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RESEARCH ARTICLE

Wind-induced sediment resuspension as a potential factor sustaining eutrophication in large and shallow Lake Peipsi

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Abstract Using sediment traps, we aimed to elucidate the temporal and spatial variations in sediment fluxes in large and shallow Lake Peipsi, over the May to October 2011 period, and analyze the factors behind those variations. The effects of weather factors (mean and maximum wind velocity, water level and water temperature) on sediment resuspension and the concentrations of suspended solids (SS), total phosphorus (TP), soluble reactive phosphorus (SRP), and chlorophyll a (Chl *a*) were investigated. Moreover, the internal loading of TP due to sediment resuspension was determined. The sediment resuspension rates were significantly higher in the shallower waters than in the deeper parts of the lake. Resuspension was a major factor in sedimentation dynamics of the lake, which is presently subject to eutrophication. The rates of sediment resuspension followed the same pattern as gross sedimentation during the study period, and their respective values differed significantly between sampling dates. The highest resuspension rates were observed in September (mean 55.4 g dw m^{-2} day^{-1}), when the impacts of wind events were particularly pronounced. Weather factors that were recorded approximately 2 weeks before water and sediment sampling affected the gross sedimentation and sediment resuspension. The water quality variables of SS, TP, SRP, Chl *a* were similarly affected. During the study, TP concentrations of the water were mainly determined by the resuspension of sediments containing a large pool of organic material. Although internal loading of TP due to resuspension was several times greater than external loading, external loading determines the amount of phosphorus that enters the lake and can be resuspended.

Keywords Sediment resuspension · Gross sedimentation · Temporal and spatial variations · Large and shallow lake · Internal loading of total phosphorus

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Introduction

The management of lake water quality is particularly complicated due to the multiplicity of factors that need to be considered. One such factor, sediment resuspension, usually accounts for the majority of the gross sedimentation, and is a natural process that has a continuous impact on lake ecosystems over long periods of time (Weyhenmeyer 1998). Wind-induced resuspension frequently causes increased concentrations of suspended solids (SS) in lake waters (Søndergaard et al. 2003). Particulate-bound forms of phosphorus (P) that have settled on the bottom of a lake may be resuspended several times before permanent sedimentation occurs (Ekholm et al. 1997). Therefore, resuspended sediments may serve as a potential source of nutrients for phytoplankton growth and reproduction.

The amount of sediment that becomes resuspended during a wind event is thought to be dependent on wind velocity and duration, effective lake fetch, morphology, in addition to sediment characteristics (Evans 1994). These are, in turn, regulated by many other factors. For example, water level (*L*) fluctuations cause large variations in lake depth (Nõges et al. 2003; Punning et al. 2009). Impacts of water temperature (*T*) on sediment characteristics include stimulation of the mineralization of organic matter, and increased sedimentation of organic material (Søndergaard et al. 2003). In general, the "dynamic ratio" of lakes is proportional to the percentage of the lake bottom that is subject to resuspension activities (Håkanson 1982, 2006). The dynamic ratio is obtained by dividing the square root of the surface area of the lake in square kilometers by its mean depth in meters (Håkanson 1982, 2006). High ratios (more than 0.8) indicate a high risk of wind resuspension events (Bachmann et al. 2000).

Examples of lakes with high dynamic ratios are Lake Okeechobee (USA), Lake Taihu (China), Lake Balaton (Hungary), and Lake Peipsi (Estonia/Russia). Wind was identified as the main driving force behind P dynamics over hourly, daily, and seasonal time scales in Lake Okeechobee (Havens et al. 2007). Wind-induced sediment resuspension in Lake Okeechobee was estimated to transport 6–18 times the amount of P in the water column as transported by diffusive flux, and up to six times the amount of P found in external loads, when the data are compared on a yearly basis (Havens et al. 2007). In Lake Taihu, total phosphorus (TP) loading due to resuspension was estimated to be 5–10 times the external load (Qin et al. 2006). Wave-reduction engineering approaches, including a concrete wave barrier and a soft enclosure, in the same lake resulted in reduced sediment resuspension (Huang and Liu 2009). In the highly calcareous Lake Balaton, the daily rate of resuspension was found to be high, but this failed to detectably increase typically low concentrations of soluble reactive phosphorus (SRP). Resuspended particles can either adsorb P from the water or release it (demonstrating either a positive or negative relationship), and this depends on the differences between equilibrium concentrations of P in sediment and water (Søndergaard et al. 2003).

High P concentration is thought to be the main reason for the degradation of the water quality in the shallow and eutrophic Lake Peipsi (Kangur and Möls 2008). However, resuspension of sediments and its contribution to the problem have never been studied in this lake. Moreover, the study contributes to the overall knowledge on the sediment resuspension in large and shallow lakes, which are expected to be particularly influenced by resuspension (Havens et al. 2007; Kelderman et al. 2012), but where there is lack of empirical studies due to complexity of the measurements in the field. Additionally, it is of great importance to analyze systematically the factors controlling resuspension, its quantitative significance, and impacts on lake metabolism (De Vicente et al. 2010). Our present study aimed at the following objectives: (a) the elucidation of the temporal and spatial variations in sediment resuspension and gross sedimentation in two limnologically different parts of the large and shallow lake; (b) an investigation into the effects of mean and maximal wind velocity (*V* and Vmax), water level (*L*), and water temperature (*T*) on sediment resuspension and the associated concentrations of TP, SS, chlorophyll a (Chl *a*), and SRP; and (c) an assessment of the internal loading of TP due to sediment resuspension.

Materials and methods

Study area

Lake Peipsi (surface area 3,555 km^2) is located on the border between Estonia and Russia (Fig. 1a). It is the largest transboundary lake in Europe. The lake extends in the meridional direction for more than 150 km and consists of three parts, each of which has different morphometry, hydrology, trophic state, and composition of biota (Kangur and Möls 2008; Table 1). Our study was conducted in Lake Peipsi sensu stricto (Peipsi s.s.; surface area 2,611 km^2, mean depth 8.3 m), and in Lake Lämmijärv (surface area 236 km^2, mean depth 2.6 m). The majority of nutrients are carried into Lake Peipsi by the rivers Velikaya and Emajõgi (Loigu et al. 2008). The mean water residence time has been estimated to be approximately 2 years for the whole lake (Jaani et al. 2008). Lake Peipsi is located in the northern temperate region, and it is normally covered with ice from December till April. In the ice-free period, the temperature stratification is unstable, and the lake is usually rich in oxygen (Haldna et al. 2008). Water level is not regulated, and it undergoes considerable natural fluctuations: 3.04 m range over the last 80 years, and 1.5 m annual mean (Jaani et al. 2008).

Punning et al. (2009) distinguished three areas of surface sediments in Lake Peipsi s.s. The erosion area is marked by coarse-grained sediments, mainly sands that occur in the near-shore area and in the southern part of the lake. The transportation area is marked by mixed sediments of silty sands. The accumulation area is marked by finely-grained sediments that generally coincide with depth contours of 8 m. Data on sediment composition in Lake Lämmijärv are scarce. Those data that do exist on Lake Lämmijärv are contradictory due to the lack of studies and complex character of the bottom that is largely affected by the water currents (Raukas 2008).

Sampling and analyses

Sampling was conducted at five sampling stations at 14-day intervals from 24 May to 10 October 2011 inclusive. Gross sedimentation and sediment resuspension were

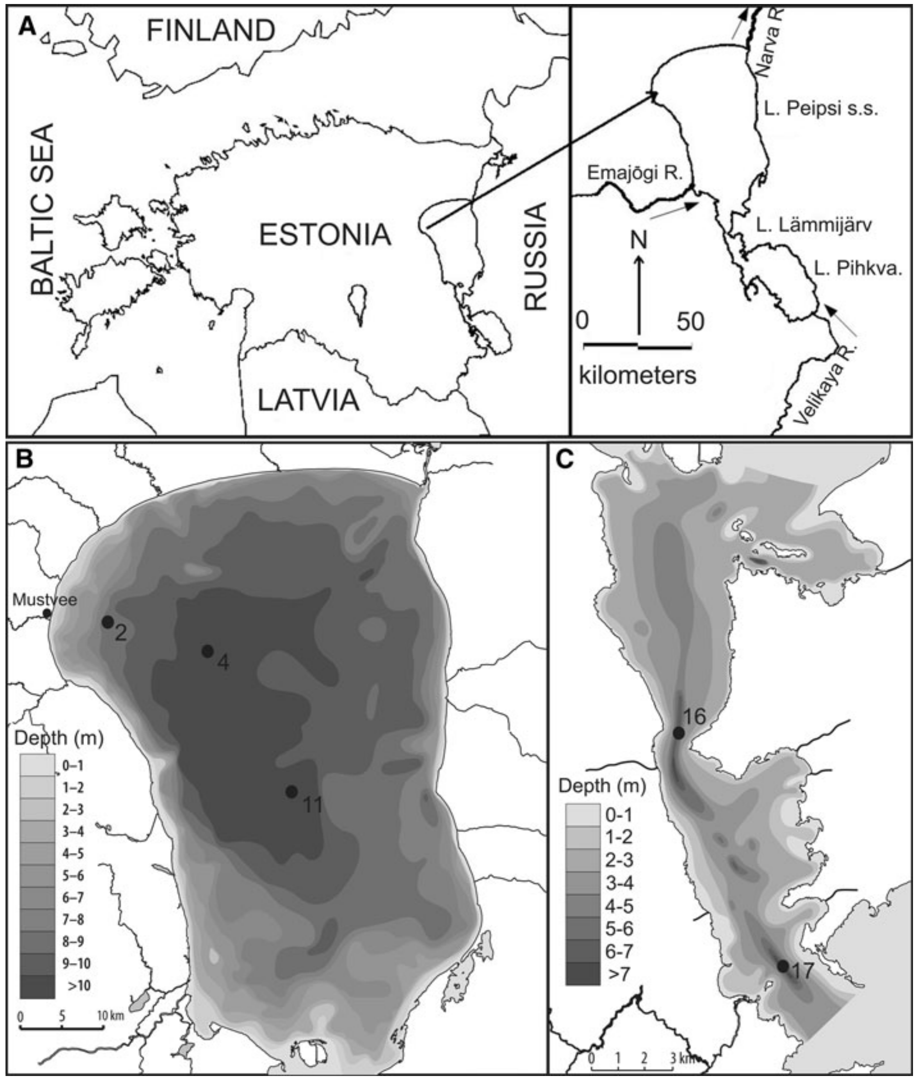

Fig. 1 **a** Location of Lake Peipsi that consists of three parts; **b** the topography and location of sampling stations (numbers 2, 4, 11) in Lake Peipsi sensu stricto; **c** the topography and location of sampling stations (numbers 16 and 17) in Lake Lämmijärv (the map of topography was modified from Raukas 2008)

Table 1 Main morphometric and water quality characteristics of the three parts of Lake Peipsi (Lake Pepsi sensu stricto, Lake Lämmijärv and Lake Pihkva)

Water quality variables are presented as geometric means and 90 % tolerance limits are given in brackets. These estimates correspond to the open water periods (Julian days 100–310 within each year) between 2006 and 2010 (modified from Kangur et al. 2013)

Characteristic	Lake Peipsi s.s.	Lake Lämmijärv	Lake Pihkva
Surface area (km^2)	2,611	236	708
Surface area in Estonia/Russia (%)	55/45	50/50	1/99
Maximum depth (m)	12.9	15.3	5.3
Mean depth (m)	8.3	2.5	3.8
Water volume (km^3)	21.79	0.6	2.68
TP (μg P l^{-1})	38 (17–82)	67 (32–140)	116 (53–251)
TN (μg N l^{-1})	703 (417–1188)	896 (573–1401)	1143 (829–1577)
Chlorophyll *a* content (μg l^{-1})	18 (6–54)	33 (14–81)	63 (26–150)
Secchi depth (m)	1.8 (1.0–3.2)	0.95 (0.6–1.5)	0.7 (0.4–1.0)
OECD (1982) classification	Eutrophic	Eutrophic/hypertrophic	Hypertrophic

quantified with the aid of cylindrical sediment traps, at sampling stations numbered 2, 4 and 11 (at depths 8, 10 and 10 m) in Lake Peipsi s.s. (Fig. 1b) and at stations numbered 16 and 17 (at depths 14 and 7 m) in Lake Lämmijärv (Fig. 1c). The sediment traps (plastic tubes, 4.4 cm in diameter and 44 cm in height) were designed to be suitable for lake conditions (Bloesch and Burns 1980). The exposure time (14-day intervals) was also within the limits recommended for experiments on settling fluxes for organic material (Bloesch and Burns 1980). Sediment traps were replicated four times and were deployed 2 m above the bottom of the lake. In the laboratory, the contents of the traps were dried at 60 °C for approximately 3 days to obtain their dry weights. The organic fraction of the entrapped material was determined by loss-on-ignition at 550 °C for 2 h.

Water samples were taken for the determination of SS, SRP, TP and Chl *a*. These samples were collected using a 2 l Van Dorn sampler that was hauled over each metre of the water column beginning from the water surface to ensure that integrated water samples were taken. The samples for SS were filtered through a Whatman GF/C filter (pore size 1.2 μm) and analysed for dry weight and loss-on-ignition. The concentrations of TP and SRP were determined using an ammonium molybdate spectrophotometric method (EVS-ES 1189). The SRP samples were initially filtered through a Whatman mixed cellulose ester filter (pore size 0.45 μm). The samples for Chl *a* were filtered through a Whatman GF/C filter (pore size 1.2 μm) and analysed spectrophotometrically after extraction with ethanol.

Surface sediment samples (top-most 0–1 cm) were collected by a HTH gravity corer (Pylonex Termokonsult, Umeå, Sweden) and the dry weights (dw) and loss-on-ignition were obtained. After wet combustion with nitric acid and hydrogen peroxide, the concentration of TP was determined for each surface sediment sample by an inductively coupled plasma mass spectrometer.

At each station, the vertical profiles of temperature were measured using a YSI-6620 (YSI Corporation, Yellow Springs, OH, USA). Daily wind velocities, wind directions, water levels and water temperatures were measured at the Mustvee station (58°50′N, 26°57′E), and these data were obtained from the Estonian Institute of Meteorology and Hydrology.

The sampling schedule was stipulated to enable the researchers to calculate the gross sedimentation (*S*), i.e., entrapped settling flux, and to quantify the rate of resuspension according to the method described by Gasith (1975). That method is one of the most commonly used, and it is suitable for shallow lakes. The method is considered to be reliable when the organic matter content of the bottom sediment is different from that of suspended seston (Horppila and Nurminen 2005). The rate of sediment resuspension (*R*) is calculated using the formula:

$$R = S\frac{(f_S - f_T)}{(f_R - f_T)},$$

where *R* the resuspended bottom sediment (dry weight). *S* the entrapped settling flux (dry weight), f_S the organic fraction of *S* (the entrapped sediment), f_R the organic fraction of the surface sediment, f_T the organic fraction of seston suspended in the water.

The internal loading of TP was calculated by multiplying the mean rate of sediment resuspension by the mean concentration of TP in the surface sediments in 2011 (Horppila and Nurminen 2003).

Statistical methods

Between-station differences in sedimentation and resuspension rates were tested using analysis of variance for repeated measurements. Paired comparisons were conducted with Tukey *t*-tests (SAS Institute Inc. 2008). All parameters were initially log-transformed to normalise the obtained distributions. The relationships between the water quality variables (the concentrations of SS, TP, SRP, Chl *a*) were studied with Pearson correlation analysis.

The influence of the weather factors [i.e., water level (*L*), water temperature (*T*), mean and maximum wind velocity (*V*, Vmax)] on the weather-dependent variables was analysed. Initially, we eliminated the influence of sampling site and time on the following variables: the sediment resuspension, the other parameters of the Gasith equation (i.e., S, f_R, f_S, f_T), and water quality variables (i.e., TP, SRP, SS, Chl *a*). For this purpose, we replaced the values of these variables with residuals, i.e., the difference between observed values and those predicted from the sampling site and time. This step can also eliminate part of the influence of weather factors due to their potential correlation with the sampling site and time. The analysis of the residuals has less ambiguity than the analysis of the raw data variables because it separates the effects of factors that are possibly associated with, but not necessarily causally depending on the weather, from the overall correlation between weather and water variables.

The residuals of each variable were separately subjected to stepwise regression analysis using predictors constructed from the weather factors. Since the weather factors varied greatly over time, but response is likely to depend on the average weather conditions over some time, we averaged the weather variables over the time intervals from 1 to 8 days, considering the time intervals measured 0–10 days earlier than the sampling. Consequently, (4 weather factors) × (8 averaging intervals) × (11 backward time shifts) = 352 various means of weather factors were associated with each sampling time. In our stepwise search, the influence of a weather factor was identified by two indices: the number of days for which the parameter was averaged and the delay of the effect of weather factor. For example, V_{7_2} denotes the mean effect of the wind velocity measured from 2 to 8 days before sampling. In the stepwise selection procedure, we used the critical significance level of $p = 0.001$ for both including a weather factor term in or excluding it from the model after the inclusion of the next significant term. The contribution of each newly added term to the model improvement was measured with the partial R^2. Selection of terms continued until no more were significant at $p < 0.001$.

Results

Weather variables

During the study period, average daily wind velocities varied from 0.2 to 5.5 m s^{-1}, and the maximum daily velocities ranged from 3.5 to 16.4 m s^{-1}. The highest values were recorded in the middle of September (Fig. 2). During the study period, the prevailing wind direction was south-west, especially for the winds of higher velocities.

The water level decreased gradually from 270 cm (measured at the level of 28 m a.s.l., according to the Mustvee hydrometric station) in May to 160 cm in October (Fig. 2). The measurements of temperature and oxygen profiles indicated that the water column was being fully mixed over the study period. The highest water temperature values were measured in the middle of the study period (July 18: 20.9 °C in Lake Peipsi s.s.).

Gross sedimentation, resuspension, and resuspension-mediated internal TP loading

The organic fraction of entrapped material (f_S) for Lake Peipsi s.s. (mean value 36.5 %) was significantly higher than that for Lake Lämmijärv (mean 28.7 %) ($p < 0.001$). In Lake Peipsi s.s., f_S peaked in July (48 %), then declined and remained between 33 and 35 % throughout August and September (Fig. 3). No July peak in f_S was observed for Lake Lämmijärv, but similar to Lake Peipsi s.s., the f_S values barely altered (range from 29 to 30 %) throughout August and September (Fig. 3).

During the study period, the organic fraction of suspended seston (f_T) varied between 50.4 and 95.4 %, which was significantly higher ($p < 0.001$) than the organic fraction of the surface sediments (f_R); therefore, the method of Gasith (1975) could be reliably used. The f_R mean was 24.3 % and significantly higher ($p < 0.001$) in Lake Peipsi s.s. (27.7 %) than in Lake Lämmijärv (19.5 %). In Lake Lämmijärv, f_R ranged from 5.6 to 26.5 %: with significantly higher values recorded after the beginning of August (Fig. 3). In Lake Peipsi s.s., there were no clear and statistically significant seasonal variations in f_R values during the study period, which ranged from 24.4 to 30.2 % (Fig. 3).

In the period from May to October, some sediment traps were lost from the sampling site for unknown reasons; as a result, the rates of gross sedimentation and resuspension in these cases could not be estimated. Generally, the gross sedimentation rates varied greatly in Lake Peipsi during the study period in 2011 (Fig. 4). In Lake Peipsi s.s., the rates varied between 1.0 and 54.3 g dw m^{-2} day^{-1}. The sedimentation rates increased steeply in the middle of August and reached the highest values in September. The differences between four replicates (expressed with the coefficients of variation = (standard deviation/average) * 100 %; as in Bloesch and Burns 1980) varied from 2 to 5 % in Lake Peipsi s.s.

The gross sedimentation rates of Lake Lämmijärv fluctuated between 28.0 and 103.2 g dw m^{-2} day^{-1}. The

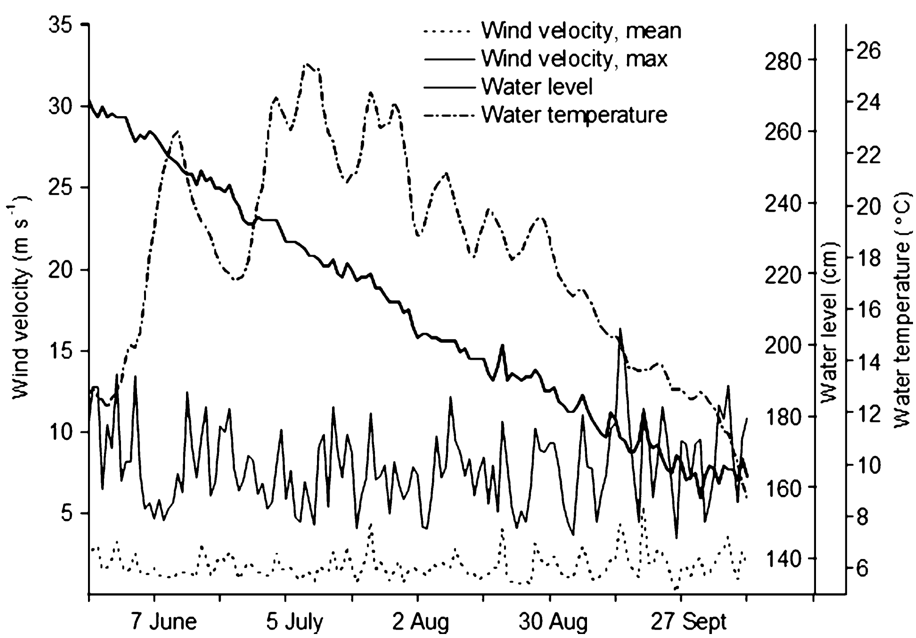

Fig. 2 Mean and maximum daily wind velocities, water level (in centimetres above the zero point 28 m) and water temperature during the study period, measured at the Mustvee hydrometric station

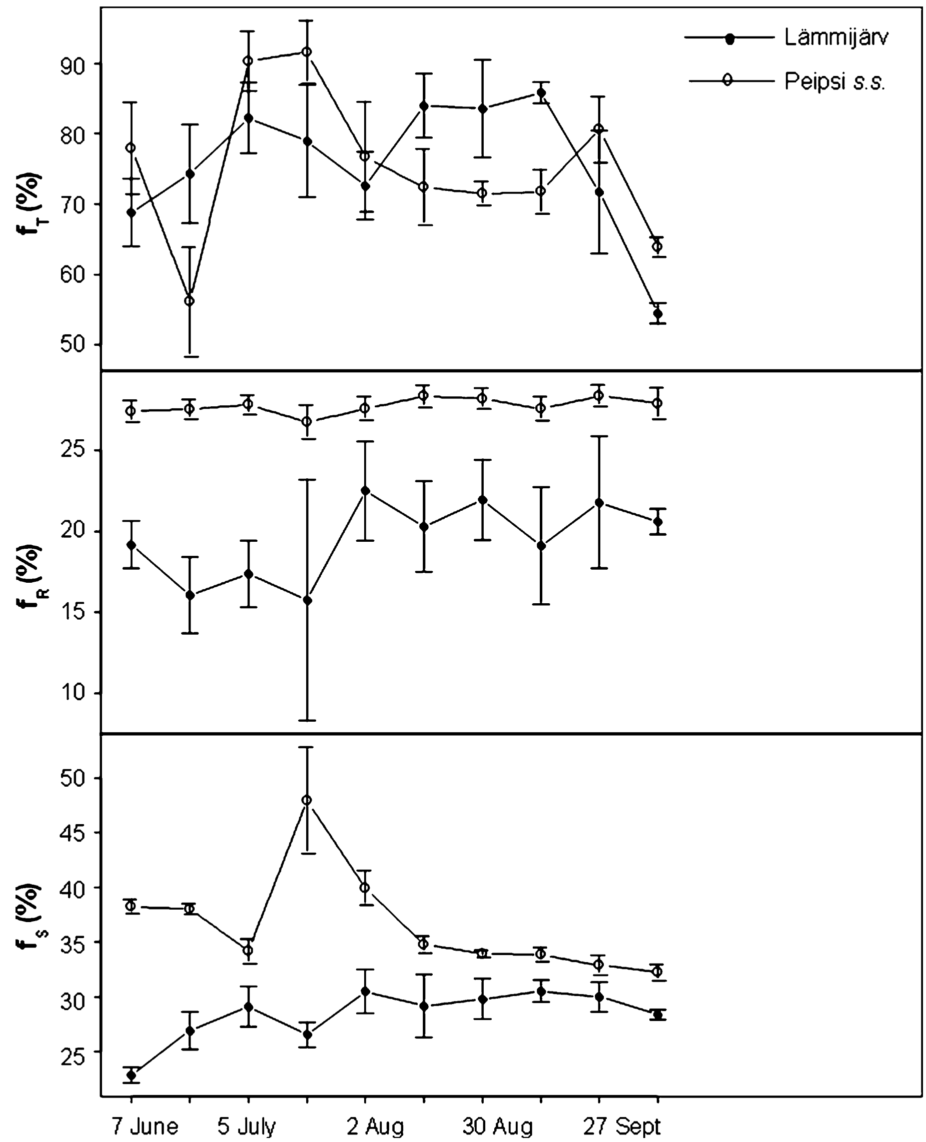

Fig. 3 Mean organic fraction (%) of the suspended seston (f_T), surface sediment (f_R), and entrapped material (f_S) with 95 % confidence limits in Lake Peipsi s.s. and in Lake Lämmijärv during the study period in 2011

lowest values were measured at the beginning of September. Thereafter, the gross sedimentation rates increased and peaked at 64.7 g dw m^{-2} day^{-1} at station 17. The highest sedimentation rates (seasonal mean 81 g dw m^{-2} day^{-1}) were measured at the deepest area (station 16), where the maximum value (103.2 g dw m^{-1}) was measured in the middle of August. At station 17, the sedimentation rate (seasonal mean 43 g dw m^{-2} day^{-1}) was significantly lower ($p < 0.001$) than that of station 16. As in Lake Peipsi s.s., the differences between four replicates were small (varied from 1 to 6 %).

The sedimentation rates were statistically significantly different between sampling stations ($p < 0.001$), and between dates ($p < 0.001$) for both Lake Peipsi s.s. and Lake Lämmijärv.

Generally, the resuspension rates followed the same seasonal pattern as the gross sedimentation in the study period in 2011 (Fig. 4). In Lake Peipsi s.s., the sediment resuspension rates accounted for between 53.8 and 92.6 % of the gross sedimentation. In Lake Lämmijärv, the rates of sediment resuspension as the percentage of the gross sedimentation varied from 76 to 94.6 %.

Based on the mean resuspension rate (Lake Peipsi s.s.: 13.5 g dw m^{-2} day^{-1}; Lake Lämmijärv: 52 g dw m^{-2} day^{-1}) and the mean P concentration of the surface sediment (Lake Peipsi s.s.: 1,756 mg P kg^{-1} dw; Lake Lämmijärv: 1,349 mg P kg^{-1} dw, measured from the accumulation area of the corresponding parts in 2011), the internal loading of TP due to resuspension can amount to 8.6 g P m^{-2} y^{-1} in Lake Peipsi s.s. and up to 25.6 g P m^{-2} y^{-1} in Lake Lämmijärv.

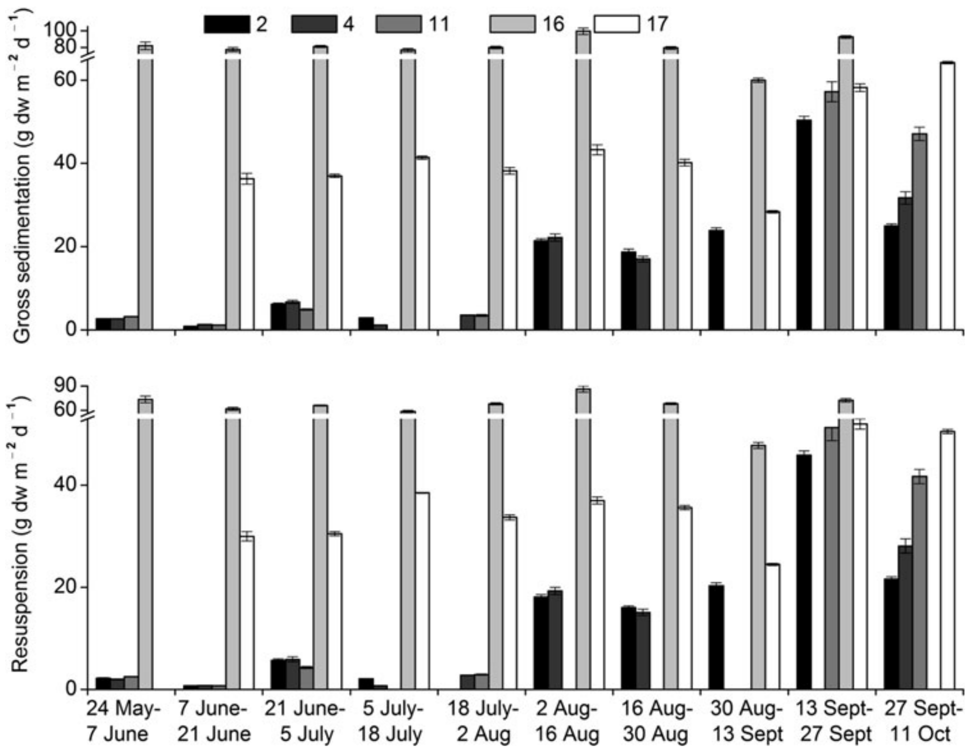

Fig. 4 Mean daily rates of sedimentation and sediment resuspension with 95 % confidence limits in Lake Peipsi s.s. (station numbers 2, 4, and 11) and in Lake Lämmijärv (station numbers 16 and 17) during the study period in 2011. Missing data were due to the disappearance of the sediment traps from the lake stations

Water quality

The concentration of SS at the end of the trap exposure period closely followed the pattern of gross sedimentation and resuspension (Fig. 5). In Lake Lämmijärv, this peaked at the beginning of August (22 mg l^{-1}), declined and then remained between 15 and 17 mg l^{-1} until the end of September, at which time a sharp increase occurred (10 October: 30 mg l^{-1}). In Lake Peipsi s.s., SS started to increase from the middle of July, and attained the highest value in the autumn (13 mg l^{-1}).

Significant correlations were found between SS and TP in Lake Peipsi s.s. ($r = 0.86$, $p < 0.001$) and in Lake Lämmijärv ($r = 0.81$, $p < 0.001$). During the study period, TP values ranged from 52 to 106 μg l^{-1} in Lake Peipsi s.s., and from 94 to 145 μg l^{-1} in Lake Lämmijärv. The TP values were the lowest at the beginning of the study period and increased towards the autumn (Fig. 5). The concentration of SRP varied from 2 to 43 μg l^{-1} in Lake Peipsi s.s., and from 6 to 36 μg l^{-1} in Lake Lämmijärv (Fig. 5). The correlation between SS and SRP was not statistically significant.

In Lake Peipsi s.s., Chl *a* levels followed a seasonal pattern close to that of SS and TP: the concentration increased towards autumn, peaking at 40.7 μg l^{-1} (Fig. 5). In Lake Peipsi s.s., a significant relationship was found between TP and Chl *a* ($r = 0.85$, $p < 0.001$), and Chl *a* and SS ($r = 0.87$, $p < 0.001$), whereas the equivalent correlations were not statistically significant for Lake Lämmijärv.

According to the regression analysis, the weather factors that prevailed approximately 2 weeks before water and sediment samples were taken showed significant effects on the studied variables (Table 2). Wind velocity was estimated to be the best predictor of sediment resuspension, as well as of the all other parameters of the Gasith equation (S, f_R, f_S, f_T), and SRP in the corresponding regression model, indicating that wind was the most important factor behind variations of these studied variables. In the cases of TP, SS, and Chl *a* concentrations, stepwise regression analysis revealed water level to be the best predictor, and wind velocity was selected as the factor, which improved the prediction of these water quality variables (see increase of the corresponding model R^2 by partial R^2). The inclusion of water temperature in the regression model resulted in the improvement of the prediction of f_S.

Discussion

Spatial and temporal variations in gross sedimentation and sediment resuspension

The rates of gross sedimentation and sediment resuspension exhibited large spatial and temporal variations in Lake Peipsi. The southern, shallow part of the lake had significantly higher values than northern part, which is larger and deeper. It is well documented that shallow lakes are usually more susceptible to wind-induced waves and water

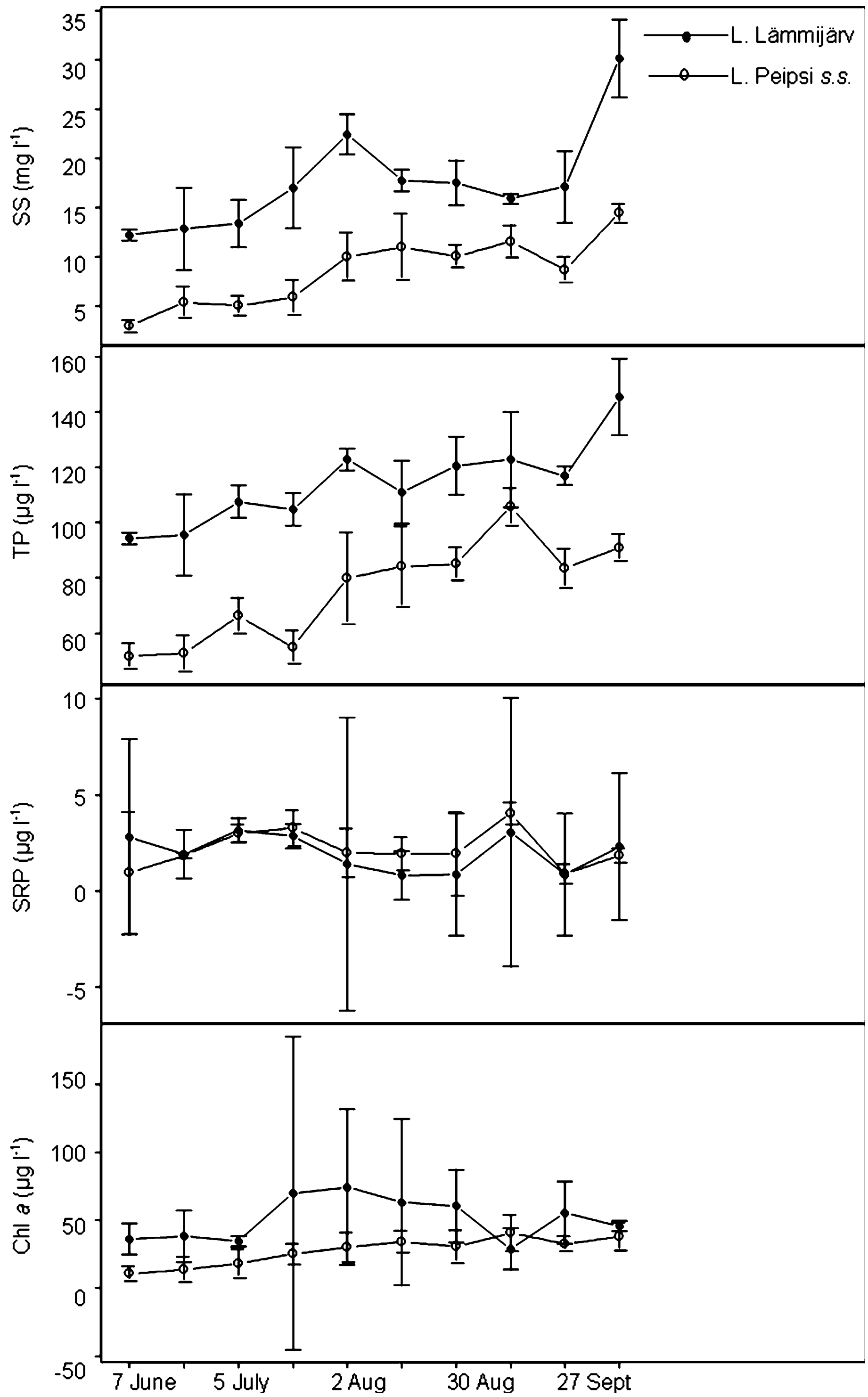

Fig. 5 Mean concentrations of suspended solids (SS), total phosphorus (TP), soluble reactive phosphorus (SRP), and chlorophyll *a* (Chl *a*) with 95 % confidence limits in Lake Peipsi s.s. and in Lake Lämmijärv during the study period in 2011

currents, and therefore more predisposed to sediment resuspension, than deep lakes (Rosa 1985; Hilton et al. 1986; Evans 1994). However, the highest gross sedimentation and resuspension rates were observed in the deepest site measured in Lake Peipsi. Earlier studies have explained this phenomenon in terms of lake bottom processes being subject to sediment focusing: i.e., sediment that is resuspended in shallow areas is often transported into deeper water zones where it is subsequently deposited (Hilton et al. 1986; Koski-Vähälä et al. 2000; Horppila and Niemistö 2008). As a result, the trap catches of the deep areas can give an overestimation of the actual sedimentation and resuspension rates (Horppila and Niemistö 2008). Additionally, Niemistö et al. (2012) emphasized the

Table 2 The most influential weather factor terms selected by stepwise regression analysis and included in the regression model as predictors of the weather-dependent variables

Dependent	Factor term	Partial R^2	Model R^2	p
Resuspension	V_{1_5}	0.59	0.59	<0.0001
	V_{2_10}	0.06	0.65	<0.0001
	$Vmax_{1\_7}$	0.03	0.68	0.0004
Sedimentation	V_{1_5}	0.64	0.64	<0.0001
	L_{1_0}	0.07	0.71	<0.0001
	L_{3_4}	0.05	0.75	<0.0001
Organic content of entrapped sediment (f_S)	$Vmax_{1\_7}$	0.12	0.12	<0.0001
	T_{1_8}	0.07	0.19	0.0004
	$Vmax_{4\_6}$	0.07	0.26	0.0002
Chlorophyll *a* (Chl *a*)	L_{1_1}	0.38	0.38	<0.0001
	V_{3_2}	0.12	0.50	<0.0001
	V_{2_0}	0.14	0.64	<0.0001
	$Vmax_{2\_3}$	0.04	0.68	<0.0001
Soluble reactive phosphorus (SRP)	$Vmax_{6\_6}$	0.37	0.37	<0.0001
	V_{1_10}	0.07	0.44	<0.0001
	$Vmax_{1\_3}$	0.07	0.51	<0.0001
Suspended solids (SS)	L_{1_8}	0.56	0.56	<0.0001
	V_{2_2}	0.10	0.66	<0.0001
	V_{4_6}	0.05	0.70	<0.0001
Total phosphorus (TP)	L_{1_0}	0.60	0.60	<0.0001
	V_{2_2}	0.08	0.68	<0.0001
	V_{1_8}	0.07	0.74	<0.0001
Organic content of surface sediment (f_R)	V_{5_6}	0.19	0.19	<0.0001
	V_{8_7}	0.08	0.27	0.0001
Organic content of suspended solids (f_S)	V_{1_4}	0.32	0.32	<0.0001
	V_{1_10}	0.15	0.47	<0.0001

The number of days over which a weather factor was averaged, and the number of days prior to sampling date are shown as numerical indices. For example, V_{2_10} denotes the mean wind velocity for 2 days (days 10–11), recorded 10 days before the measurement of the water variable. The partial R^2 of a factor term is the increment of the regression model R^2 when the corresponding term is added to the model term set

L water level, *T* water temperature, *V* mean daily wind velocity, *Vmax* maximal daily wind velocity

importance of having spatially comprehensive sedimentation measurements that cover both shallow and deep areas to circumvent this overestimation. Consequently, the present study used a comprehensive array of sample points to moderate this effect. Horizontal transport of sediments can be the reason as to how the resuspension rates in Lake Lämmijärv did not show any clear seasonal variations, as they did in Lake Peipsi s.s.

In addition to the differences in morphometry, differences in resuspension fluxes between two adjacent lakes can be attributed to differences in their sediment properties (De Vicente et al. 2010). For example, organic-matter content of the surface sediments of Lake Lämmijärv was far lower than those of Lake Peipsi s.s. The lowest value was measured at the deepest site of the lake, presumably because of the relatively high dynamic transport of sedimentary particulate organic matter in the water column. Such a phenomenon would stimulate the overall mineralization as concluded by De Vicente et al. (2010). This conclusion was also supported by Raukas (2008), who suggested the significant role of water currents in sediment redistribution in Lake Lämmijärv.

Although wind exposure has been considered to be a key factor that affects the mixing processes in large and shallow lakes (Havens et al. 2007; Kelderman et al. 2012), it is sometimes difficult to observe significant correlations between sedimentation (resuspension) rates and wind velocities (Koski-Vähälä et al. 2000). According to the regression analysis used in the present study, wind velocity was found to be a major factor in controlling the gross sedimentation and sediment resuspension processes (Table 2).

The mean daily wind velocities were relatively low during the measurement period in 2011. Nevertheless, maximum daily velocities that exceeded 10 m s^{-1} were recorded in every trap exposure period (14 days). Substantially higher rates of sediment resuspension were obtained at the end of the study period, when the incidence of maximum daily velocities >10 m s^{-1} was highest (seven times) and during which time the strongest wind of 16.4 m s^{-1} was recorded for the whole measurement period. Modelling of currents in Lake Peipsi showed that the wind velocity of 15 m s^{-1} (which was recorded 23 times during the years 1986–1998) resulted in a near-bed current speed of 55 cm s^{-1} close to the shore and in the erosion area, and a value of 20 cm s^{-1} was obtained in the accumulation area (Jaani et al. 2008). These data suggest a strong influence of winds on all bottom sediments (Jaani et al. 2008).

The occurrence of maximum daily velocities >10 m s^{-1}, similar to that measured at the end of the study period, was also recorded at the beginning of the study period (six times). However, the resuspension rates at the beginning of the study period were considerably lower than those measured at the end of the period. Wind direction had no discernable effect since winds from southwest direction prevailed (60 % of all winds) in both periods in our study. One possible explanation for the difference in resuspension rates is the drop in water levels that occurred over the study period. This drop in level may have contributed to the increment of resuspension rates recorded towards autumn. Nõges and Nõges (1999) demonstrated that severe storms that coincided with a period of low water level can entrain substantial quantities of the sediments with a deterioration of the water quality in the large and shallow Lake Võrtsjärv, which is also located in the same catchment as Lake Peipsi.

Increases in the organic content of surface sediments and increases in the organic content of entrapped material in Lake Lämmijärv during the summer indicated the contribution of phytoplankton to the substantial increases in the resuspension rates observed in August. Similarly, Søndergaard et al. (1992) reported that resuspension activity in the eutrophic Lake Arresø in August was higher than in May. Presumably this was because organic matter accumulated onto the sediment of Lake Arresø during summer. Niemistö et al. (2008) also associated the high rates of resuspension in July–August of the eutrophic Lake Kirkkojärvi with elevated autochthonous production, i.e., an abundance of fresh, loose material to resuspend. However, the organic content of surface sediments of Lake Peipsi s.s. showed no seasonal variations during the study period. Unlike the observable differences in water quality, it is sometimes difficult to detect seasonal differences in the quality of the surface sediments due to the presence of almost continuous resuspension that emanates from the lake bottom (Niemistö 2008). It is probable that a steep decline in the organic content of trapped material that followed the midsummer increase in Lake Peipsi s.s. may have been caused by intensified sediment resuspension of recently produced and rapidly mineralised organic matter.

When the Gasith (1975) method is used, erroneous estimates of S and fs may result in erroneous estimates of the resuspension rates (Horppila and Nurminen 2005). However, our estimations of S are reliable as ensured by the appropriate trap design and as indicated by the small differences between trap replicates. Only an underestimation of fs due to increased mineralization could cause an overestimation of trap catches. Such events are more likely to occur in the middle of the study period, when the highest water temperature is recorded, and consequently high rates of mineralization could be expected. Nevertheless, the seven-fold increase in the resuspension rates in Lake Peipsi s.s. found in August can hardly be attributed to erroneous estimates of fs, since even a 50 % underestimation of fs would result in only a 20 % overestimation of the resuspension rate using the Gasith method (Horppila and Nurminen 2005).

The effect of sediment resuspension on water quality

During the open water period, resuspension appeared to play a dominant role as a water quality regulator in Lake Peipsi. It is likely that wind-generated waves and currents affected all water quality variables that were mediated through the resuspension of sediment (Table 2). In Lake Peipsi, the high resuspension rates of autumn resulted in high SS concentrations, which in turn were associated with high TP values. Many authors have emphasized a clear association between high resuspension rates and high SS and TP concentrations in shallow eutrophic lakes (Kristensen et al. 1992; Istvánovics et al. 2004; Havens et al. 2007). Moreover, a similarity in patterns of resuspension, correlated with increased concentrations of SS, TP and Chl *a* in Lake Peipsi s.s. suggest that organic particles that originate from primary production are of major importance in contributing to the material susceptible to resuspension.

The wind effect on sediment resuspension along with the corresponding changes in the water quality was particularly pronounced at low water level. The increases in sediment resuspension rates, and the concentrations of SS, TP and Chl *a*, in Lake Peipsi s.s. were detected in the period of low water levels. Similar observations have been reported earlier for the large and shallow Lake Võrtsjärv (Nõges and Nõges 1999; Nõges et al. 2003). The importance of water level, along with wind velocity, in controlling the concentrations of SS, TP and Chl *a* in Lake Peipsi has also been demonstrated by our regression analysis (Table 2).

Sediment resuspension and internal phosphorus loading

Resuspension continuously mixes P-rich sediment particles into the water column, thus creating the potential for P release (Søndergaard et al. 2003). Resuspension appears to be the dominant factor in Lake Peipsi for increasing the concentration of TP in the water column. Therefore, resuspension can be considered to be the main driving force of internal P loading. The rough estimates for the internal TP loading due to resuspension in the present study (8.6 g P m^{-2} y^{-1} in Lake Peipsi s.s. and 25.6 g P m^{-2} y^{-1} in Lake Lämmijärv) are significantly higher than the fluxes at the sediment-water interface (0.2 g P m^{-2} y^{-1}) previously estimated by Punning and Kapanen (2009). The area-specific external loading was also previously found to be 0.08 g P m^{-2} y^{-1} in Lake Peipsi s.s. and 0.23 g P m^{-2} y^{-1} in Lake Lämmijärv (Loigu et al. 2008). TP internal loading due to resuspension was therefore approximately 100-fold higher (108-fold in Lake Peipsi s.s. and 111-fold in Lake Lämmijärv) compared to that of external loading. Similar trend has been found for Lake Taihu (Qin et al. 2006) and Lake Okeechobee (Havens et al. 2007). However, it is important to emphasize that the amount of material that settles on the bottom of a lake and can be resuspended, ultimately depends on the magnitude of the external nutrient loading (Ekholm et al. 1997). Therefore, both external and internal loading of P should be considered in water management plans.

The effect of sediment resuspension on P availability depends on the characteristics of the lake water, into which the sediment is mixed, and of the sediments themselves (Søndergaard et al. 2003; De Vicente et al. 2010). It is difficult to ascertain how many times bioavailable P will have been assimilated or dissimilated and chemically released or bound before entering a sediment trap in particulate form (Niemistö et al. 2012). This uncertainty can be a possible explanation as to why no significant correlations were found between SS and SRP in the present study. Nevertheless, the regression model showed that wind was the best predictor of the concentration of SRP in the lake. Moreover, Kapanen (2012) concluded that the sediments in Lake Peipsi s.s. contained a large pool of mobile P when she analyzed a core that had been obtained from the accumulation area of the lake. That author reported that the mobile P in Lake Peipsi s.s. included the inorganic P of loosely-adsorbed surface and pore-water P, inorganic P of the redox-sensitive fraction of P that is bound to oxides of reducible metals and also nonreactive P. Thus, resuspension events, particularly those that we observed in autumn in the present study, can enhance the export of the pool P from the sediments to the overlying water.

The extreme meteorological events recorded in our study (the highest wind speed and low water level) that were associated with an increase in the resuspension in autumn are of particular concern. Our observations were in accordance with the modelling results of Punning and Kapanen (2009), who found the highest release of P in Lake Peipsi s.s. occurred in autumn. Considering the forecasted effects of climate change, a higher frequency of extreme wind events can be expected in the future (Jeppesen et al. 2009), which would strongly suggest that resuspension mediated internal loading would increase.

Conclusions

Our study is based on extensive in-field measurements of sediment resuspension, carried out for the first time in the large shallow waters of Lake Peipsi. In addition, the long sampling period and the measurements taken from a comprehensive array of different sampling sites allowed us to produce a reliable mean estimate of internal TP loading due to sediment resuspension in Lake Peipsi. Sediment resuspension in Lake Peipsi is an important factor in regulating the lake's water quality through its significant influence upon loading of suspended solids and phosphorus. The magnitude of sediment resuspension, which has been determined to constitute the majority of the total settling flux, was related to lake morphometry and organic content of sediments at different sites. Wind velocity was the most important predictor for the sediment resuspension. Similarly to other large and shallow lake ecosystems, the potential for recycling of phosphorus, originally brought into a lake by external loading, is high in Lake Peipsi: resuspension-mediated internal loading of TP dominated over the external loading.

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