Eesti Maaülikool
Estonian University of Life Sciences

EFFECTS OF NATURAL AND ANTHROPOGENIC PRESSURES ON VARIATIONS IN THE WATER QUALITY OF LARGE LAKES

LOODUSLIKE JA INIMTEKKELISTE SURVETEGURITE TOIME VEE KVALITEEDI MUUTLIKKUSELE SUURJÄRVEDES

OLGA TAMMEORG *née* BUHVESTOVA

A thesis
for applying for the degree of the Doctor of Philosophy in Hydrobiology

Väitekiri
filosoofiadoktori kraadi taotlemiseks hüdrobioloogia erialal

Tartu 2014

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CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis summarizes the following articles, which are referred to by their corresponding Roman numbers (I–IV) in the text

I **Buhvestova O.**, Kangur K., Haldna M. & Möls T. (2011) Nitrogen and phosphorus in Estonian rivers discharging into Lake Peipsi: estimation of loads and seasonal and spatial distribution of concentrations. *Estonian Journal of Ecology*, **60**, 18–38.

II **Tammeorg O.**, Niemistö J., Horppila J., Haldna M. & Kangur K. (2013) Sedimentation and resuspension dynamics in Lake Vesijärvi (Finland): comparison of temporal and spatial variations of sediment fluxes in deep and shallow areas. *Fundamental and Applied Limnology*, **182**, 297–307.

III **Tammeorg O.**, Niemistö J., Möls T., Laugaste R., Panksep K. & Kangur K. (2013) Wind-induced sediment resuspension as a potential factor sustaining eutrophication in large and shallow Lake Peipsi. *Aquatic Sciences*, **75**, 559–570.

IV **Tammeorg O.**, Möls T. & Kangur K. (2014) Weather conditions influencing phosphorus concentration in the growing period in the large shallow Lake Peipsi (Estonia/Russia). *Journal of Limnology*, **73**, 11–19 (DOI: 10.4081/jlimnol.2014.768).

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Data analysis	**OT**, MH, TM	**OT**, JN, JH, MH	**OT,** TM	TM, **OT**
Manuscript preparation	**OT**, MH, KK	**OT**, JN, JH, MH, KK	**OT**, TM, JN, RL, KK	**OT**, TM, KK

Olga Tammeorg (*née* Buhvestova; **OT**), Tõnu Möls (TM), Juha Niemistö (JN), Jukka Horppila (JH), Marina Haldna (MH), Külli Kangur (KK), Reet Laugaste (RL), Kristel Panksep (KP)

*articles I and IV are based on the data that were collected by different institutes at different times. These data have been archived (the databases of the Centre for Limnology). Data on hydrochemistry have been collected under the auspices of the national monitoring program since 1992, in which the author has participated since 2007. The source of the data has been specified in the Materials and Methods. Data collection in articles I and IV refers to the preparation of the data for the analysis. Moreover, additional data were acquired from the Institute of Meteorology and Hydrology (data on wind speeds, photosynthetically active radiation, water discharge), and from the Estonian Environment Information Centre (data on the river water chemistry).

ABBREVIATIONS

Chl *a* – chlorophyll *a*
DR – dynamic ratio
Fe – iron
f_R – organic content of surface sediments
f_S – organic content of entrapped sediment
f_T – organic content of suspended solids in water
GLM – general linear model
L – water level
N – nitrogen
NTU – nephelometric turbidity unit
P – phosphorus
PAR – photosynthetically active radiation
SAS/GPLOT – procedure of SAS (Statistical Analysis System) for plot generation
SPIM – settling particulate inorganic matter
SPOM – settling particulate organic matter
SRP – soluble reactive phosphorus
SS – suspended solids
T – water temperature
TN – total nitrogen
TP – total phosphorus
TPS – thin plate spline
V – mean wind speed
Vmax – maximum wind speed

INTRODUCTION

External nutrient loading is a permanently acting factor, which determines the water quality of a water body (Rumyantsev *et al.*, 2006; Kondratyev, 2011). Large amounts of nutrients that enter a water body are found in the biota, which *inter alia* includes plankton, macrophytes, fish, and contribute to the pool of recyclable nutrients. Generally, the sedimentation represents a net loss of nutrients from the water column, and these nutrients can be found in sediments. Hence, a steady increase in biological production and decrease in lake depth over long time scales could be expected (i.e., natural successional process or ontogeny; Battarbee *et al.*, 2005; Smith *et al.*, 2006). However, it is external nutrient loading from human sources (point and nonpoint) that typically results in rapid increases in the rate of biological production and creates a wide range of undesirable water quality problems in ecosystems (i.e., cultural eutrophication or eutrophication; Battarbee et *al.*, 2005; Smith et *al.*, 2006).

Finding ways to improve water quality in lakes that undergo cultural eutrophication is considered to be one of the biggest challenges water managers across the world have to face (Spears *et al.*, 2013). The problem is reinforced by the fact that lakes may respond very slowly to the reduction in external nutrient loading due to re-equilibration processes. For P, a new state of equilibrium can be reached after 10-15 years (Jeppesen *et al.*, 2005). During the period of recovery, sediment P that has accumulated over periods of high external loading is released into the overlying water column (Sas, 1989; Jeppesen *et al.*, 1991; Welch & Cooke, 1995; Granéli, 1999; Spears *et al.*, 2012). Even in lakes that undergo no changes in external loading, internal P loading can be the principal component of P supply at maximal pelagic primary productivity during summer, as long as the lake water stays turbid and eutrophic (Istvánovics *et al.*, 2004; Søndergaard *et al.*, 2013). Therefore, lake restoration that impacts upon the retention capacity during summer might be needed over and above that of a decrease in external loading (Søndergaard *et al.*, 2013).

Wind-induced sediment resuspension may noticeably increase P release via translocation of the sediment particles into the water column (Søndergaard *et al.*, 1992; Ekholm *et al.*, 1997). In fact, the effect of sediment resuspension on P availability depends on the characteristics of the lake water, into which the sediment is stirred, and upon of the sediments themselves. Nevertheless, high concentrations of TP and SS in the water column have often been observed to associate with the high rates of sediment resuspension (Kristensen *et al.*, 1992; Havens *et al.*, 2007; Niemistö & Horppila, 2007; James *et al.*, 2009; Huang & Liu, 2009). Moreover, internal TP loading due to sediment resuspension can exceed the external loading of this nutrient (Havens *et al.*, 2007; Niemistö *et al.*, 2012). As a natural process, sediment resuspension has a continuous impact on lake ecosystems, which occurs over long periods of time (Weyhenmeyer, 1998). At the same time, nutrient enrichment from human activities can significantly modify the amounts of material that can be resuspended.

Given the projected changes of climate (IPCC, 2007), increasing attention has been recently paid to the responses of ecosystems to weather–related events (Pettersson *et al.*, 2010; Jennings *et al.*, 2012). The levels of nutrient concentrations in lakes are influenced by many weather factors, some of which may obscure and others amplify the eutrophication processes. Generally, climate change has been thought to intensify eutrophication symptoms through increasing the supply and the internal recycling of nutrients (Jeppesen *et al.*, 2009, 2011; Moss *et al.*, 2011).

Large lakes, which extend over areas of more than 10 km^2 (European Parliament, 2000) and provide a wide range of services to society, are unique ecosystems (Tilzer & Bossard, 1992; Nõges *et al.*, 2007; May & Spears, 2012). There are three main criteria that distinguish large lakes from their smaller counterparts: 1) physically distinctive littoral and pelagic zones; 2) a greater mixing depth; 3) the formation of areas with different physical structures that cause patchiness in biological processes (Tilzer & Bossard, 1992).

An understanding of the factors driving the water quality in the large lakes, particularly those related to key elements of eutrophication such as P, is critical to the protection and management of these waterbodies. An essential body of information about such factors has been collated and encompassed under the present study. This study is based on the analysis of both short-term and long-term data that were collected mainly from the large and shallow Lake Peipsi. High P concentration has been thought to be the main reason for the degradation of the water quality in the shallow and eutrophic Lake Peipsi. The contribution of the riverine nutrient loading (**I**), sediment resuspension (**III**) and weather factors (**III**, **IV**) to the water quality has been ascertained. The Enonselkä basin of the large and shallow Lake Vesijärvi, which had been undergoing eutrophication, was successfully restored in the 1990s by the reduction in external nutrient loading and the efficient removal of fish. However, recurring signs of the deterioration of the water quality triggered further investigations of the gross sedimentation and sediment resuspension, since changes in these bottom processes could be a causative factor (**II**). Large and shallow lakes are expected to be particularly influenced by the sediment resuspension (Bachmann *et al.*, 2000; Havens *et al.*, 2007; Kelderman *et al.*, 2012), but there is lack of empirical studies due to the complexity of the measurements under field conditions. Therefore, in-field measurements of sediment resuspension carried out in Lake Peipsi for the first time contribute to the overall knowledge on unique ecosystems, specifically large and shallow lakes.

To elucidate the relationship between catchment and the water quality in Lake Peipsi, the transport of N and P via the main Estonian inflows to Lake Peipsi *sensu stricto* was quantified for the years 1992–2007 inclusive. These measurements enabled comparisons to be made with the estimations of different researchers for the earlier years. Data obtained on the major inflow were used to estimate the effect of the riverine nutrient load on the in-lake nutrient concentrations (**I**). Sediment traps were exposed to examine the temporal and spatial variations of gross sedimentation and sediment resuspension in the Enonselkä basin of Vesijärvi (from May to November in 2009; **II**) and also in Lake Peipsi (from May to October in 2011; **III**). Subsequently, the factors that controlled these variations and the impacts of the sediment resuspension were analyzed. In Enonselkä, the effect of sediment resuspension (gross sedimentation) on the water turbidity was investigated, and the internal loading of SS was assessed (**II**). The relationships between sediment resuspension and the concentrations of SS, TP and SRP in Lake Peipsi were studied (**III**). Moreover, the internal loading of TP due to sediment resuspension was determined (**III**). Additionally, the effect of T, L, V and Vmax on the water quality variables was analyzed (**III**). A similar method was applied for the long-term series of Lake Peipsi in order to ascertain the contribution of the weather factors to the variations of TP concentrations (**IV**). These factors included T, L, V, Vmax, and PAR, which are directly or indirectly related to weather and defined as "weather factors" for practical purposes. Additionally, the sensitivity of TP anomalies to each of the studied weather factors was quantitatively estimated.

1. REVIEW OF LITERATURE

1.1. Relationship between the catchment processes and the lake water quality

The trophic conditions of lakes are largely determined by the processes that occur in their respective catchment areas (Wetzel, 2001). Thus, increasing inputs of P and N from a number of anthropogenic sources have led to the Earth´s most widespread water quality problem, called cultural eutrophication (Schindler, 2006, 2012; Moss *et al.*, 2011). However, the relatively rapid deterioration in water quality in response to increased emissions from industrial and municipal point sources and intensive agriculture does not automatically entail an equally rapid improvement to decreased emissions (Grimvall *et al.*, 2000).

The point source nutrient inputs to freshwaters have been successfully reduced in many countries worldwide, but improvements in water quality were in many cases attenuated, nullified or even reversed by nutrient losses from diffuse sources (Kronvang *et al.*, 2005). Generally, the hydrologically driven and therefore episodic and seasonal diffuse sources are more difficult to control, compared with the more continuous, concentrated and bioavailable P discharges from discrete point sources (Edwards & Withers, 2007; Withers & Jarvie, 2008). However, even large reductions in agricultural inputs in Eastern Europe following the collapse of the Soviet Union have led to slow and limited declines in nutrient levels in many rivers, particularly, in medium-sized and large catchments (Grimvall *et al.*, 2000; Stålnacke *et al.*, 2003, 2004). In the case of N, the resilience to reductions in N applications was explained by high groundwater nitrate concentrations resulting from previous heavy use of fertilizers. For P, despite a decline since the 1980s, the proportion of soils well supplied with P still remains quite high (varying from 10 to 50% between countries) in Central and Eastern European countries (Csathó *et al.*, 2007), and large accumulations of P will take time to leach out. Long-term improvement in water quality was thought to be achieved only by reducing diffuse P losses from agriculture in these countries. However, "P legacy", or the stores of P along the land-freshwater continuum from past management activities (Kleinman *et al.*, 2011), has also been recognized as a priority concern in many other areas of the world (Jarvie *et al.*, 2013; Sharpley *et al.*, 2013).

Spatial variations in nutrient losses to water are usually attributed to differences in climate, soil, hydrological conditions and agricultural production (Kronvang *et al.*, 2007; Ulén *et al.*, 2007). The scale of study also has to be considered. Small catchments include the main processes that govern P mobilization, source areas and hydrological pathways (Kronvang *et al.*, 2007). Larger catchments include also buffers such as lakes, reservoirs being, therefore, more prone than small catchments to P transformation and retention processes in surface waters (Kronvang *et al.*, 2007).

Climatic conditions may overshadow the effect of changes in the anthropogenic nutrient supply on water quality. For example, Grimvall *et al.* (2000) demonstrated that a dry summer and autumn, as that which occurred in Denmark in 1992, followed by an exceptionally wet winter flushed nitrates from soil to water. Moreover, a long period of dry weather (1995-1996) led to a substantial decline in both the amount of nutrient transported to water and the concentration of the nutrient in the receiving waters. Owing to higher runoff and increased non-point loss of both N and P from agricultural areas, the total riverine loading of nutrients into Danish freshwaters has not decreased during the period following the implementation of the nutrient reduction management measures (Kronvang *et al.*, 2005). Furthermore, climate change is generally expected to increase the mobilization of nutrients in the future (Jeppesen *et al.*, 2009, 2011; Moss *et al.*, 2011).

The delay in response of lake water quality to reduced external nutrient loading has also been well documented. A review of 35 case studies showed that in-lake TN concentration responded to the decrease in TN loading relatively rapidly i.e. <5 years (Jeppesen *et al.*, 2005). Decreasing external loading of TP reduced in-lake concentrations of the nutrient and phytoplankton Chl *a*, and also increased water clarity in most lakes, but internal loading delayed the recovery for about 10-15 years (Jeppesen *et al.*, 2005). The duration depends on the loading history and the capacity of the sediments to retain P (Søndergaard *et al.*, 2013). Biological factors can also explain a delayed response to decreased external P loading. For example, the probabilities of top-down control of the phytoplankton will be reduced as long as there is a high predation pressure on the zooplankton by the existing fish stock (Søndergaard, 2007). Moreover, grazing by fish and birds can delay the reestablishment of submerged macrophytes (Köhler *et al.*, 2005).

Schindler (2012) emphasized that long-term, whole-ecosystem experiments and case histories of lake recovery provide the only reliable evidence for policies to reduce eutrophication. Numerous examples of lake recovery globally, indicate the need for controlling P, because the long periods of hysteresis were concluded to result from internal P loading, high P in the catchment soils and slow recovery of fisheries (Schindler, 2012). Moss *et al.* (2013) suggested the restriction of phytoplankton production by the severe control of just one nutrient, and for practical ease, P is the best candidate. However, the effect of increased N loading on macrophyte communities e.g. reduced plant diversity, changes in the structure, loss of macrophyte communities, ensures the control of both nutrients in shallow lakes and estuaries (Moss *et al.*, 2013). Nevertheless, there is an increasing need to "close the human P cycle" given the two-sided challenge of P sustainability, i.e., pollution on one hand, and scarcity of P reserves on the other (Elser, 2012).

1.2. Internal nutrient loading

Lakes normally act as efficient nutrient traps in which much of the external nutrient load is retained (Granéli, 1999). The majority of N retained in lakes will be permanently removed via denitrification (Seitzinger, 1988; Jensen *et al.*, 1990; Saunders & Kalff, 2001). Thus, in terms of sediment-water exchange, and especially in the years after an external nutrient loading reduction, the pool of accumulated P is of major concern.

Contrary to a deep lake, sediment-released P in a shallow productive lake readily enters the trophogenic zone during the growing season and results in high concentrations in the lake water (Welch & Cooke, 1995; Søndergaard *et al.*, 2003). In many shallow nutrient-rich lakes, therefore, P concentrations in summer are considerably higher than in winter. In winter the sediment has a significant capacity to retain P, owing to lower temperatures, less sedimentation, reduced turnover of organic matter and consequently lower oxygen and nitrate consumption (Jensen & Andersen, 1992; Søndergaard *et al.*, 1999; Søndergaard, 2007). The richer in nutrients the lake is, the relatively higher is the release from the sediments during summer (Søndergaard *et al.*, 2007, 2013). The release of P from sediments, or internal P loading, has been shown to be particularly pronounced during the first years after a reduction of external P loading

(Søndergaard *et al.*, 2005, 2013; Jeppesen *et al.*, 2005; Spears *et al.*, 2012). Further establishment of clear water conditions via biomanipulation or enhanced abundances of submerged macrophytes can lead to decreased P release during summer, and consequently improve the water quality. Otherwise, P release is a permanent recurring phenomenon of shallow eutrophic lakes during summer (Søndergaard *et al.*, 2013).

The smooth changes in internal P loading can be regarded as a function of different mobilization and transport mechanisms. The mobilization has usually been related to anoxic conditions which trigger the reduction of Fe(III) to Fe(II), resulting in the breakdown of Fe-P complexes (Mortimer, 1941). Photosynthetically elevated pH can favour P liberation from metal oxyhydroxides through ligand-exchange reactions (Andersen, 1975; Boström *et al.*, 1982; Koski-Vähälä & Hartikainen, 2001; Niemistö *et al.*, 2012). Subsequent to being mobilized, P can be transported by diffusion, gas ebullition or bioturbation. However, in wind-exposed shallow lakes the most important transport mechanism is that of sediment resuspension, which is characterized by significantly higher fluctuations over temporal scales than the other transport mechanisms (Søndergaard *et al.*, 1992; Istvánovics *et al.*, 2004; Havens *et al.*, 2007).

1.2.1. Sediment resuspension as a mechanism of internal phosphorus loading

Apart from the overall seasonal pattern, quantification of the internal loading is confounded by episodic P release from the sediments during resuspension events (Ekholm *et al.*, 1997). Istvánovics *et al.* (2004) emphasized the greater importance of studies on the sediment resuspension dynamics with respect to P supply for phytoplankton, compared to conventional studies on P mobilization and P release. It is also noteworthy that sediment resuspension can influence the whole ecosystem of a lake. Sediment resuspension may increase water turbidity, and thus affect light penetration, nutrient fluxes, promoting ultimately widespread and profound biological adjustments; e.g., the phytoplankton and zooplankton community structure and abundance, fish feeding, and growth of submerged macrophytes (Scheffer, 1993; Hamilton & Mitchell, 1996; Søndergaard *et al.*, 2001; Levine *et al.*, 2005; De Vicente *et al.*, 2010).

Sediments are resuspended when bottom shear stress is sufficient to disrupt the cohesion between the sediment particles and the forces of gravity (Evans, 1994). This can be caused by wind-induced wave disturbance, currents, turbulent fluctuations, seiches, intrusions of river or groundwater, benthivorous fish or benthic animals (Weyhenmeyer, 1998; Niemistö, 2008). Sediment resuspension, usually represents the majority of the total settling flux, can be therefore regarded as a natural process with a continuous impact on lake ecosystems over long periods of time (Weyhenmeyer, 1998). However, sediments can sometimes also be disturbed by boat traffic (Weyhenmeyer, 1998).

Being a complex function of the wind speed, duration of disturbance, effective lake fetch, sediment characteristics, and lake morphometry, resuspension rates and also gross sedimentation rates are not constant within a lake, but characterized by large temporal and spatial variations (Håkanson & Jansson, 1983; Rosa, 1985; Evans, 1994; Weyhenmeyer & Bloesch, 2001; Horppila & Niemistö, 2008). In shallow areas, where sediments are often exposed to the wind-driven wave motions, resuspension is greater than in deep areas (Bloesch, 1982; Evans, 1994). Near-bottom conditions in deep stratifying areas are favourable for sediment accumulation (Håkanson & Jansson, 1983). Material resuspended in shallower sites can be transported to these deeper areas: such a phenomenon is called sediment focusing (Ohle, 1962; Likens & Davis, 1975). However, considerable sediment resuspension can occur in these areas of sediment accumulation due to internal seiches (Pierson & Weyhenmeyer, 1994; Horppila & Niemistö, 2008).

Regardless of the mechanism behind the resuspension event, the effect of resuspension on P cycling can be significant (Niemistö *et al.*, 2012). Numerous studies include Lake Okeechobee (USA), Lake Taihu (China), Lake Arresø (Denmark), Lake Kirkkojärvi (Finland) have demonstrated a connection between high resuspension rates and high TP concentrations of the lake water (Kristensen *et al.*, 1992; Havens *et al.*, 2007; Niemistö & Horppila, 2007; James *et al.*, 2009; Huang & Liu, 2009). Resuspension events can enhance P release (Søndergaard *et al.*, 1992; Koski-Vähälä & Hartikainen, 2001; De Vicente *et al.*, 2010), but P adsorption by particles can also occur (Koski-Vähälä & Hartikainen, 2000; De Vicente *et al.*, 2010). For example, De Vicente *et al.* (2010) observed a different effect of sediment resuspension on the concentrations of phosphates in two adjacent shallow coastal lakes. Those authors attributed the differences to higher concentration of phosphates in water, as well as to more abundant Fe oxyhydroxides and clay in the sediments of the lake in which resuspended particles tended to remove phosphates from the water column. However, the particles can lose their adsorption capacity at high pH. This phenomenon is common in eutrophic lakes during summer and was demonstrated in the Enonselkä basin of Lake Vesijärvi (Koski-Vähälä *et al.*, 2001). Therefore, the resultant 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. Resuspension can sometimes be regarded as a self-control mechanism either removing P from the sediment column (De Vicente *et al.*, 2010) or relaxing nutrient stresses (Istvánovics *et al.*, 2004).

1.3. Weather conditions and the lake water quality

Recent studies on P have increasingly focused on the effects that year-to-year variations in weather conditions have on both the supply and the internal recycling of P (Pettersson *et al.,* 2010). It is noteworthy that these effects depend strongly on lake type and local conditions (Blenckner, 2005; Dokulil *et al.*, 2010; Pettersson *et al.*, 2010).

The significant effect of L fluctuations on P cycling has been addressed in many studies, though the significance is strongly case dependent resulting in positive (Havens, 1997; Havens *et al.*, 2007) and negative (Kristensen *et al.*, 1992; Nagid *et al.*, 2001; Nõges *et al.*, 2003) effects. Some lakes have demonstrated no changes in TP concentrations in response to changes in L (Hoyer *et al.*, 2005; Garrison *et al.*, 2010). In the large and shallow Lake Võrtsjärv, more phosphates can be transferred into the water column by wind-induced sediment resuspension at lower L (Nõges *et al.*, 2003). At higher L in milder winters, significantly lower phytoplankton biomass was associated with worse light conditions and P availability and with the dominance of shade-tolerant filamentous cyanobacteria, but no changes in external P loading. A significant decrease in phytoplankton in wet conditions has been also related to enhanced flushing events (Carvalho *et al.*, 2012), which are particularly important for lakes with shorter residence times.

In the open area of the large and shallow waters of Lake Okeechobee, higher TP concentrations of the water column at higher water levels have been explained by enhanced diffusion releases of P from sediments during the calm summer season, and by higher sediment resuspension during the windy winter season (Havens, 1997). Wind has been suggested to be the main factor influencing year-to-year variations in pelagic TP in Lake Okeechobee in addition to being clearly the main driving force behind P dynamics over different (hourly, daily, and seasonal) time scales (Havens *et al.*, 2007). Moreover, wind-induced sediment resuspension was estimated to transport substantially higher amounts of P than diffusive flux and external loading, when yearly data were analyzed. Similarly, measurements in Lake Võrtsjärv showed that the internal P loading on one stormy day (in autumn, at extremely low L) was greater than the annual external loading of this nutrient (Nõges & Kisand, 1999).

In addition to the influence of L, and wind activities on P cycling, the contribution of T should be considered since this factor influences the rate of all processes (chemical, physiological) in a lake (Søndergaard, 2007; Olrik *et al.*, 2012). T is commonly regarded as an important driver of internal loading, through elevated microbial remineralization, the resultant onset of anoxia, and increased diffusion rates (Søndergaard *et al.*, 2003; Spears *et al.*, 2007, 2012). Thus, it is usually very difficult to disentangle the particular impact of any individual factor for P dynamics due to many other interacting inluences.

2. AIMS OF THE STUDY

Lake Peipsi (Estonia/Russia) and Lake Vesijärvi (Finland) are examples of the lakes that are undegoing eutrophication. Thus, it is of crucial importance to understand the factors that contribute to the water quality problems in these large lakes. In this study, the contribution of riverine nutrient loads, sediment resuspension, and weather factors to the variability of the water quality parameters has been examined. The present study was mainly focused on the investigation into the dynamics of P, since this nutrient has most often been regarded as the main reason for the degradation of water quality.

This study aimed at the following objectives:
1) to explore the relationship between the catchment processes and the water quality of the lake (**I**);
2) to elucidate the temporal and spatial variations of sediment resuspension and gross sedimentation processes (**II**, **III**);
3) to determine the internal loading of TP and SS due to sediment resuspension (**II**, **III**) ;
4) to assess the water quality implications of sediment resuspension (**II**, **III**);
5) to estimate the effect of weather conditions on a) TP concentrations using long-term datasets and by using advanced statistical methods (**IV**); b) sediment resuspension and associated water quality variables using the data collected during short-term in-field measurements analyzed by advanced statistical methods (**III**).

The following hypotheses were tested:

1) There is a delay in the response of the lake water quality to the changes in the nutrient loads.
2) The sediment resuspension of the shallow areas controls SS concentrations and water turbidity in the entire Enonselkä basin (the most eutrophic basin of Lake Vesijärvi).
3) In Lake Peipsi, sediment resuspension is a factor sustaining eutrophication.
4) TP anomalies (deviation of observed values from those predicted by the year, the day of the year, and geographical coordinates, which are fixed by study design) are caused by episodic weather conditions.

3. MATERIALS AND METHODS

3.1. Study areas

3.1.1. Lake Peipsi

Lake Peipsi (surface area 3555 km^2) is the main study subject of this thesis (**I**, **III**, **IV**). It is located on the border between Estonia and Russia (Fig. 1). Lake Peipsi is the fourth largest lake in Europe and it extends in the meridional direction for more than 150 km. The lake consists of three parts with a water residence time of about two years (Jaani *et al.*, 2008). The three parts differ in morphometry, hydrology, trophic state, and composition of biota (Kangur & Möls, 2008). The northern part, Lake Peipsi *sensu stricto* (Peipsi *s.s.*), is larger and deeper (2611 km^2; mean depth 8.3 m) than the southern parts, called Lake Lämmijärv (236 km^2; mean depth 2.6 m) and Lake Pihkva (708 km^2; mean depth 3.8 m). Nevertheless, the greatest depth (15.3 m) of Lake Peipsi has been measured in Lake Lämmijärv. According to the OECD (1982) classification, the existing conditions characterize Lake Peipsi *s.s.* as a eutrophic water body, whereas the trophic status of Lake Lämmijärv is close to hypertrophic and Lake Pihkva is regarded as a hypertrophic basin (Kangur & Möls, 2008).

The majority of nutrients are carried into the lake by the rivers of Velikaya and Emajõgi: their catchment areas (25200 km^2 and 9740 km^2, respectively) cover almost 80% of the total drainage basin of Lake Peipsi (Loigu *et al.*, 2008). The catchment area is shared between Russia (58%), Estonia (34%) and the remaining 8% by Latvia and Belarus (Fig. 1; Jaani, 2001). The main land cover classes are forests (61%) and agricultural land (28%; Mourad, 2008). The rest of the land cover consists of peat bogs and builtup area. Major towns are Pskov in Russia (204 181 inhabitants; source World Gazetteer, 2013) and Tartu in Estonia (97 117 inhabitants; source Statistical Office of Estonia, 2013).

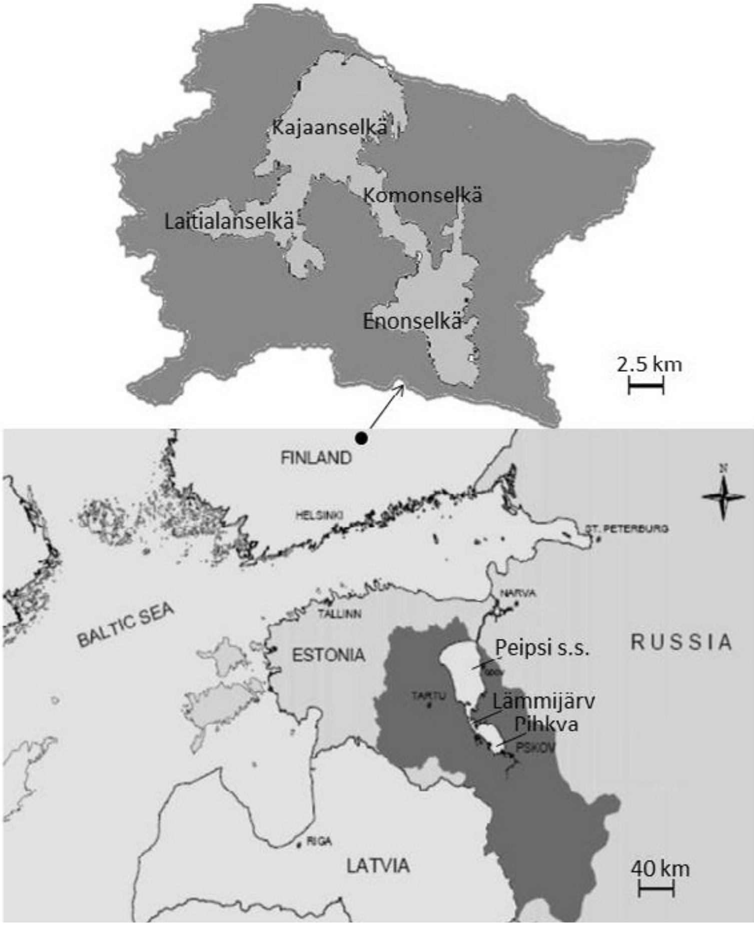

Figure 1. Location of Lake Vesijärvi (top) and Lake Peipsi (bottom; the catchment areas and all basins of the lakes are shown).

In the ice-free period (April till November), the temperature stratification is unstable, and the lake is usually rich in oxygen. The lake has undergone considerable natural fluctuations in water level: 3.04 m range over the last 80 years, and 1.5 m annual mean (Jaani *et al.*, 2008).

The sediment resuspension and gross sedimentation study was conducted in Lake Peipsi *s.s.* and in Lake Lämmijärv (**III**). Punning *et al.* (2009) discerned three areas of surface sediments in Lake Peipsi *s.s.*: 1) the accumulation area is marked by finely-grained sediments that generally coincide with depth contours of 8 m; 2) the transportation area is marked by mixed sediments of silty sands; 3) 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. Those data that do exist on Lake Lämmijärv are contradictory, due to the lack of studies and the complicated character of the lake bottom that is largely affected by the water currents (Raukas, 2008).

3.1.2. Lake Vesijärvi

Lake Vesijärvi (110 km^2) in southern Finland (61°01'N, 25°35´E; Fig. 1) comprises four basins. The study area (**II**), Enonselkä basin (area 26 km^2, mean depth 6.8 m, max. depth 33 m) with a water residence time of over 5 years, is the most eutrophic of the basins. It was severely eutrophic in the past due to urban sewage pollution. The basin started to recover after the sewage was diverted in 1976. However, cyanobacterial blooms persisted, at least partially due to roach [*Rutilus rutilus* (L.)] stock-mediated internal nutrient loading (Keto & Tallberg, 2000). Following the large-scale biomanipulation in the 1989-1993 period, which involved the mass removal of fish, the basin changed from a highly eutrophic and turbid ecosystem to a mesotrophic one, with clearer water (Koski-Vähälä *et al.*, 2000). However, in the late 1990s new signs of deterioration, such as higher turbidity, were detected. Hypolimnetic oxygen deficiency during stratification was found to have increased in the 2000s, which reached a depth of 7-10 m in 2002. In addition, cyanobacteria were again observed to bloom (Nykänen *et al.*, 2010).

3.2. Sampling and data collecting

3.2.1. External loading of nutrients

In article **I**, the external loads of TN and TP from the rivers inflowing into Lake Peipsi *s.s.* were estimated according to the method, described by Järvet (2001) and Jones (2007):

$$Load = \frac{K\sum_{i=1}^{n}(C_i Q_i)}{\sum_{i=1}^{n} Q_i}\overline{Q_r}\text{ , where}$$

K is conversion factor that takes account of the period of record, is actual concentration at that instant for the relevant individual sample (mg l^{-1}), is instantaneous rate of discharge at time of sampling (m^3 s^{-1}), *n* is the number of samples, is the mean discharge for the particular period of recording ($m^3 s^{-1}$). Observed monthly concentrations of the nutrients and mean monthly values of the river water flow were used for the calculation of nutrient flow weighted concentration, *C* (Järvet, 2001; Johnes, 2007):

$$C = \frac{K\sum_{i=1}^{n}(C_i Q_i)}{\sum_{i=1}^{n} Q_i}$$

In those cases where the site of the water sampling did not coincide with the gauging station, the water discharge for the sampling site was calculated on the basis of the proportions of the catchment areas (e.g., Sileika *et al.*, 2006). The loads calculated for the water quality sampling sites were interpolated to the mouths of the studied rivers.

To compare nutrient export among basins, the annual export coefficients were calculated by dividing the annual load value by the catchment area size of the specified river.

Water quality data of the Estonian rivers discharging into Lake Peipsi *s.s.* were gathered under the auspices of the Estonian national monitoring programme from 1992 to 2007, whereby sampling occurred mainly on a monthly basis. These data were obtained from the Estonian Environment Information Centre. Data on mean daily discharges in the studied rivers were obtained from the Estonian Institute of Meteorology and Hydrology.

3.2.2. Gross sedimentation and sediment resuspension

Gross sedimentation and sediment resuspension were quantified with the aid of cylindrical sediment traps (Fig. 2) from May to November 2009 at five sampling sites in the Enonselkä basin (trap locations: Fig. 1 in **II**), and from May to October 2011 at five sampling sites in Lake Peipsi (trap locations: Fig. 1 B, C in **III**). The traps were designed (plastic tubes, of 5.4 cm in diameter, 41 cm in height in Lake Vesijärvi (**II**); 4.4 cm in diameter, and 44 cm in height in Lake Peipsi (**III**) to be suitable for lake conditions and to avoid overtrapping and undertrapping of particulate matter (Bloesch & Burns, 1980). The exposure time of the traps (14-21 day intervals in **II**, 14-day intervals in **III**) was also within the limits recommended for experiments on settling fluxes for organic material

(Bloesch & Burns, 1980). Each sediment trap was replicated four times and all were deployed at 2 m above the bottom of the lake. Additionally, sediment traps were placed just below the thermocline (at 10 m depth) at stratifying deep stations (numbered 2 and 3) of the Enonselkä basin.

In the laboratory, the contents of the traps were dried at 60 °C for approximately 3 days to obtain their constant dry weights. The organic fraction of the entrapped material was determined by loss-on-ignition at 550 °C. In Lake Peipsi (**III**), surface sediment samples (top-most 0 - 1 cm) were collected by a HTH gravity corer (Pylonex Termokonsult, Umeå, Sweden) and the constant dry weights and loss-on-ignition were obtained. Additionally, the samples for determing the concentration of SS were collected using a 2-litre Van Dorn sampler. These samples were filtered through a Whatman GF/C filter (pore size 1.2 μm) and analyzed for dry weight and loss-on-ignition.

Figure 2. Sediment traps were used in the Enonselkä basin of Lake Vesijärvi and in Lake Peipsi to quantify the rates of gross sedimentation and sediment resuspension (photo by Aivar Roomet).

Since the inflow of allochthonous particulate matter into Lake Vesijärvi is negligible (Koski-Vähälä *et al.*, 2000), the method of Weyhenmeyer (1997) was used for determining the amount of resuspended sediment in the settling flux (**II**). In this method, it is assumed that the main sources of settling particulate matter (SPM) are sediment resuspension and new production. The rate of sediment resuspension is estimated by establishing a linear regression between the settling particulate organic matter (SPOM) and the settling particulate inorganic matter (SPIM):

$$SPOM = k * SPIM + intercept$$

The amount of resuspended particulate matter is calculated by:

R = SPM – intercept, where

R = rate of sediment resuspension,
the intercept of the SPOM/SPIM regression line designates the amount of newly-produced suspended particulate organic matter;
and SPM = gross sedimentation, i.e., the sum of SPIM and SPOM

For Lake Peipsi (**III**), the rate of sediment resuspension (*R*) was calculated according to Gasith (1975):

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

S = the gross sedimentation,
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 method is applicable for shallow water bodies and is considered to be reliable when the organic matter content of the bottom sediment is different from that of suspended seston (Blomqvist & Håkanson, 1981).

3.2.3. Internal loading of suspended solids and total phosphorus due to resuspension

In Lake Vesijärvi, the spatial loads of SS generated by resuspension were calculated by applying the mean resuspension rates at the shallow and the deep stations for the corresponding percentage of the total lake area (**II**).

In Lake Peipsi, the internal loading of TP due to resuspension was calculated by multiplying the mean rate of sediment resuspension by the mean concentration of TP in the surface sediments (Horppila & Nurminen, 2003; **III**). The concentration of TP was determined from each surface sediment sample dried at 60 ºC by an inductively coupled plasma mass spectrometer after wet combustion with nitric acid and hydrogen peroxide.

3.2.4. Lake water quality parameters

During each sediment trap exposure period in Lake Peipsi, water samples were taken for the determination of SS, SRP, TP and Chl *a* (**III**). These samples were collected using a 2 litre van Dorn sampler that was hauled vertically down each metre of the water column beginning at 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 mm). 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 mm). The samples for Chl *a* were filtered through a Whatman GF/C filter (pore size 1.2 mm) and analyzed spectrophotometrically after extraction with ethanol.

In Lake Vesijärvi (**II**), the vertical profiles of turbidity were obtained by using a YSI-6600-V2 (YSI Corporation, Yellow Springs, OH, USA). Turbidity was measured by a YSI 6136 turbidity sensor connected to a YSI-6600-V2 sonde. The turbidity values obtained with the sensor (NTU) had been previously calibrated against the concentration of suspended solids resulting in a significant linear relationship (Boss *et al.*, 2009; Holmroos *et al.*, 2009).

The long-term data on TP for Lake Peipsi (archived data sets of the Center for Limnology) were used for the analyses in **I** and **IV**. Additionally, data on TN in the lake water were examined side-by-side with external loading of TN (**I**). Water samples for nutrient analysis were collected monthly, predominantly in the ice-free period (from April-May to October-November) of 1985–2010 period. The number of the sampling sites varied markedly over the period. Since 1992, most of the data were collected at six stations in the pelagic zone of the Estonian side of Lake Peipsi, by Tartu Environmental Researches Ltd. In the earlier period (in the 1980s), samples were collected and analyzed at the Institute of Zoology and Botany in Tartu. Since 2001, generally twice a year, in March and in August joint Estonian - Russian expeditions on the whole lake have been conducted. Seasonal (monthly) water samples for TP and TN analysis have been obtained from the surface layer of 0.1–1.0 m. TP has been determined in the water samples by the ammonium molybdate spectrometric method (EVS-ES 1189). TN was determined using the method of Koroleff (1979).

3.2.5. Data on wind, water temperature, water level, photosynthetically active radiation

For Lake Peipsi, the long-term (for the years 1980-2010; **IV**) and short-term data (for the year 2011; **III**) for the mean daily values of L, T, V, and PAR; (only in **IV**), and on Vmax were obtained from the Institute of Meteorology and Hydrology of the Estonian Ministry of the Environment. L, T, V, Vmax measurements were taken at the Mustvee hydrometric station of Lake Peipsi (58°50´ N, 26°57´ E). PAR was measured at the Tõravere Observatory (at ground level), which is located at a distance of 50 km from the shore of Lake Peipsi. Data on wind speed (maximum and mean daily values) and wind direction in the area of the Enonselkä basin for 2009 (**II**) were obtained from the Laune meteorological station (Finnish Meteorological Institute) that is situated 3 km from the study area.

The vertical profiles of temperature and oxygen were obtained using a YSI-6600-V2 and YSI-6620 (YSI Corporation, Yellow Springs, OH, USA) at each station where sediment resuspension was measured for studies **II** and **III**, respectively.

3.3. Data analyses

The effects of Estonian riverine loads on the nutrient concentration in lake water was estimated on the basis of loads calculated for the largest inflow into Lake Peipsi *s.s.*, i.e. the Emajõgi River, and nutrient concentrations that were measured in the sampling station in the lake close to the river mouth (**I**, Fig. 1). The effects of season, year, and their interactions were included into the linear model (sequential type 1 model, incremental improvements in the error of the sum of squares, as each effect was added to the model) before finding the effect of TN and TP load on the nutrient in-lake concentration.

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

In the study of Lake Vesijärvi (**II**), mean turbidity values for the whole water column of the shallow areas and also for the epilimnion and the hypolimnion of the deep areas were estimated in the regression model. In this model, the type of sampling site (shallow/deep), concentration of SS, and day of the year were used as the regressors. Interpolation methods were used to construct seasonal changes in mean water turbidity at shallow and deep areas (SAS/GPLOT, SAS Institute Inc., 2008).

For Lake Peipsi, the influences of the weather factors on the potentially weather-dependent variables were analyzed. Initially, we eliminated the influence of the sampling site and time on the measured variables (**III**, **IV**). For this purpose, the values of these variables were replaced by residuals, i.e., the differences between observed values and those predicted from the sampling site and time. GLM was used to predict a value for a site on a given day of a year (**III**). For the long-term data series of TP (**IV**), this was achieved by using the TPS interpolation technique provided by the SAS TPS procedure (SAS Institute Inc., 2008). This step can also eliminate part of the effect of weather factors due to their potential correlation with the sampling site and time. The possible effects of weather factors on the residuals were tested thereafter.

Since the weather factors varied greatly over time, but response is likely to depend on the average weather conditions for some time, the values of the weather variables were averaged over varying time intervals (**III**: from 1 to 8 days; **IV**: from 1 to 6 days), considering the time intervals measured several days (**III**: from 0 to 10; **IV**: from 0 to 7) earlier than the sampling. In this analysis, the influences of weather factor terms were identified by two indices: the number of days for which the parameter was averaged, and the delay of the mean effect of weather factor (expressed by the number of days between the last day used for averaging, and the sampling day). These averaged and shifted weather factors were used as predictors of the residuals of the studied water variables in a stepwise regression analysis (**III**). The critical significance level of $p = 0.001$ was used 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 (i.e., the increase of R^2 due to the addition of the current term to the model). Selection of new terms continued until no more terms were significant at $p < 0.001$.

In the analyses of the long-term series of TP (**IV**), the effects of the weather factors (with different time-windows and backward time shifts) were estimated by using the SAS GLM procedure that predicted the residuals with the aid of a model that contained all the weather factors and also their 2nd order product terms. Only days of temperatures over 12 °C were considered. These days were analyzed in three groups: all the days, days before the 180th Julian day and days after that day. Therefore, for the final analysis, the total data set included only 1175 TP measurements (of 1862 real TP measurements) for the 1985–2010 period. The effect of a weather factor was defined as follows: the predicted percentage change of the TP concentration, when the factor is increased by one unit above its mean value, whilst the other factors are kept constant at their mean values. Technically, the effects were determined using the 'Estimate' command in the GLM procedure. Further, the effect of each factor was multiplied by the standard deviation of the factor in the period under study. This standardization of the factors enabled the removal of the scale effects and allowed the comparison of the sensitivity of TP anomalies against different factors.

4. RESULTS

4.1. Effect of the riverine nutrient loads on the water quality in Lake Peipsi (I)

The mean annual load of nutrients that was discharged to Lake Peipsi *s.s.* by the Estonian rivers that were studied during the time period of 1992–2007 was estimated to amount to 5600 tons of N and 179 tons of P. The Emajõgi River contributed approximately 86% of the N and 91% of the total Estonian riverine P load. TN export coefficients varied from 4 to 8 kg N ha^{-1} yr^{-1}. The range of TP losses was from 0.12 to 0.21 kg ha^{-1} yr^{-1}. The highest losses of TP in the study area were calculated for the catchment of the Emajõgi River.

Means of nutrient concentrations in lake water in the two periods of 1985–1990 and 1992–2007 that were characterized by different loading were compared. The mean annual in-lake concentration of TN (630 mg N m^{-3}) over the 1992–2007 period was significantly lower ($p = 0.006$) than in 1985–1990, when the value amounted to 687 mg N m^{-3}. The concentration of TP also differed significantly ($p < 0.001$) between the two periods: 39 mg P m^{-3} in 1992–2007 as opposed to 30 mg P m^{-3} in 1985–1990.

The local impacts of changes in N loads on the lake water quality were detected. TN concentration in lake water close to the Emajõgi River mouth was significantly influenced ($p = 0.002$) by the N input from the river (**I**, Fig. 7). For TP, the effect of the load on the concentration was not statistically significant (**I**, Fig. 8). However, a marginal decline in TP concentration in the lake water had occurred since 1998 ($R^2 = 0.38$, $p < 0.05$), when the Tartu wastewater treatment plant was modernized to comply with regulatory authority standards.

4.2. Gross sedimentation and sediment resuspension (II, III)

The highest rates of gross sedimentation were measured in the deepest areas of both Lake Peipsi (station numbered 16) and the Enonselkä basin (stations numbered 2, 3; Table 1). In the deep stratifying areas of the Enonselkä basin, the gross sedimentation rates measured in the upper traps (located at the depth of 10 m) differed statistically significantly ($p < 0.001$) from the lower trap measurements and were in the same range as those found for the near-bottom traps of shallow areas (with depth < 10 m). The values for the gross sedimentation in the shallow areas of the Enonselkä basin were generally lower than in those of Lake Peipsi. The rates measured in Lake Lämmijärv were higher than the rates measured in Lake Peipsi *s.s.*

In Lake Peipsi *s.s.*, the sedimentation rates increased over the ice-free period and reached their highest values in September (**III**, Fig. 4). In contrast, no clear seasonal variations were observed in Lake Lämmijärv: in its shallower part (station numbered 17), the rates varied between 36.3 and 64.2 g dw m^{-2} d^{-1}, and the highest values were recorded in September-October. The maximum value (94.6 g dw m^{-1}) of the deeps of Lake Lämmijärv (station numbered 16) was measured in the middle of August. Generally, a steep increase in the rates was observed in June in the deep areas of the Enonselkä basin. Thereafter, the rates decreased, reaching their minimum values in August. In the deep areas (stations numbered 2, 3) and in the shallow areas (stations numbered 1, 4, 5) of the Enonselkä basin and at the major areas of Lake Peipsi (stations numbered 2, 4, 11, 17), the highest ($p < 0.001$) values for sedimentation rate were observed in September and October.

The resuspension rates (Fig. 3) followed the same seasonal pattern as the gross sedimentation, and constituted most of the gross sedimentation (53.8 – 99.7%).

Table 1. Gross sedimentation rates and the percentage of the sediment resuspension from the gross sedimentation measured with the aid of sediment traps during studies in the Enonselkä basin of Lake Vesijärvi (**II**) and in two basins of Lake Peipsi (**III**).

Lake/ depth	Station nr	Trap location	Gross sedimentation (g dw m^{-2} d^{-1})	Resuspension (%)
Enonselkä				
8, 7, 6 m	1, 4, 5	2 m a.b.	2.8-28.1	83-99.3
30, 28 m	2, 3	10 m b.s.	2.2-21.6	
	2, 3	2 m a.b.	10.9-64.7	94.1-99.7
Peipsi *s.s.*				
8, 10, 10 m	2, 4, 11	2 m a.b.	0.9-57.2	53.8-91.2
Lämmijärv				
7 m	17	2 m a.b.	36.3-64.2	78.7-92.9
14 m	16	2 m a.b.	60-94.6	78.2-94.6

a.b. – above bottom

b.s. – below surface

Traps were located just below the thermocline (10 m below the lake surface area) and 2 m above the lake bottom in the deep areas of the Enonselkä basin.

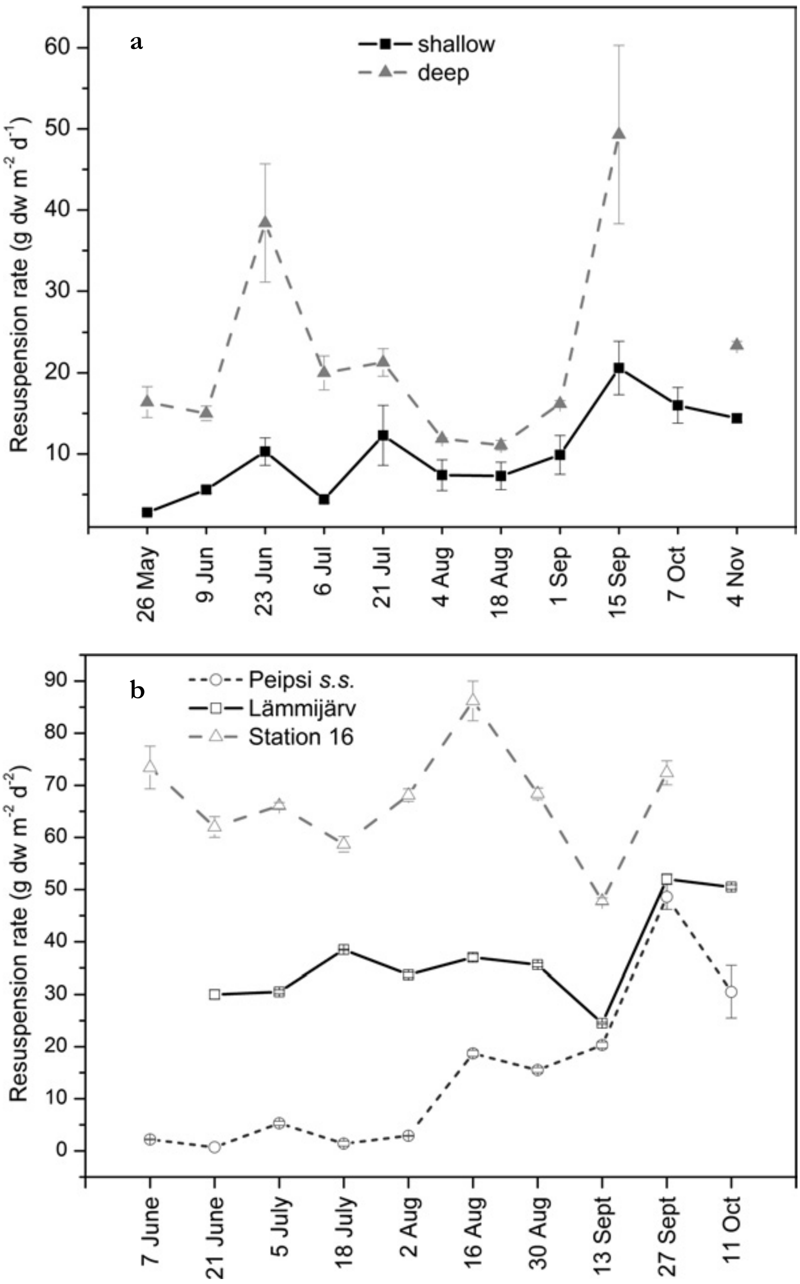

Figure 3. Sediment resuspension rates with 95% confidence limits over the study period a) in Enonselkä at the shallow (stations 1, 4, and 5) and deep areas (stations 2 and 3); b) in Lake Peipsi *s.s.* (stations 2, 4, and 11) and Lake Lämmijärv (station 17), and at the deepest station of Lake Peipsi (16), which is located in Lake Lämmijärv.

4.3. Internal loading of TP and SS due to sediment resuspension (II, III)

Most of the total SS load in the Enonselkä basin originated from the shallow areas (Table 2), which covered the major part of the lake area (83%, including the vegetated littoral areas).

Table 2. Spatial distribution of suspended solids loads due to sediment resuspension in the Enonselkä basin of Lake Vesijärvi in 2009

	Mean load (g dw m^{-2} d^{-1})	Coverage area (%)	Load from the area (t d^{-1})	Percentage of the total load
Shallow areas	10.1	83	218	66
Deep areas	24.6	17	110	34
Whole basin			328	100

Estimations of TP loads caused by resuspension showed about a three-fold difference between two adjacent lakes. Based on the mean resuspension rate (Lake Peipsi *s.s.*: 13.5 g dw m^{-2} d^{-1}; Lake Lämmijärv: 52 g dw m^{-2} d^{-1}) and the mean TP concentrations of the surface sediments in the accumulation area (Lake Peipsi *s.s.*: 1756 mg P kg^{-1} dw; Lake Lämmijärv: 1349 mg P kg^{-1} dw), 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.

4.4. Water quality implications of sediment resuspension (II, III)

Both studies in the Enonselkä basin of Lake Vesijärvi (**II**) and in Lake Peipsi (**III**) revealed an association between the resuspension/gross sedimentation rates and water turbidity. Turbidity values in the shallow stations of the Enonselkä basin, in the epilimnion and hypolimnion of the deep stations, correlated well with the concentration of SS ($r = 0.86, p < 0.001$; $r = 0.89$, $p < 0.001$; $r = 0.72$, $p < 0.001$, respectively) in the corresponding areas (**II**). Moreover, the mean turbidity values for the epilimnion of deep stations correlated strongly with those for the shallow stations ($r = 0.96$; $p < 0.001$). In the epilimnion of the deep stations and at the shallow stations the first peak of turbidity was detected at the beginning of May (3.9 and 4.7 NTU, respectively), and the second, higher peak occurred in September (5

NTU). In the hypolimnion of the deep stations, elevated turbidity values were observed at the end of June (7.8 NTU) and in September (5 NTU); the lowest values were measured in the middle of August (1.8 NTU; **II**, Fig. 6). The differences in the turbidity values in the hypolimnion and in the epilimnion of the deep stations were statistically significantly dependent on the date of the sampling ($p < 0.001$).

In Lake Peipsi, the changes in SS concentration (**III**, Fig. 5) were synchronous with those of sediment resuspension (**III**, Fig. 4). In Lake Peipsi *s.s.*, SS concentration increased over the study period, attaining highest values in the autumn. Moreover, parallel fluctuations in the concentrations of SS, TP and Chl *a* were observed (ranges: from 3 to 13 mg l^{-1}; from 52 to 106 μg l^{-1}; from 10.6 to 40.7 μg l^{-1}, respectively). Significant correlations were obtained between SS and TP ($r = 0.86$, $p < 0.001$), TP and Chl *a* ($r = 0.85$, $p < 0.001$), and Chl *a* and SS ($r = 0.87$, $p < 0.001$) in Lake Peipsi *s.s.* In Lake Lämmijärv, the concentration of SS peaked first at the beginning of August (22 mg l^{-1}), and then another sharp increase occurred in the autumn (10 October: 30 mg l^{-1}). The concentration of SS correlated well with the concentration of TP ($r = 0.81$, $p < 0.001$), whereas neither of them correlated with Chl *a*. No significant correlations were found between SS and SRP, which varied from 2 to 43 μg l^{-1} in Lake Peipsi *s.s.*, and from 6 to 36 μg l^{-1} in Lake Lämmijärv (**III**, Fig. 5).

4.5. Effect of weather factors on sediment resuspension and water quality variables (III, IV)

Analysis of both short-term (**III**) and long-term (**IV**) data of Lake Peipsi revealed a significant effect of weather conditions on the sediment resuspension/gross sedimentation (**III**), the variables of the Gasith equation (**III**), and different water quality variables: the concentrations of TP (**III**, **IV**); SS (**III**); SRP (**III**).

Wind speed was estimated to be the best predictor of sediment resuspension, as well as of the other parameters used in the Gasith equation, and SRP in the corresponding regression model (**III**, Table 1); therefore, wind was the most important factor behind variations of these studied variables. Moreover, long-term data analysis showed that V contributed predominantly to the deviations in TP from the pattern obtained by the geographical coordinates, the year, and the day of the year, or TP anomalies. After standardization, the effect of the V factor (**IV**; Table 1) appeared to be of the highest magnitude (before 180th day: -30.6%; after 180th day: 32.1%). V was also associated with frequent switches between increasing and decreasing TP values, though it appeared mainly as a negative driver of TP anomalies in the season prior to 180th day, and as a positive driver in the subsequent season (**IV**). The stepwise regression analysis used in the study of the short-term data revealed that V improved the prediction of the concentrations of TP, SS, and Chl *a* (see increase of the corresponding model R^2 by partial R^2 in Table 1, **III**), whereas L was selected to be the best predictor of the variables.

The residual analysis, based on the long-term TP data (**IV**), showed that increases in L relative to what was expected for the specific year, the day of the year and sampling site resulted in a decrease of TP concentration, regardless of whether the period before or after the 180th Julian day was considered. The decreases in TP were estimated to be about 0.14% (Table 1, **IV**) when L increases by one unit (cm) from its mean value providing that the other factors are kept at their mean values. The effects of T and PAR on TP concentrations were found to depend on the season regardless of whether they were positive or negative.

The analysis of raw short-term data (**III**) of Lake Peipsi generally showed that the highest rates of sediment resuspension (gross sedimentation), and also the highest concentrations of TP, SS and Chl *a* were measured at the period of the exceptional wind events. These exceptional wind events included the occurrence of the highest frequency of wind speeds > 10 m s^{-1}; maximum wind speed (16 m s^{-1}) in 2011 and decreased water level (150 cm measured at 28 m a.s.l). In the Enonselkä basin of Lake Vesijärvi, elevated rates of the sediment resuspension, values of turbidity coincided with the periods of disturbance in thermal stratification, when winds from a northerly direction prevailed (**II**).

5. DISCUSSION

5.1. The relationship between the catchment processes and the lake water quality (I)

The estimates of the Estonian riverine nutrient loads flowing into Lake Peipsi *s.s.* for the 1992–2007 period were of similar magnitude to those reported for the years following a decline in agricultural activity (i.e., 1992–2004 Nõges et *al.*, 2007; 2001–2005 Loigu *et al.*, 2008). Since the period of high agricultural activity passed, TN loads from the Estonian part of the catchment decreased substantially whereas the decrease in TP loads was less pronounced (Table 5, **I**). Due to the soil's capacity to retain nutrients, the leaching of nutrients can continue for a long time after reduced fertilization applications are implemented (Räike *et al.*, 2003; Stålnacke *et al.*, 2003; Iital *et al.*, 2005, 2010; Jarvie *et al.*, 2013; Sharpley *et al.*, 2013). The difference in response between N and P can be ascribed to the greater susceptibility of P to be retained within the hydrological pathways between the soil surface and the lake (Mourad *et al.*, 2006; Sharpley *et al.*, 2013).

The decrease of TN concentrations in the lake water between two periods (1985–1990 and 1992–2007) was in agreement with a decline of TN loads flowing into Lake Peipsi *s.s.* Surplus inorganic N is mainly lost to the atmosphere via denitrification; thus, the annual mean in-lake concentration of N has been reported to respond rapidly in general (in less than 5 years) to a reduction in TN loading (Jeppesen *et al.*, 2005). Therefore, the quick response in TN concentration to changes in TN loading from the Emajõgi River flowing into Lake Peipsi *s.s.* (**I**, Fig. 7) compares well with other studies.

In contrast to the rapid changes in TN concentrations, TP concentrations in the lake water were not as sensitive to year-to-year changes in riverine TP loads (**I**, Fig. 8). Based on a twofold difference in TP concentrations in Lake Peipsi that was observed between the cool and wet 2004 and the warm and dry 2005, weather variations were previously suggested to be of major importance in controlling the interannual variations of the in-lake TP concentrations (Kangur *et al.*, 2006).

On the long-term scale, a reduction of TP loads from the Estonian part of the catchment into Lake Peipsi *s.s.* was accompanied by an increase of TP concentration (**I**). Such hysteresis can result from internal loading, as it has been well documented for many other lakes that displayed a delay in response to reduced TP loading (Jeppesen *et al.*, 2005; Spears *et al.*, 2007; May *et al.*, 2012). Moreover, lower water levels in combination with higher summer temperatures created more favourable conditions for internal nutrient loading in 1992–2007, as opposed to the years 1985–1990 (Haldna *et al.*, 2008).

Calculations made by Rumyantsev *et al.* (2005) found that the mean annual TP load flowing into Lake Peipsi *s.s.* was 280 tons via the rivers of the Russian part of the catchment and the water flow from Lake Pihkva during the 1992–2003 period. Thus, the total annual TP loads into Lake Peipsi *s.s.* were comparable to those obtained for the 1980s (Table 5, **I**). Additionally, there is indirect evidence of increased TP loads emanating from the Russian part of the catchment. Increasing differences in TP concentrations between the northern and southern parts of Lake Peipsi indicates increasing inputs of TP from the south (Kangur & Möls, 2008).

5.2. Gross sedimentation, sediment resuspension: spatio-temporal variations

As in many other lakes (Weyhenmeyer, 1998), sediment resuspension constituted the majority of gross sedimentation in Lake Peipsi and in the Enonselkä basin of Lake Vesijärvi. The total amount of settling resuspended sediment differed between the lakes studied, which can be explained by the differences in their respective DRs (i.e., the square root of the lake surface area in square kilometres divided by its mean depth in meters; Håkanson, 1982). The high DR value of Lake Peipsi (Lake Peipsi *s.s.*: 6.2; Lake Lämmijärv: 5.9; the whole of Lake Peipsi: 8.4) suggests that 100% of the lake bottom will be affected by the resuspension process. In contrast, less extensive influences of the wind-induced wave action is expected on the lake bottom of the Enonselkä basin of Lake Vesijärvi, which has a DR of only 0.75, i.e. less than 33% of the bottom area was affected (Håkanson & Jansson, 1983).

The highest values of sediment resuspension were obtained from the deepest sites in both lakes (**II**, **III**). At first sight, this seems to contradict the common knowledge that shallow areas are more susceptible to wind-induced waves and water currents, and therefore subject to more sediment resuspension, than deep regions (Rosa, 1985; Hilton *et al.*, 1986; Evans, 1994). However, sediment resuspended in shallow areas has also been reported to be transported and deposited into the deeps of the lakes (Hilton *et al.*, 1986; Koski-Vähälä *et al.*, 2000; Horppila & Niemistö, 2008; Punning *et al.*, 2009; Niemistö *et al.*, 2012). Generally, the importance of a thicker water layer above the sediment trap and steep slopes near the trap has been emphasized for sediment focusing at the deep areas (Terasmaa, 2005). However, specific operating mechanisms, described in detail by Hilton *et al.* (1986), can also be involved at a specific site and at different times of the year.

More dynamic transport of sedimentary particulate organic matter in the water column would stimulate the overall mineralization process (De Vicente *et al.*, 2010). Hence, the lowest values of sediment organic content were measured at the deepest site of Lake Peipsi, located in Lake Lämmijärv (**III**). In this part of Lake Peipsi, the role of water currents for sediment redistribution has been suggested to be important (Raukas, 2008). Supporting evidence for the horizontal transport of sediments in the Enonselkä basin was provided by the similarity in resuspension rates and turbidity values between the upper traps of the deep stations and bottom traps of the shallow stations (**II**).

Although wind exposure has been considered to be a key factor that affects the mixing processes in lakes (Havens *et al.*, 2007; Kelderman *et al.*, 2012), it is sometimes difficult to obtain significant correlations between sedimentation (resuspension) rates and wind speeds (Koski-Vähälä *et al.*, 2000). No exceptional wind speeds occurred during the periods (June, September) when the highest resuspension rates were measured in the Enonselkä basin (**II**). However, temporal variations in resuspension rates in the Enonselkä basin were attributed to changes in wind direction. For instance, northerly winds prevailed in June whereby the wave action was higher than at the same wind speed of south-westerly winds (**II**). In autumn, the convective mixing was likely to create favorable conditions for direct wind and wave activities through thermal destratification in Enonselkä (**II**). In Lake Peipsi, temporal variations in sediment resuspension were associated with the maximum daily wind speeds (**III**). Wind activity was most pronounced at the lowest water level, which occurred in autumn (September).

In both lakes studied, there was some evidence that phytoplankton contributed to the variations in resuspension rates (**II**, **III**). The peaks of resuspension rates in June and in September, in the Enonselkä basin concurred with the highest values of SPOM. These were preceded by maxima of primary production whereby the two highest values of the intercept of the SPOM/SPIM regression line occurred in May and August in the Enonselkä basin (**II**). Thus, strong phytoplankton blooms modified the surface sediments to become more organic and looser, i.e., more prone to resuspension, a phenomenon also described in other studies (Søndergaard *et al.*, 1992; Niemistö *et al.*, 2008). Increases in the organic content of surface sediments in addition to the organic content of entrapped material during the summer were also observed in Lake Lämmijärv (**III**). However, in Lake Peipsi *s.s.* the organic content of surface sediments showed no seasonal variations, and a steep decline in the organic content of trapped material followed the midsummer peak. Both these phenomena have been attributed to sediment resuspension (Niemistö, 2008; **III**).

5.3. Sediment resuspension as a regulator of water quality

Resuspension controlled water quality in the Enonselkä basin (**II**) and in Lake Peipsi (**III**), bringing substantial amounts of SS into the water column, which was also a conclusion made in many other studies (Kristensen *et al.*, 1992; Søndergaard *et al.*, 1992; Istvánovics *et al.*, 2004; Havens *et al.*, 2007). Changes in SS concentration in Enonselkä were coupled to those in water turbidity, which together can be largely explained by corresponding changes in wind, stratification conditions, and sediment properties (**II**).

More than 66% of the total load of SS in Enonselkä originated from the shallow areas, as the trap contents of the deep areas were found to consist mainly of material that had been initially resuspended in the shallow areas (**II**). Littoral vegetation, particularly the submerged macrophytes, may significantly reduce sediment resuspension and erosion in some shallow areas (Horppila & Nurminen, 2003, 2005; Kaitaranta *et al.*, 2013). Nevertheless, the effect of macrophytes in Enonselkä was suggested to be low: the coverage by submerged macrophyte species was estimated to be less than 5% at the time of the study (Niemistö *et al.*, 2012). Thus, sediment resuspension in the shallow areas of Enonselkä governed the particulate matter fluxes and water turbidity in the whole basin (**II**).

In Lake Peipsi, sediment resuspension increased the concentrations of SS, which was accompanied by an increase in TP concentrations occurring towards autumn (**III**). This was also confirmed by the fact that variations of TP and SS concentrations were driven by the same factors of wind speed and water level, as for sediment resuspension and gross sedimentation (**III**). Moreover, the contribution of fresh organic material accumulating onto the sediment during summer phytoplankton blooms appeared to be high, as indicated by the similarity in patterns of resuspension and concentrations of SS, TP and Chl *a* in Lake Peipsi *s.s.*

Many researchers in this field have emphasized a positive dependence between high resuspension rates and high TP concentrations in shallow eutrophic lakes (Kristensen *et al.*, 1992; Istvánovics *et al.*, 2004; Havens *et al.*, 2007). Moreover, the TP input into the lake water appeared to be dominated by sediment resuspension in Lake Peipsi. The values for the internal TP loading due to resuspension (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) were approximately 100-fold those (108-fold in Lake Peipsi *s.s.* and 111-fold in Lake Lämmijärv) of the external loading values (**III**). Similar trends have also been reported for other large and shallow lakes (Lake Taihu, Lake Okeechobee; Havens *et al.*, 2007). In the Enonselkä basin of Vesijärvi, internal loading of TP due to resuspension was estimated to be 62-fold that of its corresponding external loading value (Niemistö *et al.*, 2012). This high ratio indicates a great potential for the recycling of material that enters the lake through external loading (Ekholm *et al.*, 1997).

Resuspension events can enhance the export of biologically available P from the sediments to the overlying water. No correlations between SS and SRP were observed in Lake Peipsi (**III**), which suggests the importance of some other factors that determine P availability after resuspension. These other factors could include the retention capacity of the resuspended particles in addition to the prevailing biological and physico-chemical conditions (Søndergaard *et al.*, 2003, Niemistö *et al.*, 2012). Nevertheless, the significant effect of wind on the concentration of SRP in Lake Peipsi suggested a rather direct influence on the pool of mobile P in the sediments, which was estimated to be large. This pool of mobile P includes loosely-adsorbed and pore-water inorganic P, redox-sensitive fraction of P bound to oxides of reducible metals, and nonreactive P (Kapanen, 2012).

5.4. The effect of weather conditions on the water quality

The P found in a lake at any given time is the result of complex equilibria between external and internal loading, together with physical and biological processes that occur in the sediment and in the overlying water (Jennings *et al.*, 2003). The interplay of these factors also determine the seasonal dynamics of TP concentration in Lake Peipsi, which was demonstrated to be typical of many shallow, eutrophic lakes in which sediment release rates are high (**IV**). The year-to-year deviations in TP concentration from the general seasonal pattern, which was well predicted by the geographical coordinates and the day of the year, or the TP anomalies (Fig. 4, **IV**), were attributed to the anomalies in weather factors (**IV**).

Due to their high DRs, large and shallow lakes are expected to be especially influenced by wind-induced waves (Bachmann *et al.*, 2000; Havens *et al.*, 2007; Kelderman *et al.*, 2012). Wind was found to be a major factor in controlling the TP anomalies on the long-term scale in Lake Peipsi with its DR of 8.4 (Table 2; **IV**). This result confirms the conclusion made previously by Spears & Jones (2010), who suggested that wind effects might supersede the temperature effects in large shallow lakes with a high fetch.

Study **III** revealed that TP concentrations were impacted by V via sediment resuspension, which also increased the concentration of SS and Chl *a* in the water column of Lake Peipsi. The wind effect on sediment resuspension, along with the corresponding changes in the water quality, was particularly pronounced at low L in late summer-early autumn, when increases of the concentrations of SS, TP and Chl *a*, in Lake Peipsi *s.s.* were detected (**III**). However, higher water levels in May reduced the ability of wind to disturb sediment surfaces (**III**). The importance of L, along with V, in impacting upon the water quality variables in Lake Peipsi has also been demonstrated by the regression analysis of the short-term data (Table 2; **III**). Similarly, Nõges & Kisand (1999) observed that severe storms can entrain substantial quantities of sediments accompanied by a deterioration of the water quality in the large and shallow Lake Võrtsjärv at low L. It is probable that similar mechanisms were behind the impact of L on the variations in TP concentrations in the long-term, as a negative dependence was found between these variables (**IV**). Moreover, the interaction between L and

V revealed from a sediment-trap field survey (**III**) provided a possible explanation for a mainly increasing effect of wind on TP values in the period after the 180th Julian day, and reducing influences in the preceding period, when long-term data were analyzed (**IV**).

In contrast to the L factor, T and PAR demonstrated the seasonal switch (season before of after 180th Julian day) between increasing and decreasing effects on TP concentration (**IV**). This observation confirmed the conclusion made by Carvalho *et al.* (2012), who found that seasonal changes in weather variables may have both positive and negative impacts on water quality. Higher water temperatures can be associated with an increased release of nutrients from the sediments into the water column (Pettersson *et al.*, 2003; Spears *et al.*, 2007). Thus, an increase of T and a decrease of L can affect water quality simultaneously triggering an increase of TP concentrations in the water column. Similarly, the concurrence of lower water levels and higher summer water temperatures in the years 2000–2003, compared to the years 1985–1988, was previously concluded to cause higher TP concentrations in Lake Peipsi (Haldna *et al.*, 2008). On the other hand, warmer spring temperatures have been suggested to have a positive effect on *Daphnia* densities and cause reduced Chl *a* concentrations in spring (in May and June) in Loch Leven in Scotland, where phytoplankton contributes significantly to the overall budget of TP (Carvalho *et al.*, 2012). Analogous mechanisms could result in the negative effects of higher spring T on TP concentration in Lake Peipsi, where Blank *et al.* (2009) reported the biomass of cladocerans correlated positively with the sum of daily water temperatures in spring (April, May, June over the 1997-2007 period). It is also likely that the negative effects of late summer or early autumn PAR on TP concentrations can be associated with the compounding influences of other factors, which correlated with PAR. In general, previous studies have revealed changing annual relationships (both positive and negative) between PAR and phytoplankton in Lake Peipsi (Laugaste *et al.*, 2001).

CONCLUSIONS

The core findings of the thesis are:

1) On the catchment-lake scale, the natural mechanisms that regulate the surplus of N work efficiently. On the other hand, only a small decrease in P loading from the Estonian part of the catchment followed the dramatic reductions in the use of fertilizers and livestock production in addition to improved wastewater treatment. Moreover, no significant changes in TP concentrations in Lake Peipsi *s.s.* occurred on the long-term scale i.e. since the 1990s. On an annual basis, the in-lake concentrations of TP were insensitive to the changes in TP loading through the major inflow. The hysteresis can be attributed to high P levels in the catchment soils, unchanged external loading from shared parts of the catchment, and internal loading (**I**).

2)

a) Sediment resuspension constituted the majority of the gross sedimentation irrespective of whether the lake was stratifying or not (**II**, **III**).

b) The spatial differences of the gross sedimentation and sediment resuspension were determined by the lake morphometry. Sediment resuspended in shallow areas of a lake was transported to the lake deeps, resulting in the highest trap yields (**II**, **III**).

c) The temporal dynamics of resuspension were driven by wind events (**II**, **III**). In Enonselkä, the wind direction was important (**II**). Moreover, sediment disturbance was enhanced during autumnal overturn (**II**). In Lake Peipsi, the periods of extreme winds, i.e. the occurrence of Vmax > 10 m s^{-1}, determined the variations of sediment resuspension rates during the study period. The effect of extreme winds on resuspension was particularly pronounced at low water level (**III**). Additionally, increases in resuspension were associated with the large pools of organic material formed during strong phytoplankton blooms (**II**, **III**).

3)

a) Resuspension, particularly in the shallow areas, triggered the internal loading of SS, which resulted in high water turbidity in the Enonselkä basin of Lake Vesijärvi (**II**). This may be associated with the recurring signs of ecosystem deterioration exhibited since the late 1990s. Macrophyte-based management of the shallow areas could contribute to the restoration of the whole basin.

b) The long sampling period and the measurements taken from a comprehensive array of different sampling sites enabled the determination of a reliable mean estimate of internal TP loading due to sediment resuspension in Lake Peipsi (**III**). Resuspension-mediated internal loading of TP dominated over the external loading. Therefore, the present study provided the first empirical evidence for the high potential for recycling of P, originally brought into the lake by external loading (**III**). This emphasizes the particular need for the control of external P loading (**I**, **III**).

4) Sediment resuspension impacted upon the water quality through its significant influence on the loading of SS, turbidity, TP, and Chl *a* (**II**, **III**). Moreover, the results obtained from Enonselkä indicated that sediment fluxes from the shallow areas may govern the water quality of the whole lake.

5)

a) The study of the long-term series of TP measurements revealed the significant contributions of water temperature, water level, photosynthetically active radiation, wind speed to the TP anomalies (**IV**). The variability of these weather factors causes the temporal and geographical deviations of the TP dynamics from the expected pattern. Our quantitative estimations of the impacts of different weather variables on TP help to predict changes in the water quality under different scenarios of climate change.

b) The attempt to estimate the effect of the individual weather factors on the variations in TP concentrations showed that highly episodic and anomalous wind events are the main cause for deviations from the predictable patterns (**IV**). Extensive resuspension measurements, carried out for the first time in Lake

Peipsi, demonstrated that the wind affected TP concentration in the water column through the sediment resuspension (**III**).

c) As a higher frequency of extreme wind events can be expected in the future due to the climate change, severe implications on the lake ecosystems may follow due to the increase of internal P loading (**III, IV**).

The thesis was a significant step in understanding the factors that effect the water quality in large shallow lakes. Apart from showing the indisputable importance of studied factors, the thesis also stresses the need for further research. More field experiments are needed for the elucidation of the mechanisms behind our findings, including sediment P release conditions, sediment trap winter-measurements, interaction between physico-chemical and biological processes. The results of such experimental studies and consideration of additional factors would provide a solid base for the comprehensive models, which would serve as a significant tool for water managers.

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SUMMARY IN ESTONIAN

Looduslike ja inimtekkeliste survetegurite toime vee kvaliteedi muutlikkusele suurjärvedes

Inimtegevuse tagajärjel rikastuvad veekogud toiteainetega, mis toob endaga kaasa primaarproduktsiooni tõusu ning vee kvaliteedi halvenemise. Eutrofeerunud järvede vee kvaliteedi parandamine on praegusel ajal veekaitse üks peamisi ülesandeid kogu maailmas. Takistab aga asjaolu, et veeökosüsteemide vastusreaktsioon toiteainete koormuse muutustele on tihti ajalise nihkega. Setetesse talletunud toitesoolade vabanemise tõttu vette võib fosfori (P) väliskoormuse alandamine avalduda järvevee kvaliteedi paranemises alles aastakümnete pärast. Järvesette P kättesaadavuse suurenemine on ka setete stohhastilise iseloomuga resuspensiooni üks paljudest võimalikest mõjudest veeökosüsteemidele. Üldiselt peetakse ka kliima soojenemist üheks teguriks, mis võimendab eutrofeerumist. Seega kujuneb järvede vee kvaliteet paljude looduslike ja inimtekkeliste survetegurite koosmõjul ning nende faktorite mõju selgitamine on esmatähtis keskkonnakaitselisest seisukohast.

Käesolevas töös uuriti jõgede reostuskoormuse, setete resuspensiooni ning ilmastiku mõju järvevee kvaliteedi muutlikkusele. Peamiseks uurimisobjektiks oli Peipsi järv, kus tähtsaimaks keskkonnaprobleemiks peetakse vee kõrget P sisaldust ja sellest tulenevaid negatiivseid muutusi veeökosüsteemis. Seepärast on antud töös erilise tähelepanu all ülalpool loetletud faktorite mõju selle järve vee P kontsentratsioonile. Kvantitatiivselt hinnati P kontsentratsiooni tundlikkust ilmastikutegurite suhtes, mida on siiani vähe uuritud. Esmakordselt uuriti Peipsil katseliselt setete resuspensiooni. Kuigi suuri madalaid järvi peetakse eriti mõjustatuks setete tuuletekkelise resuspensiooni poolt, jäävad empiirilised andmed tihti puudulikeks keeruliste uurimistingimuste tõttu.

Võrdluseks uuriti tugevalt eutrofeerunud Vesijärve osa, Enonselkä (Soomes), mille vee kvaliteet paranes 1990. aastatel tänu toiteainete väliskoormuse alandamisele ning kalade väljapüügile. 2000. aastatel täheldati seal taas vee kvaliteedi halvenemist, mis ajendas settimise ja setete resuspensiooni kui selle potentsiaalse põhjuse uurimist.

Käesoleva töö eesmärgid olid:

1) hinnata Eesti-poolsete jõgede reostuskoormuse mõju Peipsi Suurjärve vee kvaliteedile (**I**);
2) selgitada settimise ja setete resuspensiooni ajalist ja ruumilist muutlikkust Enonselkäs ja Peipsis (**II**, **III**);
3) hinnata resuspensiooni tekitatud hõljuvaine (SS) ja üldfosfori (TP) sisekoormust (**II**, **III**);
4) hinnata setete resuspensiooni mõju Enonselkä ja Peipsi vee kvaliteedile (**II**, **III**);
5) hinnata ilmastiku mõju vee kvaliteedile a) kasutades pikaajalisi andmeridu TP kontsentratsioonide kohta (**IV**); b) kasutades lühiajalisi (ühe aasta jooksul saadud) andmeid vee kvaliteedi (TP; SS, SRP ja Chl a kontsentratsioon) kohta (**III**).

Hinnati Eesti poolelt Peipsi Suurjärve suubuvate jõgede üldlämmastiku (TN) ja TP koormust ajavahemikul 1992–2007 ja võrreldi seda varasemate andmetega. Jõgede toiteainete koormuse mõju järve vee kvaliteedile vahetult jõe suudme ees analüüsiti Emajõe näitel, mille suudme vahetus läheduses asub üks seirepunkt järves (**I**). Settimise ja setete resuspensiooni ruumilis-ajalise muutlikkuse määramiseks paigaldati settelõksud Enonselkä (maist novembrini 2009; **II**) ning Peipsi järve (maist oktoobrini 2011; **III**). Selgitati resuspensiooni varieeruvust kontrollivaid faktoreid ning resuspensiooni mõju vee kvaliteedi mitmetele näitajatele. Enonselkäs määrati setete resuspensiooni mõju vee hägususele ning hinnati ka SS sisekoormust (**II**). Peipsis uuriti seoseid setete resuspensiooni ning SS, TP ja SRP kontsentratsioonide vahel (**III**). Samuti hinnati esmakordselt resuspensiooni tekitatud TP sisekoormust Peipsis (**III**). Analüüsiti ka ilmastiku (veetase ja veetemperatuur, tuule kiirus) mõju järve vee kvaliteedile (**III**). Peipsi pikaajaliste andmeridade statistilist analüüsi rakendati ilmastiku panuse selgitamiseks TP kontsentratsioonide varieeruvusse (**IV**). TP väärtuste tundlikkus ilmafaktorite suhtes kvantifitseeriti (**IV**).

Käesoleva töö põhitulemused:

1) Üleliigse N eemaldavad looduslikud protsessid (nt. denitrifikatsioon) toimivad efektiivselt N allika ja pinnaveekogu vahel ning ka järv ise on paindlik N sissekande suhtes. Vastupidi, täheldati vaid vähest Eesti-poolsete jõgede fosforikoormuse muutust

põllumajandustegevuse vähenemise järel 1990. aastate alguses, ning Peipsi vee P kontsentratsioon alates 1990., pikemaajalise perioodi keskmisena, ei muutunud oluliselt. Aastakeskmine järve vee TP kontsentratsioon ei reageerinud aastast-aastasse muutuvale P reostuskoormusele. Võimalikeks põhjusteks võivad olla pinnase kõrge P-sisaldus, kõrge toiteainete sissekanne Venemaa-poolselt valglalt ning P suurenenud vabanemine setetest e. sisekoormus (**I**).

2)

a) Setete resuspensioon moodustas valdava osa kogu settimisvoost, sõltumata sellest, kas oli tegemist kihistunud või kihistumata järve või selle osaga (**II**, **III**).

b) Setete resuspensiooni (settimisvoo) ruumiline varieeruvus sõltus peamiselt järve morfomeetriast. Järve madalates piirkondades resuspendeerunud sete liikus sügavamate alade suunas, mis põhjustas seal mõõdetud suuruste kõrgeimaid väärtusi (**II**, **III**).

c) Setete resuspensiooni ajaline dünaamika oli seotud tuule mõjuga (**II**, **III**). Kihistuse häirimine suve esimesel poolel (mil domineeriv tuule suund tagas suurema jooksumaa ning seega võimsama lainetegevuse) ning kihistuse puudumine sügisel suurendasid järve setete tundlikkust tuule mõju suhtes Enonselkäs. Peipsis seostusid setete resuspensiooni muutused tugevate tuulte (> 10 m s^{-1}) esinemissagedusega. Nende mõju oli eriti tugev madala veetaseme korral (**III**). Lisaks oli resuspensiooni dünaamika seotud veeõitsengu tagajärjel tekkinud orgaanilise aine varuga (**II**, **III**).

3)

a) Madalate alade setete resuspensioon oli SS sisevoogude ning suurenenud veehägususe põhjuseks (**II**). Antud nähtust võib seostada Enonselkäs ka vee kvaliteedi halvenemisega alates 1990. lõpust. Võib kaaluda selle järve tervendamist makrofüütide abil.

b) Pikk mõõtmiste periood ning proovivõtupunktide varieeruvus võimaldas hinnata resuspensiooni tekitatud TP sisekoormust Peipsis (**III**). Seega saadi esimene empiiriline tõend selle kohta, et valglalt pärit P taasringluse potentsiaal Peipsis on väga kõrge: resuspensiooni tekitatud TP sisekoormus ületas tunduvalt väliskoormuse väärtust. Antud tulemus rõhutab eelkõige väliskoormuse piiramise vajalikkust (**I, III**).

4) Setete resuspensioon reguleeris vee kvaliteeti, mõjutades SS (või vee hägususe), TP ja Chl *a* kontsentratsiooni (**II**, **III**). Vesijärve uuringud näitasid, et järve madalamates piirkondades resuspendeeritud setete ümberpaiknemine võib kontrollida kogu järve vee kvaliteeti.

5)

a) Uuritud ilmastikunäitajad (veetase ja vee temperatuur, päevakeskmine ja maksimaalne tuule kiirus, fotosünteetiliselt aktiivne kiirgus) osutusid olulisteks vee kvaliteedi surveteguriteks (**III**, **IV**).

b) TP kontsentratsiooni muutused olid eriti tundlikud tuule kiiruse muutuste suhtes (**IV**). Ulatuslikud resuspensiooni mõõtmised, mida tehti Peipsis esmakordselt, näitasid, et tuule mõju vee kvaliteedile avaldub just setete resuspensiooni kaudu (**III**).

c) Vastavalt saadud uuringutulemustele (**III, IV**) võivad kliimamuutuste tagajärjed veeökosüsteemidele olla dramaatilised. Ekstreemselt kõrge tuulekiiruse juhtude sagenemine, mida prognoositakse seoses kliimamuutustega, võib esile kutsuda P sisekoormuse suurenemist tulevikus.

Käesolev töö on oluline samm suurte järvede vee kvaliteeti mõjutavate faktorite väljaselgitamisel. Lisaks uuritud faktorite (toiteelementide välis- ja sisekoormus, setete resuspensioon, ilmastikutegurid) tähtsusele rõhutab see ka uuringute jätkamise vajadust. Esmatähtis oleks katseliste uuringute tegemine, mis võimaldaksid seletada ka käesoleva töö tulemusi: tuleks uurida toitesoolade setetest vabanemise tingimusi, setete resuspensiooni talvel ning füüsikalis-keemiliste ja bioloogiliste protsesside interaktsioone. Eksperimentaaluuringute tulemused ning lisafaktorite arvessevõtt oleksid oluline baas rakendusmudelite väljaarendamiseks. Need mudelid võimaldaksid omakorda paremat veekasutuse ja -kaitse planeerimist.

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CURRICULUM VITAE

Personal data

Name: Olga Tammeorg *(née* Buhvestova)
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Education

Since 2008	Estonian University of Life Sciences, PhD studies in Environmental Sciences, Limnology
2008	University of Tartu, Faculty of Science and Technology, MSc *cum laude* in Natural Sciences
2006	University of Tartu, Faculty of Physics and Chemistry, BSc *cum laude* in Environmental Sciences
2003	Mustvee Russian Gymnasium

Professional appointments

Since 2013	University of Helsinki, AQUADIGM project, PhD student
Since 2007	Estonian University of Life Sciences, specialist

Research funding

2013-2015	"The function and management of aquatic ecosystems in the changing environment: the effect of paradigm shifts (AQUADIGM)"
2008-2013	Estonian Target Financed Project SF 0170006s08 "Effects of natural and man induced pressures on the ecosystems of large lakes"
2008–2011	Estonian Science Foundation grant No. 7643 "Creation and theoretical reasoning of the generalized synthetic database for water and biota of Estonian freshwater waterbodies".
Since 2007	Hydrobiological monitoring of transboundary water bodies (Lake Peipsi, Narva Reservoir)

Scientific expert positions
Research interests: lake nutrient dynamics

Awardee of the World Student Meeting on Aquatic Sciences sponsored by WWCN/WWCF & ILEC (2011)

Experience in higher education

Co-teacher in course "The monitoring of Estonian waterbodies", Estonian University of Life Sciences, since 2008. I have published my lectures at weebly.peipsiseire.com.

I have supervised a BSc thesis by Ahti Kikas titled "The temporal and spatial variation of sediment resuspension in large and shallow Lake Peipsi" (in Estonian) in the Estonian University of Life Sciences (2012).

List of main publications

Buhvestova O., Kangur K., Haldna M. & Möls T. (2011) Nitrogen and phosphorus in Estonian rivers discharging into Lake Peipsi: estimation of loads and seasonal and spatial distribution of concentrations. *Estonian Journal of Ecology*, **60**, 18–38.

Haldna M., Möls T., **Buhvestova O.** & Kangur K. (2013) Predictive model for phosphorus in large shallow Lake Peipsi: approach based on covariance structures. *Aquatic Ecosystems Health and Management*, **16**, 222–226.

Kaitaranta J., Niemistö J., **Buhvestova O**. & Nurminen L. (2013) Quantifying sediment resuspension and internal phosphorus loading in shallow near-shore areas in the Gulf of Finland. *Boreal Environment Research*, **18**, 473–487.

Kangur M., Puusepp L., **Buhvestova O**., Haldna M. & Kangur, K (2013) Spatio-temporal variability of surface sediment phosphorus fractions and water phosphorus concentration in Lake Peipsi (Estonia/Russia). *Estonian Journal of Earth Sciences*, **62**, 171–180.

Minella M., Laurentiis E.D., **Buhvestova** O., Haldna M., Kangur K., Maurino V., Minero C. & Vione D. (2013) Modelling of lake-water photochemistry: A three-decade assessment of the steady-state concentration of photoreactive transients ($^{\bullet}$OH, $CO_3^{\bullet}$ and ^{3}CDOM*) in the surface water of polymictic Lake Peipsi (Estonia/Russia). *Chemosphere*, **90**, 2589–2596.

Tammeorg O., Möls T. & Kangur K. (2014) Weather conditions influencing phosphorus concentration in the growing period in the large shallow Lake Peipsi (Estonia/Russia). *Journal of Limnology*, **73**, 11–19 (DOI: 10.4081/jlimnol.2014.768).

Tammeorg O., Niemistö J., Horppila J., Haldna M. & Kangur K. (2013) Sedimentation and resuspension dynamics in Lake Vesijärvi (Finland): comparison of temporal and spatial variations of sediment fluxes in deep and shallow areas. *Applied and Fundamential Limnology*, **182**, 297–307.

Tammeorg O., Niemistö J., Möls T., Laugaste R., Panksep K. & Kangur K. (2013) Wind-induced sediment resuspension as a potential factor sustaining eutrophication of large and shallow Lake Peipsi. *Aquatic Sciences*, **75**, 559–570.

Participation in international conferences

The 5th Shallow Lakes Conference, Punta del Este, November 23-28, 2008. Oral presentation: Buhvestova O. & Kangur K. The effect of Estonian riverine loads of nutrients on water quality of large shallow Lake Peipsi.

The 6th Symposium for European Freshwater Sciences, Sinaia, Romania, August 17-21, 2009. Oral presentation: Buhvestova O., Kangur K. & Haldna M. The seasonality of nutrient dynamics in two parts of large shallow Lake Peipsi.

The 7th International shallow Lake Conference, Wuxi, China, April 24-28, 2011. Oral presentation: Buhvestova O., Möls T. & Kangur K. Natural variables as the factors behind phosphorus seasonality in shallow eutrophic Lake Peipsi.

The 10th AEHMS international conference, Siena, Italy, June 13-15, 2011. Poster presentation: Buhvestova O., Haldna M. & Möls T. Predictive model for phosphorus in large shallow Lake Peipsi: approach based on covariance structures.

The 3rd World Lake Student Meeting: The need and future direction for inland water monitoring and data processing, Tahoe Environmental Research Center, Nevada, USA, October 25-28, 2011; the 14th World Lake Conference, Austin, Texas, USA, October 31-November 4, 2011. Oral presentation: Buhvestova O. The importance of the monitoring tradition for large shallow Lake Peipsi (Estonia/Russia).

ASLO Aquatic Sciences Meeting, Otsu, Japan, 8-13 July, 2012. Oral presentation: Buhvestova O. Wind-induced sediment resuspension as a factor behind eutrophication of a large and shallow Lake Peipsi.

Self-improvement

Course of the 3rd Jyväskylä Winter School of Ecology "Winter Limnology", Konnevesi Reseach Station, February 9-13, 2010.

Project “Internal loading of phosphorus in Lake Vesijärvi”, University of Helsinki, April- September, 2009.

The courses of the 3rd World Lake Student Meeting “The need and future direction for inland water monitoring and data processing”, Tahoe Environmental Research Center, Nevada, USA, October 25-28, 2011.

ELULOOKIRJELDUS

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Haridustee

Alates 2008	Eesti Maaülikool, doktoriõpe keskkonnateaduse ja rakendusbioloogia erialal
2008	Tartu Ülikool, Loodus- ja tehnoloogiateaduskond, loodusteaduste magistrikraad (*cum laude*)
2006	Tartu Ülikool, Füüsika-keemia teaduskond, keskkonnateaduste bakalaureusekraad (*cum laude*)
2003	Mustvee Vene Gümnaasium

Teenistuskäik

Alates 2013	Helsingi Ülikool, Veeteaduste osakond, doktorant
Alates 2007	Eesti Maaülikool, Limnoloogiakeskus, spetsialist

Uuringute finantseerimine

2013-2015	Soome sihtfinantseeritav teema "Veeökosüsteemine funktsioneerimine ja nende majandamine muutuvas keskkonnas: paradigmade nihete mõju (AQUADIGM)".
2008-2013	Eesti sihtfinantseeritav teema SF0170006s08 „Looduslike ja inimtekkeliste surveteguri te toime suurjärvede ökosüsteemile".
2008–2011	ETF grant 7643 „Eesti mageveekogude veeja elustiku üldistatud sünteetilise andmebaasi loomine ja teoreetiline põhjendamine".
2007-	Piiriveekogude hüdrobioloogiline seire (Peipsi järv, Narva Veehoidla)

Teaduslik ja arendustegevus

Uurimissuunad: järvede toiteainete dünaamika
Eksperdipositsioon:
Maailma tudengite veeteaduste alase kokkutuleku (WWCN/WWCF & ILEC finantseeritud) eripreemia (2011)

Kõrgkoolipedagoogika:

Loengud kursuse “Eesti veekogude seire” raames, Eesti Maaülikool alates aastatst 2008 (materjalid avaldatud: weebly.peipsiseire.com).

Juhendasin Ahti Kikase bakalaureusetööd “Setete resuspensiooni ajalis-ruumiline muutlikkus suures madalas Peipsi järves” 2012, Eesti Maaülikool.

Peamiste publikatsioonide loetelu

Buhvestova O., Kangur K., Haldna M. & Möls T. (2011) Nitrogen and phosphorus in Estonian rivers discharging into Lake Peipsi: estimation of loads and seasonal and spatial distribution of concentrations. *Estonian Journal of Ecology*, **60**, 18–38.

Haldna M., Möls T., **Buhvestova O.** & Kangur K. (2013) Predictive model for phosphorus in large shallow Lake Peipsi: approach based on covariance structures. *Aquatic Ecosystems Health and Management*, **16**, 222–226.

Kaitaranta J., Niemistö J., **Buhvestova O**. & Nurminen L. (2013) Quantifying sediment resuspension and internal phosphorus loading in shallow near-shore areas in the Gulf of Finland. *Boreal Environment Research*, **18**, 473–487.

Kangur M., Puusepp L., **Buhvestova O.**, Haldna M. & Kangur, K (2013) Spatio-temporal variability of surface sediment phosphorus fractions and water phosphorus concentration in Lake Peipsi (Estonia/Russia). *Estonian Journal of Earth Sciences*, **62**, 171–180.

Minella M., Laurentiis E.D., **Buhvestova** O., Haldna M., Kangur K., Maurino V., Minero C. & Vione D. (2013) Modelling of lake-water photochemistry: A three-decade assessment of the steady-state concentration of photoreactive transients ($^{\bullet}$OH, $CO_3^{\bullet}$ and ^{3}CDOM*) in the surface water of polymictic Lake Peipsi (Estonia/Russia). *Chemosphere*, **90**, 2589–2596.

Tammeorg O., Möls T. & Kangur K. (2014) Weather conditions influencing phosphorus concentration in the growing period in the large shallow Lake Peipsi (Estonia/Russia). *Journal of Limnology*, **73**, 11–19 (DOI: 10.4081/jlimnol.2014.768).

Tammeorg O., Niemistö J., Horppila J., Haldna M. & Kangur K. (2013) Sedimentation and resuspension dynamics in Lake Vesijärvi (Finland): comparison of temporal and spatial variations of sediment fluxes in deep and shallow areas. *Applied and Fundamential Limnology*, **182**, 297–307.

Tammeorg O., Niemistö J., Möls T., Laugaste R., Panksep K. & Kangur K. (2013) Wind-induced sediment resuspension as a potential factor sustaining eutrophication of large and shallow Lake Peipsi. *Aquatic Sciences*, **75**, 559–570.

Ettekanded rahvusvahelistel konverentsidel:

The 5th Shallow Lakes Conference, Punta del Este, November 23-28, 2008. Suuline ettekanne: Buhvestova O. & Kangur K. The effect of Estonian riverine loads of nutrients on water quality of large shallow Lake Peipsi.

The 6th Symposium for European Freshwater Sciences, Sinaia, Romania, August 17-21, 2009. Suuline ettekanne: Buhvestova O., Kangur K. & Haldna M. The seasonality of nutrient dynamics in two parts of large shallow Lake Peipsi.

The 7th International shallow Lake Conference, Wuxi, China, April 24-28, 2011. Suuline ettekanne: Buhvestova O., Möls T. & Kangur K. Natural variables as the factors behind phosphorus seasonality in shallow eutrophic Lake Peipsi.

The 10th AEHMS international conference, Siena, Italy, June 13-15, 2011. Posterettekanne: Buhvestova O., Haldna M. & Möls T. Predictive model for phosphorus in large shallow Lake Peipsi: approach based on covariance structures.

The 3rd World Lake Student Meeting: The need and future direction for inland water monitoring and data processing, Tahoe Environmental Research Center, Nevada, USA, October 25-28, 2011; the 14th World Lake Conference, Austin, Texas, USA, October 31-November 4, 2011. Suuline ettekanne: Buhvestova O. The importance of the monitoring tradition for large shallow Lake Peipsi (Estonia/Russia).

ASLO Aquatic Sciences Meeting, Otsu, Japan, 8-13 July, 2012. Suuline ettekanne: Buhvestova O. Wind-induced sediment resuspension as a factor behind eutrophication of a large and shallow Lake Peipsi.

Täiendõpe:

Kursus “Winter Limnology” (3rd Jyväskylä Winter School of Ecology), Konnevesi uurimisjaam, Soome, 9-13 veebruar 2010.

Osavõtt projektist “Internal loading of phosphorus in Lake Vesijärvi”, Helsingi Ülikool, Soome, aprill – september, 2009.

Kursus “The need and future direction for inland water monitoring and data processing” (3rd World Lake Student Meeting), Tahoe keskkonnauuringute keskus, Nevada, USA, 25-28 oktoober 2011.

VIIS VIIMAST KAITSMIST

LEILA MAINLA

CHANGES IN THE BIOCHEMICAL COMPOSITION OF APPLE (*Malus domestica* Borkh.)
FRUITS DEPENDING ON ROOTSTOCK AND CALCIUM TREATMENT
MUUTUSED ÕUNTE BIOKEEMILISES KOOSTISES SÕLTUVALT AED-ÕUNAPUU
(*Malus domestica* Borkh.) POOKEALUSEST JA KALTSIUMIGA VÄETAMISEST
Professor **Kadri Karp**, dotsent **Ulvi Moor**
15. november 2013

FLOORTJE VODDE

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TORMIKAHJUSTUSTE KÄIGUS TEKKINUD MIKROALADE DÜNAAMIKA JA HÄIRINGUJÄRGNE PUURINDE UUENEMINE HEMIBOREAALSES SEGAMETSAS
Professor **Kalev Jõgiste**, professor **Frits Mohren** (*Wageningen University, The Netherlands*)
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MEELIS SEEDRE

DISTURBANCE EFFECTS ON BOREAL FOREST ECOSYSTEM CARBON DYNAMICS
HÄIRINGUREŽIIMI MÕJU BOREAALSE METSAÖKOSÜSTEEMI SÜSINIKUVOOGUDELE
Professor **Kalev Jõgiste**, prof. **Han Chen** (*Lakehead University, Canada*)
16. detsember 2013

HEDI HARZIA

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Prof. *emer.* **Olav Kärt**, prof. **Ursel Soomets** (Tartu Ülikool), vanemteadur **Kalle Kilk** (Tartu Ülikool)
20. detsember 2013

PIRET KALMUS

CLINICAL MASTITIS IN ESTONIA: DIAGNOSIS, TREATMENT EFFICACY AND ANTIMICROBIAL RESISTANCE OF PATHOGENS IN ESTONIA
KLIINILISTE MASTIITIDE DIAGNOOSIMINE, RAVI TULEMUSLIKKUS JA PATOGEENIDE ANTIMIKROOBNE RESISTENTSUS EESTIS
Professor **Toomas Orro**, dotsent **Kalle Kask**
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