaled up to the whole lake, 67% of the resuspended P came from the shallow areas (depth <10 m) during the open water season (Table 3).

Mass balance calculations for P

The EL of P to the Enonselkä basin was 0.45 mg P m^{-2} day^{-1} and the OF was 0.09 mg P m^{-2} day^{-1} when fish removal 0.03 mg P m^{-2} day^{-1} were taken into account. The storage change of P (dm/dt) in the water column for the time period 14 May–4 November 2009 was 0.13 mg P m^{-2} day^{-1} (Table 3).

The mass balance calculation gave a value of 27.75 mg P m^{-2} day^{-1} for the IL when the values mentioned above and spatially comprehensive GS value was used. Thereby, the IL/EL ratio was 62. When the GS data of site two was used, the IL was

Table 1 Phosphorus concentration of surface sediment and entrapped material in sites 1–7, seasonal averages (mg P g^{-1})

Site	Surface sediment		Entrapped material
	mg P g^{-1} (±SD)	Fe/P ratio (±SD)	mg P g^{-1} (±SD)
1	1.89 (0.04)	21 (0.7)	1.95 (0.30)
2	2.40 (0.15)	17 (0.8)	2.57 (0.87)
3	2.21 (0.14)	18 (1.1)	2.39 (0.58)
4	1.75 (0.07)	22 (1.1)	1.99 (0.82)
5	1.67 (0.08)	23 (0.7)	1.79 (0.62)
6	1.72 (0.17)	21 (0.9)	1.91 (0.47)
7	2.98 (0.63)	17 (2.0)	1.80 (0.31)

Table 2 Partial terms of P mass balance calculation

	Spatially comprehensive data used (mg P m^{-2} day^{-1})	Only site 2 data used (mg P m^{-2} day^{-1})
EL	0.45	0.45
OF	0.09	0.09
d*m*/d*t*	0.13	0.13
GS	27.99	67.71
IL	27.75	67.47
IL/EL	62	150

Gross sedimentation measured 14 May–4 November 2009: *EL* external P load, *OF* outflow of P, *dm/dt* storage change of P in the water column, *GS* gross sedimentation of P, *IL* internal P load

67.47 mg P m^{-2} day^{-1} which was 2.6-fold compared to the spatially comprehensive IL. The resuspension method obtained an IL of P which exceeded the budget calculation being 104% of that. The sampling site seven was the only site in which the P concentration of entrapped material was lower than the P concentration of the surface sediment (Table 1). When this exceptional data were excluded, the corresponding resuspended P constituted 93% of the budget calculation.

Discussion

Spatial variation of gross sedimentation and sediment resuspension

Sediment resuspension constituted the majority of the gross sedimentation in the Enonselkä basin as is common for many lakes (Weyhenmeyer, 1998). The long sampling period was necessary to get reliable average estimates for the open water season, due to the

Table 3 Spatial distribution of phosphorus load caused by resuspension

	Average load (mg P m^{-2} day^{-1})	Coverage area (%)	Load from the area (mg P m^{-2} day^{-1})	Fraction of the total load (%)
0–10 m	22.98	83	19.07	67
10–30 m	56.18	17	9.55	33
Whole basin		100	28.62	100

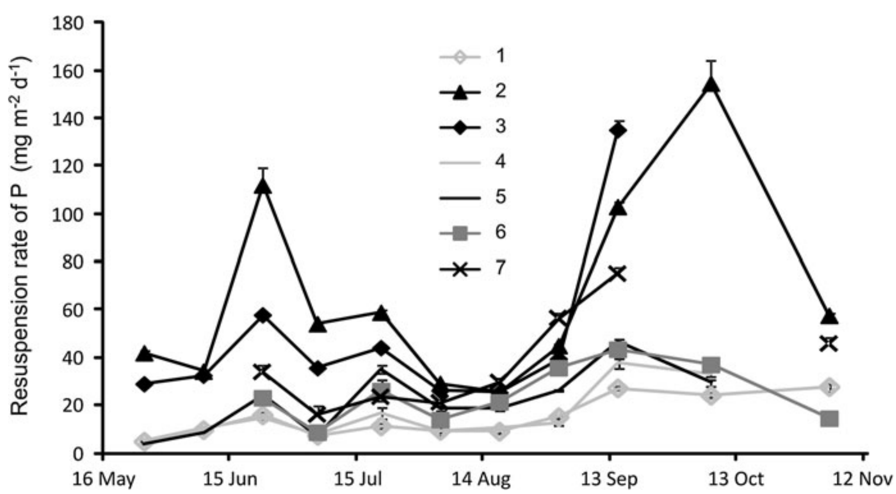

Fig. 4 Resuspension rate of phosphorus in the Enonselkä basin in 2009 at sites 1–7 (+95% conf. limits)

seasonal variation in sedimentation and resuspension. The highest values were recorded in the stratifying deep stations although, in the basin scale, most of the sediment was resuspended in the shallow unstratified areas. The transport of resuspended material from shallow to deep areas has been shown by the earlier paleolimnological and sedimentation studies (Liukkonen et al., 1997; Koski-Vähälä et al., 2000). These studies have also shown that the composition of the settled material suggests that the resuspension of autochthonous material rather than allochthonous material plays a major role in gross sedimentation (Koski-Vähälä et al., 2000). The sedimentation data obtained from the shallow and deep areas led to convergent conclusion when spatially weighted. The resuspended sediment that emanates from the unstratified shallow areas can be focused on the lake deeps (Bloesch & Uehlinger, 1986; Hilton et al., 1986). Due to this sediment focusing, the trap catches of the deep areas give an overestimation of the actual sedimentation and resuspension rates, if used alone or not correctly weighted (Horppila & Niemistö, 2008). Thereby, spatially comprehensive sedimentation measurements were essential for accuracy.

Budget calculations versus resuspension measurements

Internal processes such as gross sedimentation and internal nutrient loading are often of great importance in eutrophic lakes after a reduction of external loading (Cullen & Forsberg, 1988; Søndergaard et al., 2001). According to budget calculations, the gross sedimentation rate of P in the Enonselkä basin governed the IL during the open water season 2009, since all the other values of the budget were relatively low. Sediment resuspension constituted most of the total settling flux. Therefore, the resuspension of P was the most important in-lake process that influenced P cycling. This was verified by the fact that resuspended P exceeded the IL of the mass balance calculation by 4%. The shallow areas were of special importance, since 67% of the resuspended P originated from bottoms over which the water depth was shallower than 10 m. The resuspension method probably gave an overestimate of the IL, since the resuspension rate of P was assumed to be the same for all the shallow areas including the macrophyte covered areas, although vegetation is known to prevent sediment resuspension (Horppila & Nurminen, 2005). However, the effect of macrophytes was considered to be low, since the coverage of the submerged species, the most effective life form against resuspension (Horppila & Nurminen, 2005), is less than 5%. In addition, the exceptionally high concentration of P in the surface sediment layer of the site seven may have resulted in overestimation associated with this method. Such high concentrations were not found in the other areas of the lake and this site is clearly having an erosion bottom (low water and organic content) in which resuspendable material is rarely found. However, the overall governing effect of resuspension on internal P load cannot be denied, since even after excluding the data of the site seven, resuspension of P accounted for 93% of the IL of the budget calculation.

It is worth noticing that as discussed in the case of the gross sedimentation rates, the material resuspended in the shallow areas also reached the traps in the lake deeps. This was the case, since the fairly narrow deep areas are surrounded by the shallow areas which are prone to resuspension throughout the open water season. Also, the low variation in the organic content of the entrapped material (proved by the high R^2-value of the regression line) in the deep and shallow stations gives evidence for this conclusion. Thus, the effect of shallow areas on P cycling was probably even greater than the calculated effect. Therefore, the spatially comprehensive measurements were also necessary for accurate mass balance calculations, and this was indicated by the IL being 2.6-fold when only the deep site (no. 2) data were used.

Although, according to our calculations, the gross sedimentation of P dominated the IL due to strong sediment resuspension in the Enonselkä basin, it is important to notice that EL is the factor directly contributing to P increase in the lake.

The fate of resuspended P

Part of the sedimentary P may be resuspended several times in particulate form without being bioavailable before final burial. However, the cycling of P includes much more than just the resuspension or settling of P with particles. The cycling of P between the sedimentary particles and the water column is dependent on several biological and physico-chemical factors (Boström et al., 1982). Phosphorus in both the water column and sediment is continuously being assimilated into the biomass and then released again by the decomposition within a short time interval and the net release result can be very variable (Boström et al., 1988a). Moreover, the exchange of P between resuspended particles and surrounding water phase, adsorption–desorption reaction, is affected by the concentration and P saturation of solids, particle-size distribution, redox conditions, pH, $CaCO_3$ content, and organic carbon (Berkheiser et al., 1980; Boström et al., 1982, 1988a; Drake & Heaney, 1987; Holmroos et al., 2009; Niemistö et al., 2011). Therefore, it is difficult to know how many times a phosphate ion will have been assimilated or dissimilated as well as chemically released or bound before entering our sediment trap in particulate form. In addition, sediment resuspension is a more effective mechanism to remove the soluble phosphorus from the pore water into the water column than is the diffusion (Reddy et al., 1996). Altogether, resuspension causes a high flux of sedimentary nutrients, in soluble or particulate form, into the water column and this flux has large temporal and spatial variations. Thus, when excluding the biological cycling, the fate of P after resuspension depends on the retention capacity of resuspended particles in addition to the prevailing physico-chemical conditions.

In the aerobic conditions of the Enonselkä basin, the P retention capacity of sedimentary particles is known to be high due to the high concentration of metal oxides (Kairesalo et al., 1995; Hartikainen et al., 1996; Tuominen et al., 1998). The high Fe/P ratios (17–23) of the surface sediment that were measured in the shallow and in the deep areas support the finding of a high retention capacity of P in aerobic conditions according to the criterion described by Jensen et al. (1992). On the other hand, P can be released from metal oxyhydroxides via ligand-exchange reactions in which P is substituted by OH^- at high pH independent of prevailing oxygen conditions (Hingston et al., 1967; Andersen, 1975; Hartikainen, 1979; Lijklema, 1980). This phenomenon has been reported in a study on the sediment of the Enonselkä basin (Koski-Vähälä et al., 2001). Moreover, nowadays pH values 8–9, in which the ligand-exchange reactions are possible, are commonly observed. High water pH may also have a secondary effect on phosphorus release, because when ferrous iron and phosphate are released from anaerobic sediment and mixed into aerobic lake water, only some of the released phosphate ions will be bound to reprecipitated ferric iron compounds (Boström et al., 1988b).

Resuspension in relation to management measures

The improvement in the water quality achieved by biomanipulation in the Enonselkä basin in the early 1990s was considered to result mainly from the decreased input of fish-mediated P from benthic to pelagic habitats (Horppila & Kairesalo, 1992; Horppila et al., 1998). Fish stocks can make sediment more prone to resuspension and thereby enhance internal P loading (Sheffer et al., 2003). The cyprinid fish removal is at a considerably lower level today than during the biomanipulation (ca. 80 → 20 kg ha^{-1} a^{-1}) and cyprinid fish stocks have increased in the Enonselkä basin (Nykänen et al., 2010). Therefore, the internal P loading via resuspension in the shallow areas has most likely been enhanced. The hypolimnetic anaerobic P loading was considered to play a minor counteracting role in the recovery process in 1990s due to high downward flux of particulate P and the resuspension rates were not affected by the biomanipulation (Koski-Vähälä et al., 2000). The improved water quality also led to lowered pH conditions (9 → 7), which most likely contributed to the recovery of the lake by decreasing the internal loading of P from the resuspended particles under oxic conditions (Koski-Vähälä et al., 2000). This together with our calculations, show that resuspension from the shallow areas governs the internal P load of the whole basin, and gives additional evidence for the importance of aerobic shallow area processes in P cycling.

After the successful biomanipulation in 1990s, in the state of improved water quality, sediment resuspension was concluded not to cause internal P loading (Koski-Vähälä et al., 2000). In the eutrophicated state the water is in today, the new spatially comprehensive data of this study agrees with the suggestion of Koski-Vähälä et al. (2000) that sediment resuspension can help in the recovery of the eutrophicated basin, if the state of lower pH conditions is achieved and the P retention capacity of resuspended particles is increased. It remains to be seen, if aeration with moderate fish removal will be the restoration measure that decreases the P concentrations and cyanobacteria blooms of the Enonselkä basin. Nevertheless, sediment resuspension will definitely be an important process involved in possible recovery.

Conclusions

Internal loading of phosphorus was of great importance in the Enonselkä basin, since it was 62-fold compared to that of external loading. Data on spatially comprehensive sedimentation measurements are necessary in order to get reliable mass balance calculations.

Sediment resuspension, a common phenomenon in many lakes, constituted most of the gross sedimentation and the internal loading of phosphorus. However, external loading of phosphorus was also of importance, since the phosphorus once entering the lake may be resuspended several times before final burial.

Sediment resuspension from the shallow areas governed the internal P loading of the whole basin. Resuspension coupled with aerobic release processes was probably the most important mechanism that causes internal P loading. However, sediment resuspension may help in the recovery of the eutrophicated basin, if the state of lower pH conditions is achieved.

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