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Variations of internal phosphorus loading and water quality in a hypertrophic lake during 40 years of different management efforts

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ABSTRACT

Variations of internal phosphorus (P) loading and water quality in the hypertrophic Lake Tuusulanjärvi (southern Finland) were studied over a period covering 40 years (1970–2010). The lake has hosted numerous different management efforts. Diversion of sewage waters away from the lake in 1979 resulted in a considerable reduction of external P loading. Due to diffuse loading from agricultural areas, external loading however still exceeds the critical loading of the lake, thus having an effect on the water quality. The total P concentration of surface layers has decreased but is still on a hypertrophic level (90 $\mu g\,l^{-1}$). The high productivity of the lake is maintained also by intensive internal P loading, and the sediment has a potential to release P to the water for decades even if external loading would be reduced to a tolerable level. Internal P loading has not decreased over the studied decades despite numerous within-lake management efforts (aeration with different methods, food web management). In opposite, our results demonstrated that destratification applied since 1998 resulted in a persisting internal P loading. Destratification has increased the concentration of oxygen and decreased the concentration of soluble P in deep water, but at the same time it has accelerated P release from aerobic bottoms. This can be due to elevated near-bottom temperatures, enhanced liberation of organic P through accelerated mineralization, and increased sediment resuspension by aeration-induced turbulence. Additionally, increasing wind velocities may have a role in the increasing aerobic internal loading. Food web management has compensated for the amplified P-cycling, revealed by the decreasing chlorophyll:total P ratio.

1. Introduction

In lakes, nutrients are continuously accumulated in the bottom, depending on the relationship between inflow and outflow, basin morphometry and flushing rate (Vollenweider, 1976; Søndergaard et al., 2003). Consequently, the greatest storage of nutrients in a lake ecosystem is usually in the sediment (Pettersson, 1998). These sediment nutrients have often implications on the water quality, because numerous mechanisms tend to recycle them back to the overlying water. Especially such internal loading of phosphorus (P) may delay or prevent the recovery of lakes from eutrophication after the reduction of external nutrient loading (Marsden, 1989; Jeppesen et al., 1991; Søndergaard et al., 2003). Hence, also the estimation of internal P loading has a central role in lake management and restoration.

Despite the importance of internal loading, quantification of P fluxes from the sediment to the water remain one of the main problems in limnology (Håkanson, 2004; Nürnberg, 2009). Anaerobic P release in the deeps of thermally stratifying lakes takes place because in low oxygen concentrations often prevailing in the sediment, Fe^{3+} is reduced to Fe^{2+} with a subsequent dissolution of P (Mortimer, 1941; Boström et al., 1982). Gas bubbling from the anoxic sediment can also contribute to internal P loading (e.g. Varjo et al., 2003). Internal loading in lake deeps can be estimated by measurements of P accumulation in the hypolimnion. In shallow non-stratifying areas, where the water column remains oxic throughout the growing season, internal P loading can also take place through various mechanisms. These include effects of photosynthetically elevated water pH on P release, sediment resuspension due to waves, water currents and biota, mineralization of organic matter and diffusion (Boström et al., 1982; Carvalho

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et al., 1995; Søndergaard et al., 2003; Tammeorg et al., 2015). The quantification of such internal P loading is very difficult. The accumulation approach used in the stratifying areas cannot be used in shallow areas due to continuous mixing and uptake by biota (Nürnberg, 2009). This is a major problem, because shallow non-stratifying areas often constitute to a large percentage of the lake area. Additionally, they are often in contact with the photic zone and can therefore strongly affect the productivity of lakes (Welch and Cooke, 1995; Søndergaard et al., 2003). Consequently, shallow lakes are generally more productive than deep ones (Oglesby, 1977). While redox conditions in the sediment considerably affect P release, the importance of low oxygen concentrations in lake deeps for P cycling and retention may have been overestimated. Low hypolimnetic oxygen concentrations and anaerobic P release may be considered as parallel symptoms of high sedimentation of P and organic matter (Gächter and Wehrli, 1998; Moosmann et al., 2006; Hupfer and Lewandowski, 2008). The discussion has been accelerated by minor effects of artificial oxygenation on lake water quality (Gächter and Wehrli, 1998; Salmi et al., 2014; Kuha et al., 2016).

In the present study, internal P loading and P accumulation in the hypertrophic Lake Tuusulanjärvi during 40 years were examined. The lake has been almost continuously aerated during the study years to counteract the anaerobic release of P from sediments. On the contrary to the earlier years, the aeration was realized via destratification during the years of 1998–2010, making the lake continuously mixing. It was hypothesized that this mixing has caused a decrease in anaerobic internal P loading and an increase in aerobic internal P loading. To test the hypothesis, the anoxic component of internal loading was separated from the total internal P loading. Moreover, the development of water quality over the years, in which also other different restoration activities occurred, was analyzed.

2. Material and methods

2.1. Study lake and restoration activities

Lake Tuusulanjärvi is situated in southern Finland (60° 26 N′, 24° 59 E′). It has a surface area of 5.95 km^2, mean and maximum depths of 3.2 m and 10.0 m, respectively. The catchment area of the lake covers 125 km^2. In the lake, the area that is naturally thermally stratified during the summer covers c. 20% of the lake surface. The theoretical water retention time of the lake is 250 d and the estimated critical external P loading is 353 mg P m^{-2} y^{-1} (Marttila, 2005; Muukkonen, 2009). The critical loading has been calculated with the method by Vollenweider (1976), based on the relationship of areal P loading and the water residence time of the lake (e.g. Brett and Benjamin, 2008). The lake became eutrophic already during the 19th century, and eutrophication was accelerated since 1950's due to increasing settlements and agriculture (Harjula, 1972; Lepistö et al., 2006). To reduce the symptoms of eutrophication (e.g. fish kills), winter aeration by Nokia aerators (five aeration floats) was started in 1972 and it lasted until 1980 (Malve et al., 2004) (Fig. 1). The aerators led bubbled compressed air to the hypolimnion with a capacity of 1350 kg O_2 d^{-1} (Kolehmainen, 1974; Malve et al., 2004). Municipal wastewaters were diverged from the lake in 1979, and summer aeration was started 1982 with a Hydixor aerator, which pumped hypolimnetic water to the surface, where it was aerated and pumped back. The flux of dissolved oxygen was 240 kg d^{-1} (Malve et al., 2004). In 1988, aeration however failed due to technical problems. In 1990, the aeration system was changed to another model (Planox) with an average oxygen flux of 450 kg d^{-1} (Fig. 1). This aeration continued until 1997. Despite the restoration activities, heavy cyanobacterial blooms still developed in the 1990's, and in 1998 the aeration method was changed again. Aeration was started with Mixox aerators that pump oxygen-rich epilimnetic water to the hypolimnion with a capacity of 460 000 m^3 d^{-1} (Saarijärvi and Lappalainen, 2005). Five Mixox pumps were installed in 1998 and one more in 1999 (in 2003, aeration was exceptionally not performed). All six pumps were used during summer, and one or two during the ice-cover period (December–April). The aim was to prevent summertime stratification and to maintain the hypolimnetic concentration of dissolved oxygen above 2 mg l^{-1}. Additionally, to restore the food web, biomanipulation through removal of planktivorous and benthivorous fish was started in autumn 1997 (Sammalkorpi, 2000; Saarijärvi and Lappalainen, 2005) (Fig. 1). The total catch during 1997–2010 was 666 000 kg (1109 kg ha^{-1}), annual catch varying between 31 and 180 kg ha^{-1} (Keski-Uudenmaan Vesiensuojelun Kuntayhtymä, 2012). The main target species were the cyprinids bream (*Abramis brama* L.) and roach (*Rutilus rutilus* (L.)) (Olin et al., 2006). The stocks of predatory fish (eel *Anguilla anguilla* L., pike *Esox lucius* L., pikeperch *Sander lucioperca* L., burbot *Lota lota* L.) were strengthened by stocking. In the catchment area, efforts to reduce diffuse loading from agricultural areas were increased in the 2000's and wetlands have been built in the catchment to trap nutrients and suspended solids on their way to the lake. The largest wetland (Rantamo-Seitteli) has an area of 28 ha.

2.2. Sampling and calculations

The total internal P loading (IP_{tot}) in Tuusulanjärvi was calculated by comparing mass balance computed P retention (R_{mb}) and sediment-derived P retention (R_{sed}). R_{mb} is calculated by a mass balance approach but retention will be underestimated if internal loading of P is significant but ignored (Dillon and Molot, 1996). Therefore, the deviation of R_{sed} from R_{mb} can be used to estimate the magnitude of internal loading as follows (Nürnberg, 1984; modified by Tammeorg et al., 2016).

$$IP_{tot} = TP_{in} \times (R_{sed} - R_{mb}/R_{sed})$$

where IP_{tot} is total internal load (mg P m^{-2} y^{-1}) and TP_{in} is the external load of P. TP_{in}-values were calculated by widely used methodology (e.g. Dillon and Evans, 1993; Knuuttila et al., 1994) based on the monitoring of P coming to the lake via river inflow, point loading from industry and municipalities, diffuse loading and precipitation (data from Ojanen, 1979; Marttila, 2005; Muukkonen, 2009; Hertta database, 2015). The water sample based estimates of external loading have also been shown to match those modelled with the VEPS-model used by Finnish Environment Institute (Tattari and Linjama, 2004; Marttila, 2005). The model takes into account all the P sources listed above. Data on temperature, water column pH and concentrations of TP, O_2 and chlorophyll *a* were obtained from the Hertta database of Finnish Environment Institute (Hertta database, 2015).

R_{mb} (mg P m^{-2} y^{-1}) in the lake was calculated as follows (e.g. Hupfer and Lewandowski, 2008),

$$R_{mb} = TP_{in} - TP_{out}$$

where TP_{in} is the external loading of P and TP_{out} is the ouflow of P.

R_{sed} was obtained from a dated sediment core (Dillon and Evans, 1993; Moosmann et al., 2006). The sediment core was taken with HTH gravity corer (Renberg and Hansson, 2008) from the deepest site of the lake. The core was sectioned into 0.5 cm slices to a depth of 20 cm to cover the period for which comprehensive water quality monitoring data were available (since 1970). The sediment samples were freeze-dried and ground. The TP concentration in each sediment layer was measured after wet digestion with sulphuric acid and hydrogen peroxide in the microwave digestion system using