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PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
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CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract

Internal loading has a fundamental role in the nutrient recycling and ecosystem functioning of large and shallow lakes, but it can also influence deep lakes. This deliverable includes one article and a manuscript, that deal with the temperature-induced changes on internal loading in shallow and deep lakes, and long-term trends and seasonal changes in P retention in shallow Danish lakes.

Manuscript by Järvinen et al.
Marko Järvinen, Kari Kallio & Ahti Lepistö
Effects of temperature changes on internal loading in shallow and deep lakes
Manuscript

Impacts of temperature changes on the internal loading of nutrients in shallow and deep lakes were assessed using high-frequency monitoring data from a shallow eutrophic lake basin in southern Finland and output from literature. Temperature affects internal loading largely by influencing stability of the water column, and the duration of the ice-covered period. Resultant responses to the duration and intensity of stratification and mixing influence the primary drivers of internal nutrient loading in the water column and the water-sediment interface: dissolved oxygen concentrations, Redox-conditions, temperature-dependent metabolism and microbial degradation, and resuspension. Higher temperature is likely to lead to longer and stronger stratification episodes in summer which may increase the importance of O_2 *and Redox conditions in the phosphorus (P) release relative to resuspension in relatively shallow lakes. In deep lakes, longer stratification results in accumulation of nutrients in the hypolimnion and the nutrients typically become available to upper water layers only after degradation of thermal stratification in autumn or by partial breakdown of the thermocline. This together with expected delayed freezing dates in future can strengthen and prolong the duration of autumnal diatom and cyanobacterial blooms also in deep lakes. Daily data from Säkylän Pyhäjärvi support the finding that shallow lakes react rapidly to changes in thermal regime, and mixing brings nutrients and other suspended material to surface water layers which will increase algal biomass and also the probability for cyanobacterial blooms.*

Article by Søndergaard et al.
Martin Søndergaard, Rikke Bjerring & Erik Jeppesen
Persistent internal phosphorus loading during summer in shallow eutrophic lakes.
Hydrobiologia DOI 10.1007/s10750-012-1091-3 (Springer Online FirstArticles 2012)

Twentyone years of monthly mass balance and lake chemistry data from six shallow eutrophic and fast flushed eutrophic Danish lakes were used to investigate long-term trends in yearly and seasonal patterns of P retention. In only one of the lakes, the external P input has experienced major changes during the last >20 years. The lakes showed a distinct seasonal pattern with high P concentrations and typically negative P retention during summer (up to -300% of the external loading from May to August). During winter, P retention was up to 50% of the external loading from December to April. Internal P loading from the sediment delayed lake recovery by approximately 10 years in the lake with the most recently reduced external loading, but in all the lakes net release of P from the sediment occurred during summer. P release in the lakes has not abated during the past decade, indicating that the sediment of eutrophic and turbid shallow lakes remains a net source of P during summer. The seasonal variations in P retention became more pronounced with increasing P levels, and retention decreased with increasing temperature, but increased if clear water conditions were established.

Manuscript

EFFECTS OF TEMPERATURE CHANGES ON INTERNAL LOADING IN SHALLOW AND DEEP LAKES

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Abstract

Impacts of temperature changes on the internal loading of nutrients in shallow and deep lakes were assessed using high-frequency monitoring data from a shallow eutrophic lake basin in southern Finland and output from literature. Temperature affects internal loading largely by influencing stability of the water column, and the duration of the ice-covered period. Resultant responses to the duration and intensity of stratification and mixing influence the primary drivers of internal nutrient loading in the water column and the water-sediment interface: dissolved oxygen concentrations, Redox-conditions, temperature-dependent metabolism and microbial degradation, and resuspension. Higher temperature is likely to lead to longer and stronger stratification episodes in summer which may increase the importance of O_2 and Redox conditions in the phosphorus (P) release relative to resuspension in relatively shallow lakes. In deep lakes, longer stratification results in accumulation of nutrients in the hypolimnion and the nutrients typically become available to upper water layers only after degradation of thermal stratification in autumn or by partial breakdown of the thermocline. This together with expected delayed freezing dates in future can strengthen and prolong the duration of autumnal diatom and cyanobacterial blooms also in deep lakes. Daily data from Säkylän Pyhäjärvi support the finding that shallow lakes react rapidly to changes in thermal regime, and mixing brings nutrients and other suspended material to surface water layers which will increase algal biomass and also the probability for cyanobacterial blooms.

Keywords

resuspension, mixing, thermal stratification, phosphorus, climate change

Introduction

Internal loading of nutrients has a fundamental role in the nutrient recycling of large and shallow lakes and it is often the reason for the failure or delay of successful lake management of eutrophic (shallow) lakes, by supporting blooms of diatoms and harmful cyanobacteria, also after reductions in external nutrient loading (e.g. Søndergaard et al. 2003, 2012, Håkanson 2004, French & Petticrew 2007). The ultimate reason behind internal loading is generally a long eutrophication history: external loading has led to high lake nutrient levels, increased phytoplankton biomass and increased sedimentation of organic matter to the bottom areas of the lake, which eventually leads to phosphorus (P) release from the P-rich surface sediments (e.g. Kleeberg & Kozerski 1997, Ventelä et al. 2011).

Internal loading of nutrients in lakes depends on several mechanisms and in-lake processes that are often coupled to each other: water temperature, resuspension, Redox conditions, pH, iron (Fe) chemistry, chemical diffusion, bioturbation, mineralization and microbial processes in the sediments and the presence of macrophytic vegetation in the littoral and shallow lake areas (e.g. Boström et al. 1982, Søndergaard et al. 2003, Niemistö 2008). Many of the listed mechanisms have a strong dependency on the meteorological forcing and they are thus sensitive to any changes in future climate (French & Petticrew 2007, Adrian et al. 2009, Pettersson et al. 2010).

Air temperature, wind speed, cloud cover and turbulent kinetic energy are the principal drivers of thermal stability of the water column that is expressed as the depth of the thermocline, and changes in thermal stratification and mixing of lakes (Imboden et al. 1983, Adrian et al. 2009). Shallow lakes typically have weak thermal stability which increases the likelihood of intermittent breakdowns of stratification during the open water periods even under moderate wind conditions.

Effects of climate change on lakes are complex (e.g. Blenckner 2001, George 2010). Responses are modified by regional differences, and they strongly depend on the characteristics of the catchment and lake mixing regimes (Blenckner 2001, Nõges et al. 2009, Adrian et al. 2009). It is evident that internal loading has a key influence on the nutrient availability and ecosystem productivity in eutrophic shallow lakes, and frequently mixing polymictic lakes (Kleeberg & Kozerski 1997, Søndergaard et al. 2003, 2012). Due to shallowness and small water volume, shallow lakes are also likely more susceptible to direct impacts of changes in temperature. Internal loading caused by mixing events and internal wave activity can also be important in the shallow and isolated parts or in the littoral of deep dimictic lakes, and obviously in the pelagial during spring and autumn overturns (e.g. Niemistö 2008).

Here were discuss on how temperature-induced changes affect internal nutrient loading in lakes with varying depth by using results from a shallow Finnish polymictic lake and output from literature. We demonstrate that the internal loading have importance throughout the summer in shallow lakes, whereas in the pelagial of dimictic deep lakes the impacts of internal loading are generally discernible following the late summer-autumn break-down of stratification. As the temperature increase accelerates many mechanisms of internal loading (e.g. Nõges et al. 2011a), we suggest that in the future warmer climate, P release in shallow lakes is likely to increase. Although macrophyte communities play an important role in the recycling of nutrients and overall the ecosystem functioning of shallow lakes (Jeppesen et al. 1997, Søndergaard et al. 2003) their responses to temperature changes and implications to internal loading will not be dealt here.

Methods

The study is largely based on high-frequency (one hour measurement interval) monitoring data from May-October 2009 from the shallow and polymictic lake Pyhäjärvi (Säkylä, SW Finland. Pyhäjärvi is a large (155 km^2) and shallow (z_m = 5.5 m) lake suffering from eutrophication. Increased eutrophication of Pyhäjärvi has been a major concern since the late 1980s as blooms of cyanobacteria became more frequent particularly during the 1990s. Between 1970 and 1992 total P (TP) concentrations doubled, but have decreased since then (Ventelä et al., 2007). Recently, new information of spatial variability of cyanobacterial biomass in different parts of the lake has been obtained from moving-boat transect measurements (Lepistö et al., 2010). The main concerns for the status of the lake, also with respect to changing climate, are possible changes in external nutrient loads (Ekholm et al., 1997, Ventelä et al., 2011).

For Pyhäjärvi, hourly vertical profiles of water temperature and oxygen were recorded at the depths of 5, 10 and 19 m by a real-time lake raft which located in the deepest part of lake in May-October 2009 (Kallio et al., 2010). Turbidity, chlorophyll *a* fluorescence (phytoplankton biomass) and phycocyanin fluorescence (cyanobacteria biomass) have been recorded hourly during the same period at the depth of 1 m. Water chemistry data (see below for details) have been collected manually from the depths of 1, 5, 10, 15, 20 and 24 m in 1980-2008 and in 2009-2011 from the depths of 1, 15 and 24 m. The results from the depths of 0-5 and 15-24 m were averaged to represent values in the epi- and hypolimnion, respectively.

Phosphate phosphorus (PO_4-P), total phosphorus (TP), ammonium nitrogen (NH_4-N) and iron (Fe) were analyzed using standard methods (e.g. APHA, 2000). Stability of the water column was calculated as the Schmidt stability (J m^{-2}) from the daily water temperature profiles. The stratification periods were distinguished from the mixing/weak stratification periods using the stability criterium of >3.5 J m^{-2}, which corresponded well with the water temperature difference exceeding 1 °C between the surface and the bottom layer.

For the synthesis we also compiled results from previously published studies dealing with internal loading and its mechanisms as well as its relationships with the meteorological forcing and the future climate change.

Results and discussion

Temperature affects internal loading indirectly by influencing the stability conditions of the water column (Soranno et al. 1997, Wilhelm & Adrian 2008, Niemistö et al. 2007, 2009). High-resolution measurements of water temperature show that stability conditions of Säkylän Pyhäjärvi changed rapidly during the open water season of 2009 (Fig. 1). Stratification collapsed several times during the measurement period, being strongest from late June till early July. The periods of low stability were discernible as increased deep water concentrations of O_2, and turbidity of the uppermost water layers, both indicating increased mixing of the water column (Fig. 1). Despite intermittent mixing periods during summer, which temporarily improved hypolimnetic O_2 concentrations, deep water O_2 decreased throughout the summer from mid-June until the start of autumn turn-over in mid-August. As a whole, O_2 and P concentrations in the hypolimnion differed between the contrasting stability conditions in Pyhäjärvi in 2009-2010. O_2 concentrations were significantly lower (p=0.006, Mann-Whitney U-test, n=12) and PO_4-P concentrations higher (p=0.004, n=12) in the hypolimnion during periods of stratification (Fig. 2; see also Fig.1). The same was observed for ammonium-nitrogen (NH_4-N; p=0.002) where hypolimnetic concentrations were on average 4.5-times higher (180 µg l^{-1}, n=5) during stratified periods than during mixed periods (40 µg l^{-1}, n=7) in June-September. Total-P concentrations were at the same level (p=0.328 epi; p=0.082 hypo, n=12) among the different stability periods, and also the epilimnetic PO_4-P did not differ significantly between the periods (p=0.195, n=12) (Fig. 2). There are also large annual differences in the summer

O_2 and nutrient concentrations in Pyhäjärvi (Fig. 3). Deep water (23-25 m) average O_2 concentrations are typically lowest and inorganic N and P concentrations highest in late winter under the ice in 1980-2011. The annual variation in PO_4-P and NH_4-N in the deep water layer is also highest during winter. Ice-out in April-May is followed by a complete overturn and the whole water column becomes oxygenated and this with the nutrient uptake by spring phytoplankton could explain the decrease of PO_4-P and NH_4-N concentrations also in the hypolimnion (Fig. 3). During summer (June-September) O_2 and nutrient concentrations show high variation between the years depending largely on the prevailing stratification and mixing events. The results of Pyhäjärvi do not allow detection of mechanisms behind the above described patterns in internal nutrient loading in summer, but they are likely related to changes in Redox conditions as well as resuspension (see e.g. Søndergaard et al. 2003). The release of P from sediments often results from Redox-dependent release of P bound to iron and microbial processes which can also happen in shallow well-mixed eutrophic lakes with organic rich sediments because the oxic layer of the sediment cannot prevent release of P from the deeper parts of the sediment (Søndergaard et al. 2003). Fe concentrations were highest near bottom under the ice during winter, and the Fe concentrations and their variation between the years were clearly lower in summer, when Pyhäjärvi was mixing several times. Although resuspended nutrients are generally mostly in particulate form (Ekholm et al. 1997), resuspension has been shown to generally increase both total phosphorus (P) and inorganic P concentrations in the water (Niemistö et al. 2008, French & Petticrew 2007, Søndergaard et al. 2011). The change in total P could not be found in Pyhäjärvi (Fig. 2), possibly due the rather limited number of observations.

As also indicated by Pyhäjärvi data, temperature can influence directly and indirectly on many key variables responsible for internal loading (Fig. 4, Søndergaard et al. 2003). Mineralization of organic material and the metabolism rates of microbes in the sediment depend on water temperature (e.g. Boström et al. 1982). As a result of frequent mixing of the water column during summer which is typical for many shallow lakes, warmer surface water is transported and mixed to deeper water layers, thus heating the hypolimnion and the upper layers of the sediment. Higher water temperatures in the hypolimnion will accelerate processes in the settled organic material, O_2 consumption and release of P (Boström et al. 1982, Koski-Vähälä et al. 2011, Niemistö 2008). Søndergaard et al. (2012) showed that the seasonal P retention in 21 eutrophic shallow Danish lakes was negatively related to water temperature in summer when higher temperature and a thin oxidized surface sediment layer probably resulted in a Redox-sensitive P release from the sediments. The changes in hypolimnetic temperature are less likely in deep stratified lakes where both increases and decreases have been reported in relation to meteorological forcing (Arvola et al. 2010, Jones et al. 2010).

Temperature affects directly also the duration of ice-covered period in the lakes of northern Europe (Blenckner et al. 2004). Higher air water temperatures cause earlier ice-break in spring and later freezing in autumn, thus increasing the length of the open water period (Fig. 4, Elo et al. 1998, Blenckner et al. 2010). In deep lakes this may lead, together with higher surface water temperatures, to longer stratification (Blenckner et al. 2010, Jones et al. 2010), which would increase the duration of isolation of deeper water layers and would thus increase the probability for O_2 depletion, decrease in Redox conditions and the dissolution of P from the sediments in eutrophic, but also in humic lakes during summer (Fig. 4, Forsius et al. 2010). However, this does not necessarily lead to significant changes in P concentrations during autumn mixing as with the advent of autumnal circulation, ferrous iron (Fe^{2+}) is rapidly oxidized and a large proportion of the phosphate is precipitated as ferric phosphate (e.g. Wetzel 2001). Despite this, increased mixing may have an important role in the loading of P and for cyanobacterial blooms in summer by deepening of the thermocline and consequent upwelling of nutrients (Soranno et al. 1997).

In shallow lakes, the prolongation of ice-free period can intensify resuspension and increase the annual load of suspended solids and nutrients from the sediment. For instance, Niemistö et al. (2007) estimated, using scenario model by Kuusisto (1989), that doubling of CO_2 would increase 28 % the annual loading of total P by resuspension in a shallow and eutrophic basin of Lake Hiidenvesi in southern Finland, due to a shortening of ice-covered period and more intensive mixing during open water period. For deeper Finnish lakes, PROBE model simulations have suggested prolongation of summer stratification (Elo et al. 1998). Longer stratification periods in shallow lakes would increase the importance of O_2 and Redox conditions relative to resuspension (Behrend et al. 1993). Niemistö (2008) estimated that for some shallow lakes with greater than average turbulence, large littoral areas and small anaerobic hypolimnia, P release from sediments can be much larger than values (10-30% of total loading) for deeper, more stratified lakes.

As climate change is likely to lead higher water temperatures in summer (Fig. 4, e.g. Arvola et al. 2010) this will evidently favour the occurrence of large-sized cyanobacteria in eutrophic lakes (Paerl & Huisman 2008, Wagner & Adrian 2009, Blenckner et al. 2010, Kosten et al. 2012), that are less edible to grazing zooplankton. This will in turn increase the sedimentation of organic matter and consumption of O_2 in the bottom layers of lakes. High phytoplankton production may also increase pH to a level (pH >9) where P desorption may occur, in particular when the bottom water temperature is high enough, >15°C (Koski-Vähälä et al. 2001, Niemistö 2008, French & Petticrew 2007).

The lakes in Europe and North America show increasing trends in dissolved organic carbon (water colour), and this so-called brownification has been related to climate-induced changes in precipitation and DOC loading from the catchment to lakes and/or the recovery of lakes and their catchments from acidicification (e.g. Hongve et al. 2004, Monteith et al. 2007). Possible increases in water colour by humic substances in future will influence thermal regime of lakes by affecting the light absorption and stratification characteristics (e.g. Forsius et al. 2010), which are likely reflected also in internal loading.

Conclusions

To conclude, temperature changes influence internal loading in lakes mainly by modifying the stability conditions of the water column, and influencing the duration of ice-covered period in northern Europe. The exchange of P between sediments and the overlying water depends on the ability of the sediments to retain P, the conditions of the overlying water and the biota within the sediments that modify exchange equilibria and affect P transport back to the water (Boström et al. 1982, Søndergaard et al. 2003). Overall, the results from Pyhäjärvi and literature suggest that the reduction of nutrient loads in particular in shallow lakes suffering from eutrophication may prove difficult in future due to impacts of warmer temperatures that support internal loading.

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FIGURE CAPTIONS

Figure 1. Daily variation of Schmidt stability (J m^{-2}) (grey bars), minimum dissolved oxygen concentration (O_2 mg l^{-1}) at 19 m depth (black solid line), and maximum turbidity (FNU) (dashed line) at 1 m depth, and the concentration of phosphate-P (PO_4-P µg l^{-1}) in the hypolimnion (black dots) of Säkylän Pyhäjärvi (SW Finland) in May-October 2009.

Figure 2. Box plot presentation of Schmidt stability (J m^{-2}), dissolved O_2 concentration in hypolimnion (mg l^{-1}), phosphate-P (PO_4-P µg l^{-1}) and total phosphorus (tot-P µg l^{-1}) in the epilimnion (epi) and hypolimnion (hypo) of Lake Pyhäjärvi during stratified (str) and mixed (mix) periods in June-August 2009-2010. n=5 for str and n=7 for mix, except for stability where n=37 and n=55, respectively. Median values with 25th and 75th percentiles, and minimum and maximum values (whiskers). * = statistically significant difference ($p < 0.05$; Mann-Whitney U-test).

Figure 3. Mean monthly (1980-2011) concentrations of A) dissolved oxygen (mg l^{-1}), B) iron (Fe µg l^{-1}), C) phosphate-P (PO_4-P µg l^{-1}) and D) ammonium-nitrogen (NH4-N µg l^{-1}) in the hypolimnion (23-25 m) of Lake Pyhäjärvi (SW Finland). Solid smoothed lines = average, broken smoothed lines = 5th and 95th percentiles. n=5-67 for different months.

Figure 4. A conceptual chart presenting the impacts of increased temperature on key mechanisms of internal loading in shallow lakes. The dashed line separates the epimnion and hypolimnion. P = phosphorus, Fe = iron, S = sulphur, OC = organic carbon, WT = water temperature, O_2 = dissolved oxygen.

Fig 1.

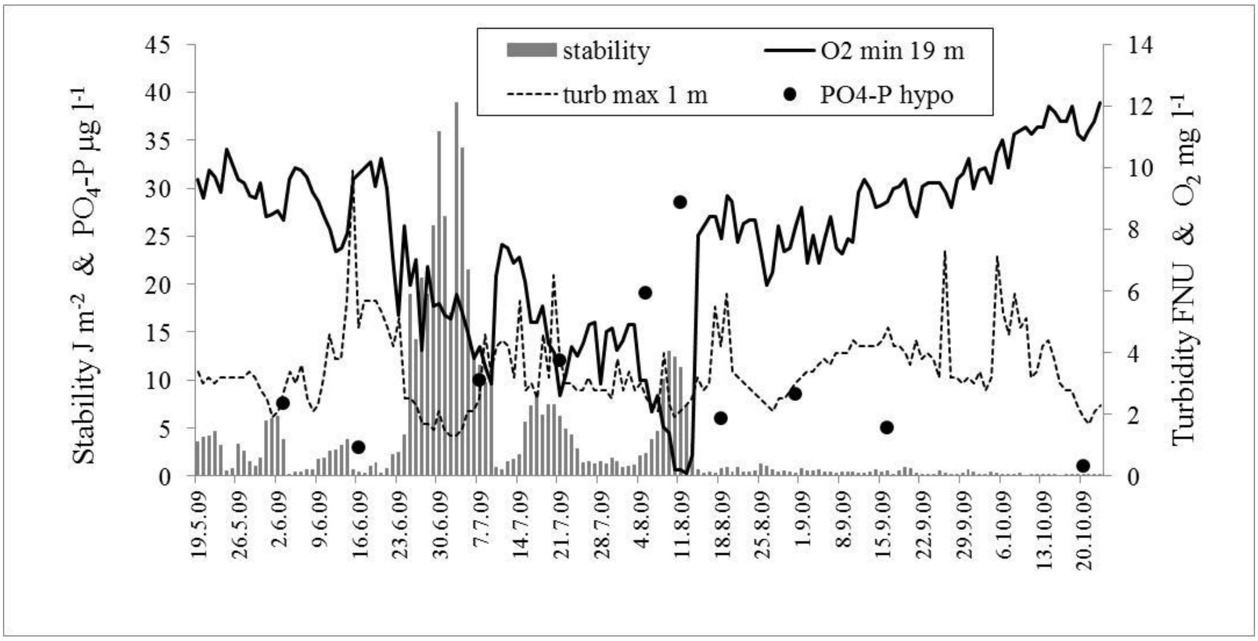

stability
O2 min 19 m
turb max 1 m
PO4-P hypo
Stability J m-2 & PO4-P µg l-1
Turbidity FNU & O2 mg l-1
45
40
35
30
25
20
15
10
5
0
14
12
10
8
6
4
2
0
19.5.09
26.5.09
2.6.09
9.6.09
16.6.09
23.6.09
30.6.09
7.7.09
14.7.09
21.7.09
28.7.09
4.8.09
11.8.09
18.8.09
25.8.09
1.9.09
8.9.09
15.9.09
22.9.09
29.9.09
6.10.09
13.10.09
20.10.09

Fig. 2

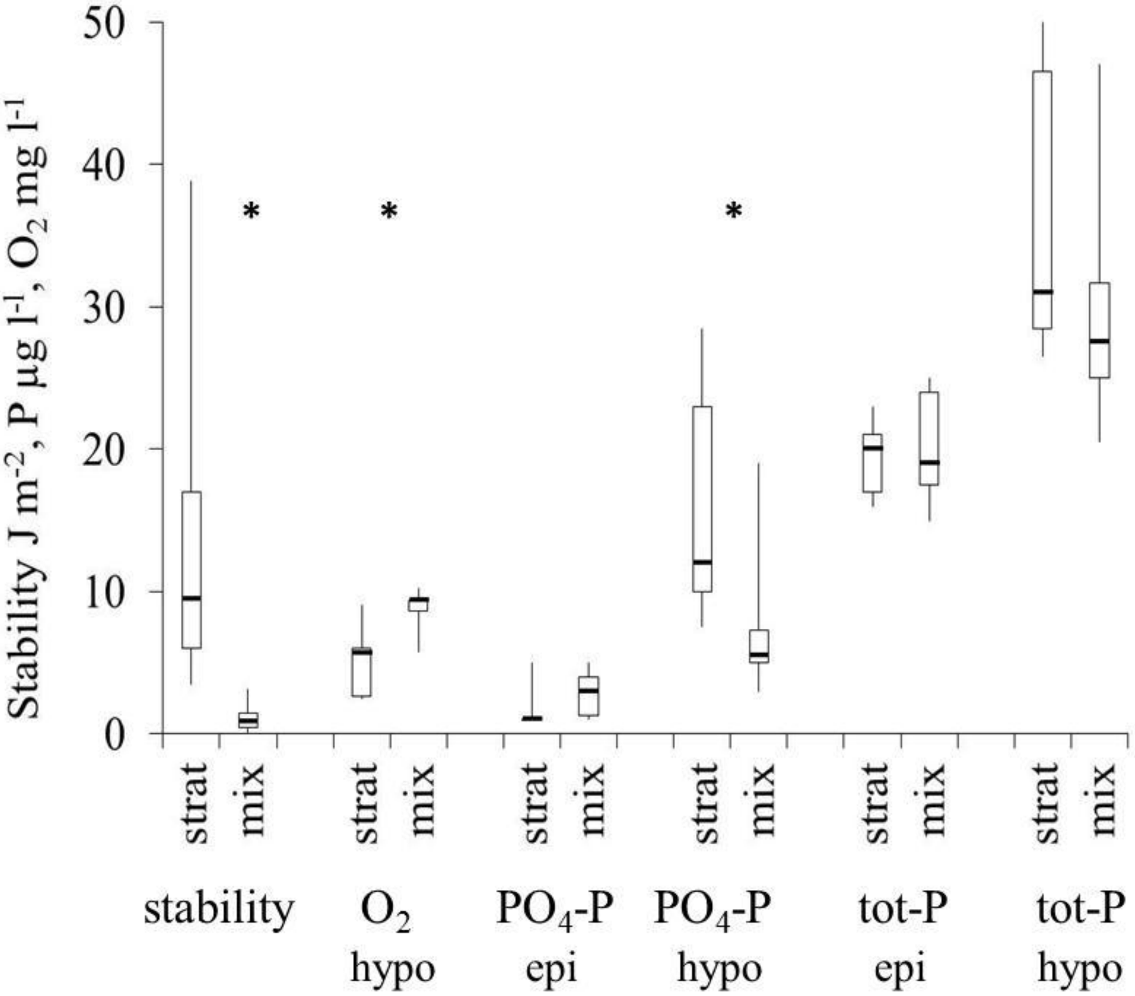

Stability J m-2, P µg l-1, O2 mg l-1
50
40
30
20
10
0
*
*
*
strat
mix
strat
mix
strat
mix
strat
mix
strat
mix
strat
mix
stability
O2 hypo
PO4-P epi
PO4-P hypo
tot-P epi
tot-P hypo

Fig. 3

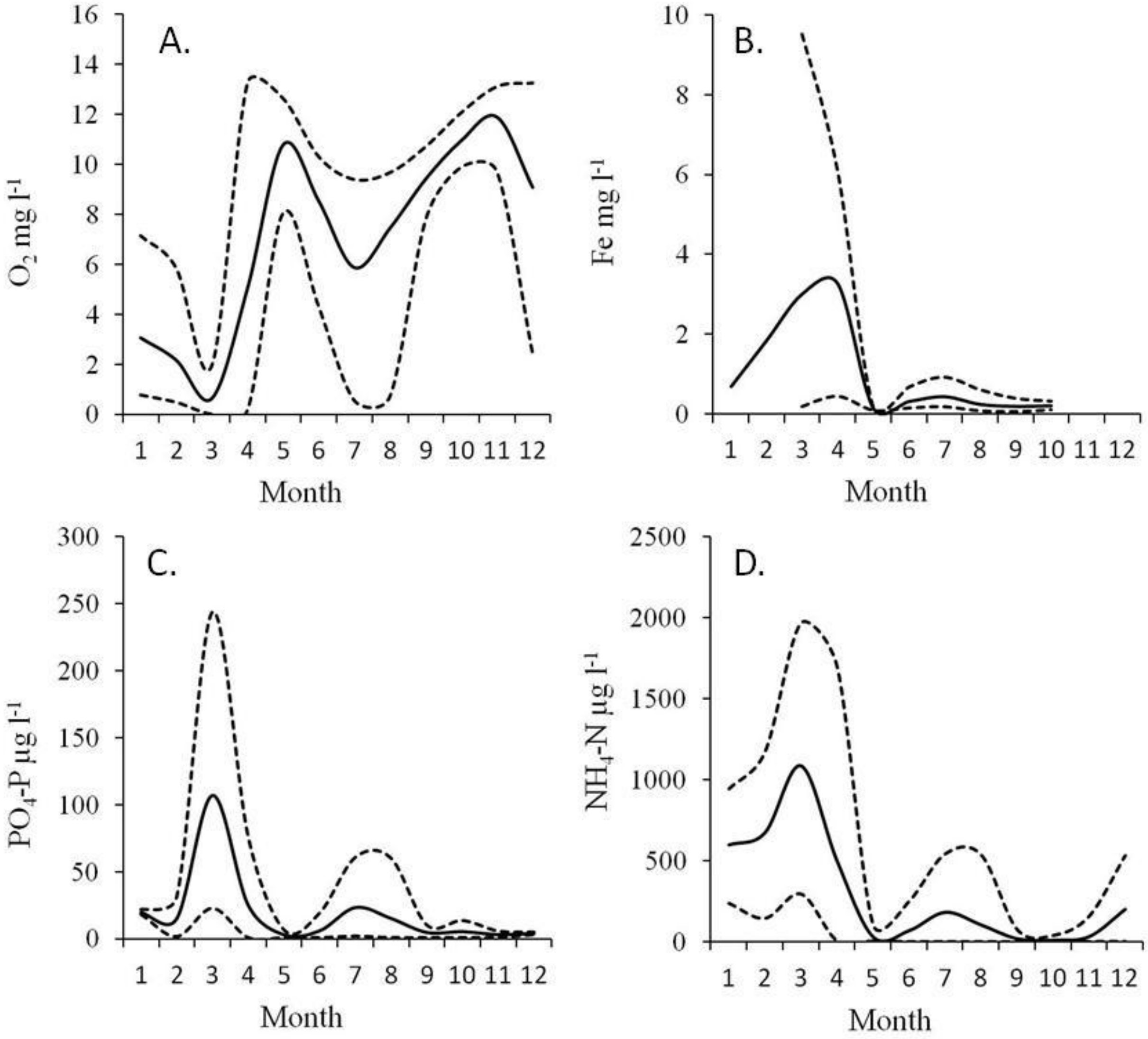
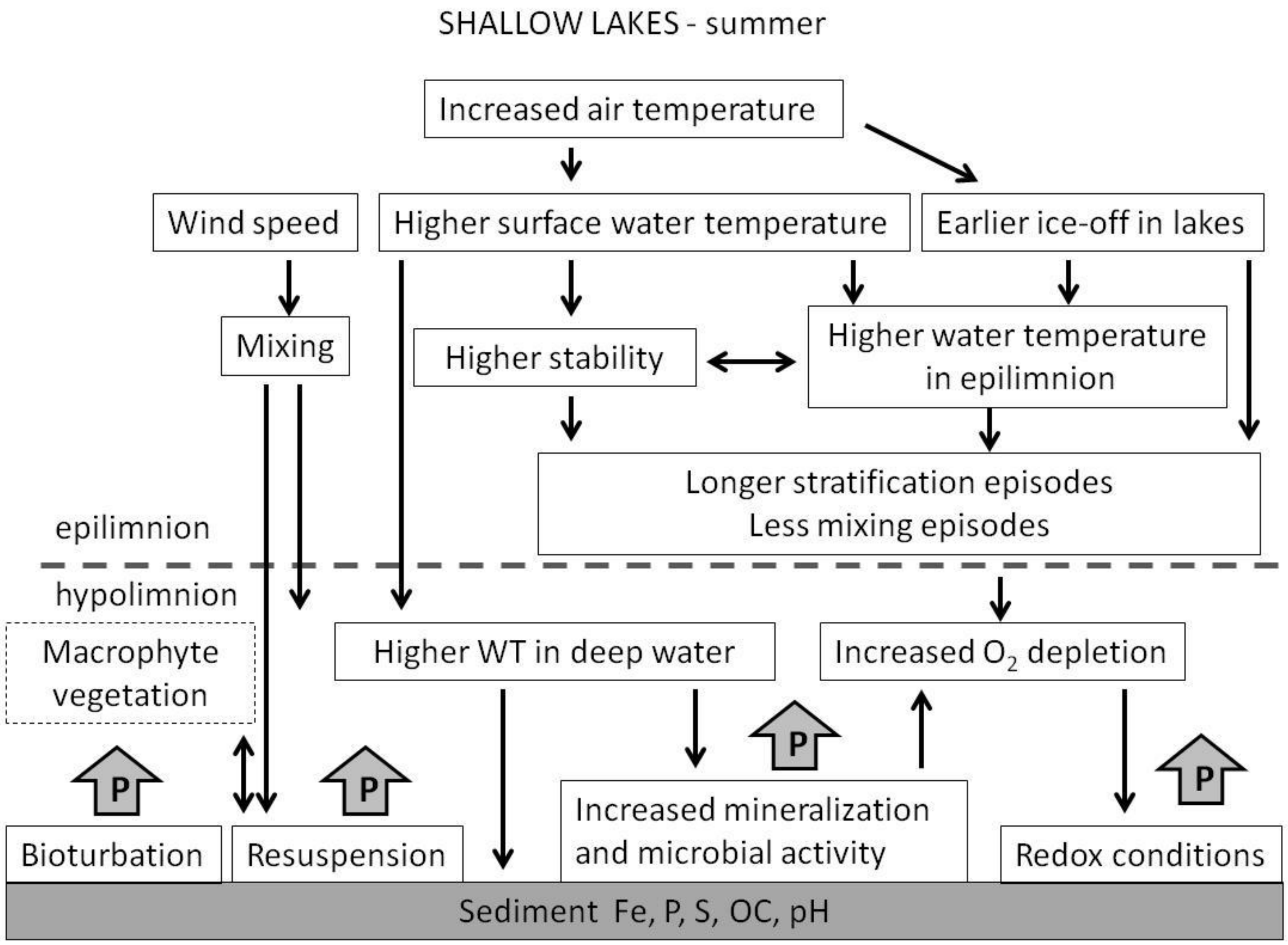

A.
O_2 mg l^{-1}
0
2
4
6
8
10
12
14
16
1 2 3 4 5 6 7 8 9 10 11 12
Month
B.
Fe mg l^{-1}
0
2
4
6
8
10
1 2 3 4 5 6 7 8 9 10 11 12
Month
C.
PO_4-P µg l^{-1}
0
50
100
150
200
250
300
1 2 3 4 5 6 7 8 9 10 11 12
Month
D.
NH_4-N µg l^{-1}
0
500
1000
1500
2000
2500
1 2 3 4 5 6 7 8 9 10 11 12
Month

Fig. 4


SHALLOW LAKES - summer
Increased air temperature
Wind speed
Higher surface water temperature
Earlier ice-off in lakes
Mixing
Higher stability
Higher water temperature in epilimnion
Longer stratification episodes
Less mixing episodes
epilimnion
hypolimnion
Macrophyte vegetation
Higher WT in deep water
Increased O2 depletion
P
P
P
P
Bioturbation
Resuspension
Increased mineralization and microbial activity
Redox conditions
Sediment Fe, P, S, OC, pH