highest magnitude (before the 180^{th} day: -30.6%; after the 180^{th} day: 32.1%), and it was three-fold of those TP value changes attributed to temperature. Fluctuating V and Vmax were associated with frequent switches between positive and negative influences. Nevertheless, our analysis resolved the switch of the mean effect of V from strongly negative in the period prior to 180^{th} Julian day to strongly positive for the period after 180^{th} Julian day.

DISCUSSION

Lake Peipsi is similar to many shallow lakes, whereby internal loading tends to be the principal component of P supply for phytoplankton in summer when external nutrient loading is low: a trough of the hydrograph has been reported at this time of the year (Jaani, 2001; Starast *et al.*, 2001). It has been widely accepted that internal P loading delays the recovery of shallow lakes from eutrophi-

Tab. 1. Significant effects of weather factors on total phosphorus concentration.

Weather factor	Effect days	Effect count	Mean effect (%)	Min effect (%)	Max effect (%)
All days (1175 TP observations)					
Water temperature (°C)	4-8	5	1.31	1.04	1.58
Water level (cm)	0-12	46	-0.14	-0.20	-0.10
Photosynthetically active radiation (MJ m^{-2})	0-9	31	-1.98	-2.73	-1.30
Wind speed (mean) (m s^{-1})	1-12	8	-19.5	-52.2	35.2
Wind speed (max) (m s^{-1})	3-6	4	-8.03	-16.7	4.61
Days before the 180^{th} Julian day (479 TP observations)					
Water temperature (°C)	0-8	19	-3.17	-5.22	-1.99
Water level (cm)	0-10	16	-0.28	-0.35	-0.20
Photosynthetically active radiation (MJ m^{-2})	0-12	6	0.47	-6.74	4.79
Wind speed (mean) (m s^{-1})	2-12	10	-32.2	-87.0	121
Days after the 180^{th} Julian day (703 TP observations)					
Water temperature (°C)	0-8	8	2.48	1.95	2.99
Water level (cm)	2-5	4	-0.15	-0.17	-0.13
Photosynthetically active radiation (MJ m^{-2})	0-9	25	-3.46	-5.49	-2.22
Wind speed (mean) (m s^{-1})	7-7	1	31.1	31.1	31.1
Wind speed (max) (m s^{-1})	1-5	3	-18.3	-23.6	-8.55

TP, total phosphorus concentration. The residuals were calculated by subtracting the logarithmic total phosphorus concentration (LTP) value predicted by spline technique from the observed LTP by using the long-time trend, seasonal dynamics and geographical coordinates as predictors. We used to average over 1 to 6 days, for 0 to 7 days before the TP sampling. Analyses revealing significant ($P<0.001$) factor effects are called positive and their number is called effects count. For positive analyses the minimal, maximal and mean factor effects are given.

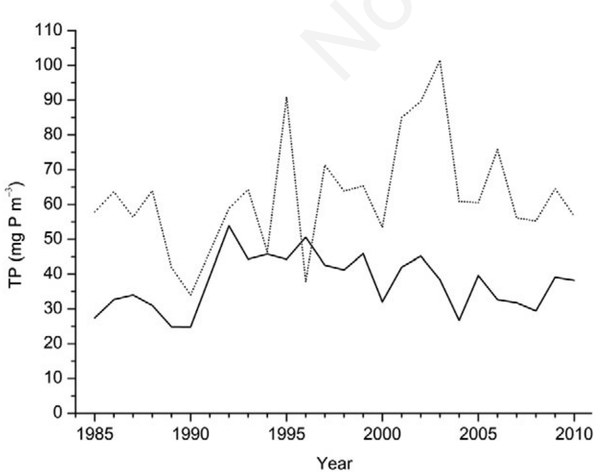

Fig. 6. Mean annual phosphorus concentrations for Lake Peipsi *sensu stricto* (solid line) and Lake Lämmijärv (dashed line) measured in the growing season (Julian days 100-310 within each year) during the study period (1985-2010).

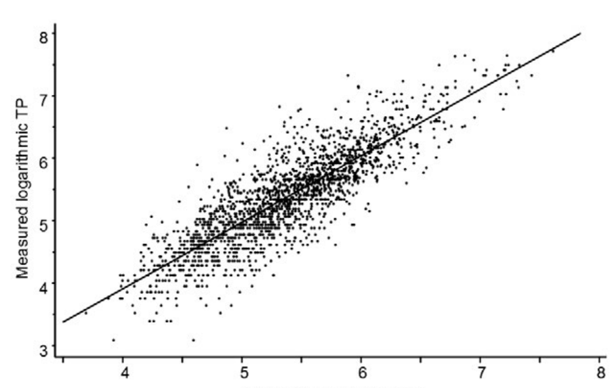

Fig. 7. Relationship between measured and predicted (from year, day of the year and geographical coordinates) logarithmic total phosphorus concentration [log2 (TP)] in Lake Peipsi.

cation (Søndergaard *et al.,* 2002; Jeppesen *et al.*, 2005; Spears *et al.*, 2012). However, slow decline in internal P loading has been reported after the reduction in loading for a number of lakes (Søndergaard *et al.,* 2002, 2013; Spears *et al.*, 2012). Similar changes, *i.e.* a sharp increase, followed by a steady decline, have been observed in annual mean and maximum TP in Lake Peipsi *s.s.*, which experienced drastic changes in the supply of nutrients in the late 1980s and early 1990s (Loigu *et al*., 2008). In addition to the high internal loading, the current high TP levels compared to those of the 1980s have been associated with unchanged external loading from the Russian part of the catchment area to climate change and to changes in the biotic structure (Nõges *et al.*, 2007; Buhvestova *et al.*, 2011). The importance of lake morphology in terms of changes in water quality has also been demonstrated by the modelling results (Janse *et al.,* 2008). Owing to smaller depth, size, and in addition to higher TP values in the water, Lake Lämmijärv appears to be more sensitive than Lake Peipsi *s.s.* to the disturbances, as was indicated by a more pronounced seasonal pattern, higher fluctuations in annual mean TP (Fig. 6), higher variation of summer TP (Figs. 4 and 5a). This is in accordance with the conclusion made by Søndergaard *et al.* (2013), who reported more pronounced seasonal variations in P retention with increasing P levels. These various smooth and regular changes in the lake TP mentioned above can be rather well predicted by geographical coordinates, year and day of the year (Fig. 7).

The present study has found an effect of weather factors on P variability, additional to those that have been already captured by fitting a seasonal dynamics to the data. Since temperature controls the rate of almost all processes in the lake, it has been generally suggested to act as a major integrating factor for a number of influences (Søndergaard, 2007). According to the results of the present study, no other factor had the magnitude of effect on TP that was attributed to wind. The result confirms the conclusion made previously by Spears and Jones (2010), who suggested that wind effects might supersede the temperature effects in large shallow lakes with high fetch.

The mechanisms behind the influences, leading to fluctuations in TP, are less easily explained. Changes in the summer levels of TP (after 180th day) in Lake Peipsi are probably associated with weather variables through the effect on internal release of P. Higher temperatures lead to an increased release of nutrients from the sediments into the water column (Pettersson *et al*., 2003; Spears *et al*., 2007). On the other hand, lower water levels can also be associated to an increased probability of sediment disturbance due to sediment resuspension (Kristensen *et al*., 1992; Nagid *et al*., 2001; Nõges *et al*., 2003). The synergistic effects of L and T on water quality in Lake Peipsi, *i.e.* increases in TP during periods with lower L and higher T (for the 2000-2003 period compared to the 1985-1988 period), have been well documented (Haldna *et al*., 2008).

However, warmer spring temperatures have been suggested to have a positive effect on *Daphnia* densities and cause reduced chlorophyll *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). Similar mechanisms could be responsible for the negative effects of higher spring water temperatures on TP in Lake Peipsi, where the biomass of cladocerans has been found to correlate positively with the sum of daily water temperatures in spring (April, May, June over the 1997-2007 period; Blank *et al*., 2009). It is likely that PAR in the period after 180th day was associated with decreasing TP values via the compounding influences from other factors. In general, the correlations between PAR and phytoplankton in previous studies on Lake Peipsi revealed changing annual relationships (both positive and negative; Laugaste *et al*., 2001). Thus, our results confirm the conclusion of Carvalho *et al.* (2012), who showed that seasonal changes in weather conditions can have both positive and negative impacts on water quality.

The TP anomalies were found to be the most sensitive to the anomalies in wind speed. Wind has been demonstrated to impact sediment-water interactions, particularly in large shallow lakes (Bachmann *et al*., 2000; Havens *et al*., 2007; Kelderman *et al*., 2012; Spears *et al*., 2012). Wind-induced resuspension mixes P-rich sediment particles and interstitial P into the water column, and this transport at any given time can be orders of magnitude greater than other inputs of P such as by diffusion and external loading (Havens *et al*., 2007; Niemistö *et al*., 2012).

In a recent study on sediment resuspension in large shallow waters of Lake Peipsi, wind was identified to be the main driving force behind the variations in sediment resuspension (Tammeorg *et al*., 2013). The effect of wind was found to be particularly pronounced at lower water levels in September, when the highest rates of sediment resuspension, and when the highest concentrations of suspended solids, TP, and Chl *a* were measured. Moreover, higher water levels in May reduced the ability of wind to disturb sediment surface. Thus, the results of the present study, which revealed a mainly increasing effect of wind on TP values in a period after the 180th Julian day, and reducing influences in the preceding period, are in close agreement with the results obtained from a sediment-trap field survey (Tammeorg *et al*., 2013). Therefore, the results of the present study suggest severe implications of climate change on the lake ecosystems such as an increase of internal phosphorus loading, since a higher frequency of extreme wind events can be expected in the future (Jeppesen *et al.,* 2009).

CONCLUSIONS

It is a complex task to identify all the factors that determine TP in large shallow lakes because the P cycle is influenced by multiple processes. The factors affecting P dynamics are generally interrelated, and these interactions confound attempts to separate one specific effect, *e.g.* that due to weather variables. Long-term datasets for Lake Peipsi, together with advanced statistical methods, have enabled us to reveal the contribution of weather factors including L, T, PAR, and V to the variability in P concentrations. Some variability of P remains after statistical removal of the effects of those factors (*i.e.* geographical coordinates, year and seasonality) that determine consistency over long time-scales. Highly episodic wind events were identified to be the main drivers behind TP anomalies. This suggests severe implication of climate change for the quality of the lake water.

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REFERENCES

Bachmann RW, Hoyer MV, Canfield DE, 2000. The potential for wave disturbance in shallow Florida lakes. Lake Reserv. Manage. 16:281-291.

Blank K, Haberman J, Haldna M, Laugaste R, 2009. Effect of winter conditions on spring nutrient concentrations and plankton in a large shallow Lake Peipsi (Estonia/Russia). Aquat. Ecol. 43:745-753.

Buhvestova O, Kangur K, Haldna M, Möls T, 2011. Nitrogen and phosphorus in Estonian rivers discharging to Lake Peipsi: estimation of loads and seasonal and spatial distribution of concentrations. Est. J. Ecol. 60:18-38.

Carvalho L, Miller C, Spears BM, Gunn IDM, Bennion H, Kirika A, May L, 2012. Water quality of Loch Leven: responses to enrichment, restoration and climate change. Hydrobiologia 681:35-47.

Garrison PJ, Laliberte GD, Ewart BP, 2010. The importance of water level changes and shoreline development in the eutrophication of a shallow, seepage lake. P. Acad. Nat. Sci. Phila. 160:113-126.

Haldna M, Milius A, Laugaste R, Kangur K, 2008. Nutrients and phytoplankton in Lake Peipsi during two periods that differed in water level and temperature. Hydrobiologia 599:3-11.

Haldna M, Möls T, Buhvestova O, Kangur K, 2013. Predictive model for phosphorus in large shallow Lake Peipsi: approach based on covariance structures. Aquat. Ecosyst. Health 16:222-226.

Havens KE, Jin KR, Iricanin N, James RT, 2007. Phosphorus dynamics at multiple time scales in the pelagic zone of a large shallow lake in Florida, USA. Hydrobiologia 581:25-42.

Hoyer MV, Horsburgh CA, Canfield DE, Bachmann RW, 2005. Lake level and trophic state variables among a population of shallow Florida lakes and within individual lakes. Can. J. Fish. Aquat. Sci. 62:2760-2769.

Iital A, Pachel K, Loigu E, Pihlak M, Leisk Ü, 2010. Recent trends in nutrient concentrations in Estonian rivers as a response to large-scale changes in land-use intensity and life-styles. J. Environ. Monitor. 12:178-188.

Iital A, Stålnacke P, Deelstra J, Loigu E, Pihlak M, 2005. Effects of large-scale changes in emissions on nutrient concentrations in Estonian rivers in the Lake Peipsi drainage basin. J. Hydrol. 304:261-273.

IPCC, 2007. Summary of policymakers, p. 7-22. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.), Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the Fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Istvánovics V, 2008. The role of biota in shaping the phosphorus cycle in lakes. Freshw. Rev. 1:143-174.

Jaani A, 2001. The location, size and general characterisation of Lake Peipsi and its catchment area, p. 10-17. In: T. Nõges (ed.), Lake Peipsi: meteorology, hydrology, hydrochemistry. Sulemees Publ.

Janse JH, De Senerpont Domis LN, Scheffer M, Lijklema L, Van Liere L, Klinge M, Mooij WM, 2008. Critical phosphorus loading of different types of shallow lakes and the consequences for management estimated with the ecosystem model PCLake. Limnologica 38:203-219.

Jennings E, Jones S, Arvola L, Staehr PA, Gaiser E, Jones ID, Weathers KC, Weyhenmeyer GA, Chiu CY, Eyto ED, 2012. Effects of weather-related episodic events in lakes: an analysis based on high-frequency data. Freshwater Biol. 57:589-601.

Jeppesen E, Kronvang B, Meerhoff M, Sondergaard M, Hansen KM, Andersen HE, 2009. Climate change effects on run off, catchment phosphorus loading and lake ecological state, and potential adaptations. J. Environ. Qual. 38:1930-1941.

Jeppesen E, Søndergaard M, Jensen JP, Havens KE, Anneville O, Carvalho L, Coveney MF, Deneke R, Dokulil MT, Foy B, Gerdeaux D, Hampton SE, Hilt S, Kangur K, Köhler J, Lammens EHHR, Lauridsen TL, Manca M, Miracle MR, Moss B, Nõges P, Persson G, Phillips G, Portielje R, Romo S, Schelske CL, Straile D, Tatrai I, Willén E, Winder M, 2005. Lake responses to reduced nutrient loading: an analysis of contemporary long-term data from 35 case studies. Freshwater Biol. 50:1747-1771.

Kangur K, Kangur P, Ginter K, Orru K, Haldna M, Möls T, Kangur A, 2013. Long-term effects of extreme weather events and eutrophication on the fish community of shallow Lake Peipsi (Estonia/Russia). J. Limnol. 72:376-387.

Kangur K, Möls T, 2008. Changes in spatial distribution of phosphorus and nitrogen in the large north-temperate lowland Lake Peipsi (Estonia/Russia). Hydrobiologia 599:31-39.

Kangur K, Möls T, Milius A, Laugaste R, 2003. Phytoplankton response to changed nutrient level in Lake Peipsi (Estonia) in 1992-2001. Hydrobiologia 506-509:265-272.

Kelderman P, Ang'weya RO, De Rozari P, Vijverberg T, 2012. Sediment characteristics and wind-induced sediment dynamics in shallow Lake Markermeer, the Netherlands. Aquat. Sci. 74:301-313.

Kristensen P, Søndergaard M, Jeppesen E, 1992. Resuspension in shallow lake. Hydrobiologia 228:101-109.

Lagomarsino L, Pérez GL, Escaray R, Bustingorry J, Zagarese HE, 2011. Weather variables as drivers of seasonal phosphorus dynamics in a shallow hypertrophic lake (Laguna Chascomús, Argentina). Fund. Appl. Limnol. 178:191-201.

Laugaste R, Nõges P, Nõges T, Yastremskij VV, Milius A, Ott I, 2001. Algae, p. 31-49. In: E. Pihu, J. Haberman (eds.), Lake Peipsi: flora and fauna. Sulemees Publishers.

Loigu E, Leisk Ü, Iital A, Pachel K, 2008. [Pollution load and water quality of the Lake Peipsi basin], p. 179-199. In: J. Haberman, T. Timm, A. Raukas (eds.), [Peipsi]. [Book in Estonian]. Eesti Loodusfoto.

Nagid EJ, Canfield DE, Hoyer MV, 2001. Wind-induced increases in trophic state characteristics of a large (27 km^2), shallow (1.5 m mean depth) Florida lake. Hydrobiologia 455:97-110.

Niemistö J, Tamminen P, Ekholm P, Horppila J, 2012. Sediment resuspension, rescue or downfall of a thermally stratified eutrophic lake. Hydrobiologia 686:267-276.

Nõges T, Järvet A, Kisand A, Laugaste R, Loigu E, Skakalski B, Nõges P, 2007. Reaction of large and shallow lakes Peipsi and Võrtsjärv to the changes of nutrient loading. Hydrobiologia 584:253-264.

Nõges T, Nõges P, Laugaste R, 2003. Water level as the mediator between climate change and phytoplankton composition in a large shallow temperate lake. Hydrobiologia 506-509:257-263.

Pettersson K, George G, Nõges P, Nõges T, Blenckner T, 2010. The impact of the changing climate on the supply and recycling of phosphorus, p. 121-137. In: D.G. George (ed.), The impact of climate change on European lakes. Springer.

Pettersson K, Grust K, Weyhenmeyer G, Blenckner T, 2003. Seasonality of chlorophyll and nutrients in Lake Erken: effects of weather conditions. Hydrobiologia 506-509:75-81.

Rumyantsev VA, Kondrat'ev SA, Shmakova MV, Basova SL, Shilin BV, Zhuravkova ON, Savitskaya NV, 2005. [The external loading of Lake Peipsi and its response]. [Article in Russian]. Water Management of Russia 7:569-585.

SAS, 2008. SAS OnlineDoc, version 8. SAS Institute Inc. ed., Cary. Available from: http://v8doc.sas.com/ sashtml/

Søndergaard M, 2007. Nutrient dynamics in lakes - with emphasis on phosphorus sediment and lake restoration. PhD thesis. National Environmental Research Institute, University of Aarhus, Denmark: 276 pp.

Søndergaard M, Bjerring R, Jeppesen E, 2013. Persistent internal phosphorus loading during summer in shallow eutrophic lakes. Hydrobiologia 710:95-107.

Søndergaard M, Jensen JP, Jeppesen E, Møller PH, 2002. Seasonal dynamics in the concentrations and retention of phosphorus in shallow Danish lakes after reduced loading. Aquat. Ecosyst. Health 5:19-23.

Søndergaard M, Kristensen P, Jeppesen E, 1992. Phosphorus release from resuspended sediment in the shallow and wind-exposed Lake Arreso, Denmark. Hydrobiologia 228:91-99.

Spears BM, Carvalho L, Paterson DM, 2007. Phosphorus partitioning in a shallow lake: implications for water quality management. Water Environ. J. 21:47-53.

Spears BM, Carvalho L, Perkins R, Kirika A, Paterson DM, 2012. Long-term variation and regulation of internal phosphorus loading in Loch Leven. Hydrobiologia 681:23-33.

Spears BM, Carvalho L, Perkins R, Paterson DM, 2008. Effects of light on sediment nutrient flux and water column nutrient stoichiometry in a shallow lake. Water Res. 42:977-986.

Spears BM, Jones I, 2010. The long-term (1979-2005) effects of the North Atlantic Oscillation on wind-induced wave mixing in Loch Leven (Scotland). Hydrobiologia 646:49-59.

Starast H, Milius A, Möls T, Lindpere A, 2001. Hydrochemistry, p. 97-130. In: T. Nõges (ed.), Lake Peipsi. Meteorology, hydrology, hydrochemistry. Sulemees Publishers.

Stewart KM, Markello SJ, 1974. Seasonal variations in concentrations of nitrate and total phosphorus, and calculated nutrient loading for six lakes in western New York. Hydrobiologia 44:61-89.

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. Aquat. Sci. 75:559-570.