Management options to improve water quality in Lake Peipsi: insights from large scale models and remote sensing

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Abstract

Nutrient pollution causes frequent blooms of potentially harmful cyanobacteria in Lake Peipsi (Estonia/Russia). Although external nutrient loading has reduced since the 1990s, lake water quality has barely improved, and eutrophication is still considered a threat to lake biota and water usage. To understand the recovery dynamics of the lake it is necessary to analyse the effects of land use and lake management on water quality to develop mitigation strategies. Comprehensive analysis has thus far failed due to information gaps inherent to conventional monitoring strategies. We show how two large-scale hydrological models using Earth observation data provide spatial information on pollution and can help explain the causes of past and current lake eutrophication. WaterGAP3.2 provides valid estimates of present and probable future phosphorus concentration in the lake water, based on past hydrological conditions. WaterWorld models spatial potential water quality and a scenario of optimal pollution reduction. Remotely sensed optical water quality data can be used to analyse recent, spatial water quality dynamics. The spatial and temporal algae distributions and can help explain eutrophication causes at Lake Peipsi and its catchment, adding value to in situ monitoring and supporting river basin management with large scale data.

Keywords

Lake Peipsi, eutrophication, lake phosphorus balance, cyanobacteria, algae blooms, lake management

1 Introduction

Anthropogenic nutrient sources have negatively affected European lake water quality over the last decades (e.g. Jeppesen et al. 2009). Intensive agriculture and growing urban pressures have caused widespread eutrophication in surface waters including regime shifts from clear to turbid states and predominance of cyanobacteria. In Eastern Europe, nutrient emissions and concentrations in river and lake basins declined due to efforts in water pollution management and political changes in the 1990s (Fink et al. 2018; Ital et al. 2005; Piirimäe et al. 2015). Despite these efforts, eutrophication still affects lake water usage and biota. Lake Peipsi, a large transboundary lake located in Estonia and Russia, has shown the typical response of shallow lakes to eutrophication and subsequent nutrient management, which includes a shift in phytoplankton abundance and composition towards cyanobacterial blooms (Paerl et al. 2011) and slow or non-existent recovery from a turbid state to clear water with submerged macrophytes (Scheffer et al. 1993; Sand-Jensen et al. 2017). Nutrient reduction efforts in Lake Peipsi started in the early 1990s but cyanobacterial blooms still occur annually even 20 years later (Laugaste et al. 2001), despite persistent low nutrient pollution (Blank et al. 2017).

It is crucial for lake water quality management to understand the processes governing eutrophication. Pollution management of Lake Peipsi can draw upon several recent studies. Blank et al. (2017) found only a small shift towards eutrophication recovery between the periods 2003-2007 and 2008-2012. Tammeorg et al. (2015) reported that high internal loading is the primary cause of continued high nutrient concentrations. Insensitivity of lake water phosphorus concentrations to riverine nutrient loads (Buhvestova et al. 2011) provides further evidence of the internal loading as a driving factor. The continued eutrophic state of Lake Peipsi has changed macrophyte species richness and composition (Mäemets et al. 2010). Strong and persistent algae blooms and fish kills were noted in recent years (Kangur et al. 2013). The biomass of harmful cyanobacteria is on average higher in the southern (L.

Pihkva/Pskov) than in the northern part (Kangur et al. 2003), due to higher nutrient concentrations. Phosphorus concentrations show increasing spatial polarity with lower values in the north and higher values in the southern part (Kangur and Möls 2008).

Despite numerous studies, monitoring data and current knowledge are not sufficient to evaluate phytoplankton dynamics in the whole lake ecosystem. The Estonian side of the lake is monitored monthly in May to October, while the Russian side of the lake is sampled by infrequent joint campaigns (the latest expeditions took place in May 2014 and March 2015). Algae blooms can be local, short-lived, and thus likely to remain unobserved. The most intensive blooms are found in the southern part of the lake, mostly located in Russia. No attempt has yet been made to build a spatial model of nutrient fluxes and balances of Lake Peipsi. Studies that couple catchment water quality models like SWAT (Neitsch, et al. 2011) or GLOBAL NEWS (Seitzinger and Harrison 2005) with process based lake nutrient model (e.g. Imboden 1974) are also lacking in the literature. Such models are nevertheless needed to integrally assess the interplay of eutrophication relevant processes like inflow and outflow, external loading, internal loading, and spatial and temporal pollution processes in the catchment.

The overall aim of this paper is to present complementary practises and their potential for eutrophication monitoring at Lake Peipsi, based on hydrological models and Earth Observation (EO) data, which are both information-rich but not currently included in river basin management plans under the European Water Framework Directive (WFD), (EU 2000). This paper is, to our knowledge, the first study that highlights the complementary value of large scale hydrological and water quality models (WaterGAP3 and WaterWorld) and lake water quality estimated from EO satellites.

To demonstrate the added value of new large scale approaches at Lake Peipsi, we introduce their methodologies, present their input into eutrophication assessments, and finally discuss the capabilities of these methods and their core findings for optimal eutrophication management of Lake Peipsi in the following sections.

2 Lake Peipsi and its eutrophication problem

Lake Peipsi *sensu lato* (*s.l.*) is situated at the border of Estonia and Russia. 44% of the lake area is Estonian and 56% Russian. The lake measures 3555 km^2, the deepest point is 15.3 m and the average depth is 7.1 m. The lake consists of three parts (Fig. 1): the northern L. Peipsi *sensu stricto* (*s.s.*, 2611 km^2, mean depth 8.3 m, maximum depth 12.9 m), the southern L. Pihkva/Pskov (708 km^2, mean depth 3.8 m, maximum depth 5.3 m), and the small and river-like L. Lämmijärv connecting northern and southern parts (236 km^2, mean depth 2.5 m, maximum depth 15.3 m). The residence time of water in the unstratified and well mixed Lake Peipsi *s.l.* is about two years. Ice cover is common from December to April although ice-cover and ice-off dates have been highly variable in recent years. Numerous small inflows, and the two primary inflows Velikaya River (L. Pihkva/Pskov) and Emajõgi River (L. Peipsi *s.s.*) guarantee a relative stable lake volume of about 25 km^3. The Narva River outflow ultimately leads into the Gulf of Finland. For detailed information about the lake and its hydrology, see Kangur et al. (2012) and Jaani (1996).

The lake catchment is 47800 km^2 to its outlet in the north at Vasknarva, and covers parts of Estonia, Russia, Latvia, and Belarus which have different land use patterns. The catchment is largely rural, with most of the croplands and pastures to the west and south of the lake. The Estonian part of the catchment has mostly dispersed forested and other natural areas, interspersed with areas of intensive cropland (>0.5 area fraction). The Russian part of the catchment includes a greater area of croplands and pasture, plus a wide area of forest in the south. The Latvian part of the catchment is a mosaic of less intensive (<0.5 area fraction) of croplands and pasture, plus a large forested area on the border with Russia.

Sediment cores indicate that before the 1950s, ecosystem productivity was relatively low, stable and resistant to human activities (Nõges et al. 2006; Heinsalu et al. 2007) and Lake Peipsi was mesotrophic. However, palaeodata show that substantial changes in the L. Pihkva/Pskov ecosystem started in the 1930s when mesotrophic conditions in the lake turned increasingly eutrophic. Comparison of palaeoecological data with long-term water level dynamics indicates that important shifts in the lake ecosystem in the 1930s can be related to a sharp decline in water level. The average use of fertilizer in the lake catchment was below 20 kg NPK ha^{-1} yr^{-1} and about 7 t manure ha^{-1} in 1939 (Astover and Rossner 2013; NPK: Nitrogen, Phosphorus, Kalium).

In the 1950s and 60s, nutrient pollution increased. Mineral fertilizer increased to more than 130 kg NPK ha^{-1} yr^{-1} and manure usage increased to about 10 t ha^{-1} yr^{-1} until the end of the 1960s (Astover and Rossner 2013). The diatom species composition in lake sediment cores indicates a change to eutrophic conditions and increasing anthropogenic impact (Nõges et al. 2006; Heinsalu et al. 2007). Cyanobacteria bloom repeatedly in warm summers (Laugaste et al. 2001). Laugaste et al. (2001) show coherence of high phytoplankton biomass with periods of low water level.

Nutrient pollution peaked in the 1970s and 1980s. Approximately 200 kg NPK ha^{-1} yr^{-1} and 11 t manure ha^{-1} yr^{-1} were used in the late 1980 (Astover and Rossner 2013). A high abundance of planktonic diatoms in sediment cores of Lake Peipsi *s.s.* indicates increased productivity and reflects progressive eutrophication (Nõges et al. 2006; Heinsalu et al. 2007).

In the 1990s, nutrient pollution fell sharply. Fertilizer use dropped below 80 kg NPK ha^{-1} yr^{-1} and 5 t manure ha^{-1} yr^{-1} (Astover and Rossner 2013). Mourad et al. (2005) showed that Estonian and Russian rivers discharging into Lake Peipsi *s.s.* dropped nutrient loads from 288 t TP yr^{-1} and 16.7 kt N yr^{-1} in the period 1985-1989 to 187 t TP yr^{-1} and 11.8 kt N yr^{-1} in the period 1995-1999. Diatom flora in sediments indicate an unstable, eutrophic ecosystem with high algae abundance despite slight recovery (Nõges et al. 2006; Heinsalu et al. 2007).

Today, despite low pollution (fertilizer application comparable to the 1990s) the lake is still eutrophic. Algae blooms during heat waves cause fish kill (Kangur et al. 2005; Kangur et al. 2013). For example, in the hot and dry summer 2002 all physical requirements for algae growth were met and a massive cyanobacteria bloom and high concentrations of cyanotoxins along with a low water table, low night-time oxygen and high ammonium ion concentrations led to high fish mortality (Kangur et al. 2005). Although efforts have been made to restore the lake e.g. to achieve WFD targets, water quality is not as good as expected. Resuspension of phosphorus (P) from sediments is the dominant process that affects the P cycle and high P concentrations of Lake Peipsi (Tammeorg et al. 2015). It is assumed that recovery from the high nutrient pollution during the second half of the 20th century will take up to decade for virtually any lake that has suffered extensive and prolonged eutrophication (Jeppesen et al. 2005).

3 Large scale methods for eutrophication analysis

3.1 WaterGAP3.2

The large-scale modelling framework WaterGAP3.2 (Water – Global Assessment and Prognosis) is a grid-based, integrative assessment tool (Verzano 2009; Flörke et al. 2013; aus der Beek et al. 2010; Voß et al. 2012). It operates on a 5 arc minute global grid (approximately 9.2 km in North-South direction and 2.4 km in East-West direction at Lake

Peipsi). The modelling framework includes a distributed global hydrology module (Alcamo et al. 2003; Eisner 2016) that simulates global hydrology at daily resolution. A water use module includes five sectoral water use models (Flörke et al. 2013; aus der Beek et al. 2010). The water quality model WorldQual (Voß et al. 2012) simulates monthly loadings and in-stream concentrations from point sources and diffuse sources. In this version, total phosphorus (TP), fecal coliform bacteria, total dissolved solids, and biochemical oxygen demand are implemented (Punzet et al. 2012; Voß et al. 2012; Williams et al. 2012; Reder et al. 2015).

The WaterGAP3.2 phosphorus module for lake eutrophication is based on the model proposed by Imboden (1974). This is a two-box nutrient model that calculates the phosphorus balance in the epilimnion (warm and turbulent surface layer) and hypolimnion (colder deep-water layer) of a stratified water body. Because Lake Peipsi is not stratified and polymictic, the implemented algorithm changes the model to a one-box model (no hypolimnion and with direct contact between the mixed layer and sediments). As a modification of the original approach, we separated resuspension of particulate P and diffusion of dissolved P.

The spatiotemporally averaged TP concentration from all monthly in situ measurements in the period 2006-2010 is 42 mg TP m^{-3}, as derived from the volume-weighted mean of both the northern (incl.L. Lämmijärv) and southern lake parts. The data indicated that P concentrations in L. Pihkva are approximately two times that of L. Peipsi s.s. WaterGAP3.2 gives a corresponding estimate of 45 mg TP m^{-3}. Although the model reproduces the measured annual periodicity (up to more than 70 mg TP m^{-3} in autumn, <30 mg TP m^{-3} in spring), the amplitude of the modelled cycle was less pronounced in the model results (between 56 mg TP m^{-3} and 36 mg TP m^{-3}). Further comparison to average concentrations reported by Blank et al. (2017), and Mäemets et al. (2010) were also well reproduced by WaterGAP3.2 when comparing volume-weighted mean values.

3.2 WaterWorld

WaterWorld (Mulligan, 2013) is a fully distributed, process-based hydrological model, that utilises remotely sensed and globally available datasets to support hydrological analysis and decision-making globally, with a focus on ungauged and/or data-poor environments. WaterWorld delivers insights into the interplay of human impact in the lake basin and water quality. WaterWorld is a spatial policy-support system (PSS) enabling modelling application and scenario analysis to users without specific technical or hydrological capacity and it has a web browser-based interface (www.policysupport.org/waterworld). WaterWorld runs at 10-km^2, 1-km^2 t or 1-ha resolution. It simulates a hydrological baseline as a mean for the period 1950-2000 and can be used to calculate hydrological scenarios of climate change, land use change, land management options, impacts of extractives (oil & gas and mining) and impacts of changes in population and demography. The model is 'self-parameterising' (Mulligan 2013): all data required for model application anywhere in the world are provided, or these can be substituted by user data. Model equations, processes, and reliability are detailed in Mulligan and Burke (2005) and Mulligan (2013). The model is not routinely calibrated to observed flows as it is designed for hydrological scenario analysis and use in ungauged basins, where calibration is inappropriate (Sivapalan et al. 2003). Moreover, it is assumed that if a model is capable of reproducing current conditions based only on physical relationships, it is likely to continue to do so under scenario conditions where the physical relationships remain the same (Mulligan 2013).

WaterWorld uses the metric Human Footprint on Water Quality HFWQ (Mulligan 2009) as a proxy for water contamination. HFWQ calculates the potential water quality in a grid cell and represents the parameter-independent cumulation of upstream influences of point (mining, oil and gas, roads, urban areas) and non-point (pastures and croplands outside of protected areas) sources of contamination. It is assumed that there are no pollution sinks. Each of the pollution sources is given an equal weighting in terms of its capacity to generate contamination. It is supposed that this pollution capacity primarily depends on the volume of water available for contamination. For each grid cell the human footprint index represents the percentage of water coming from upstream that is influenced by these point and non-point sources, as a percentage of total rainfall. Areas with extensive agriculture or urban areas will leave a significant footprint on water downstream. This may be diluted with waters from undisturbed or protected areas. The influence of small (areal) footprint sources such as mines or oil and gas will tend to diminish quickly downstream whereas large areal footprint areas (like agriculture) will influence downstream waters much further.

3.3 EO data

Time-series of chlorophyll-*a* (Chl-*a*) were derived from Level 1B (third reprocessing) satellite imagery of the Medium Resolution Imaging Spectrometer (MERIS) onboard the European Space Agency ENVISAT satellite (2002-2012), using the *Calimnos* (v1.04) processing chain operated at PML. Data processing included: (1) geolocation correction using AMORGOS (v3.0) which performs precise orbit determination, instrument pointing and ortho-rectification (Bicheron et al. 2011); (2) spatial subsetting of satellite passes around the lake location ; (3) MERIS Radiometric Correction (v5.0.3) including radiometric equalisation (Bouvet and Ramoino, 2010) ; (4) Pixel identification as land, cloud, water, and ice/snow with Idepix-Water v2.2.10 ; (5) Atmospheric correction using POLYMER v3.5 (Steinmetz et al. 2011), parameterized to use the Park and Ruddick (2005) bidirectional reflectance distribution function, and operating only on pixels identified as water by Idepix; (6) Optical Water Type (OWT) fuzzy classification analogous to Moore et al. (2001) but using standardized water-leaving reflectance. Class memberships were calculated against the 13 inland water OWTs defined in Spyrakos et al. (2017); (7) Chl-*a* concentration retrieval based on Gons et al.

(2005) for OWTs 1, 4, 5 and 6, Gilerson et al. (2010) for OWTs 2, 8, 11 and 12, Mishra et al. (2014) for OWT 7, and the OC2 algorithm (oceancolor.gsfc.nasa.gov/cms/atbd/chlor_a) for OWTs 3, 9, 10 and 13. Steps 2-4 above used the BEAM Earth Observation Toolbox and Development Platform (v5). Specific tuning of each algorithm against in situ data corresponding to the respective OWTs, contained in the LIMNADES database, was carried out as part of the GloboLakes project (Neil et al. pers. comm.). In the current work, EO-derived Chl-*a* concentrations correspond to the OWT-algorithm combination for which a pixel had the highest-scoring OWT class membership. Satellite images with < 10% observable water pixels (e.g. due to cloud cover) were omitted from the analysis.

4 Results from large-scale methods

4.1 Phosphorus balance of Lake Peipsi

WaterGAP3 calculations show that the average TP concentration in Lake Peipsi changed to high concentrations during the 1950s, increasing from ~25 mg m^{-3} in 1951 to a stable high level of 44 mg TP m^{-3}. In the 1990s the modelled spatial average concentration stayed stable around 43 mg TP m^{-3}. TP concentrations showed strong seasonality: during the first half of the 1950s, TP changed during each year from low winter concentrations below 20 mg TP m^{-3} to approximately 30 mg TP m^{-3} in autumn. During the period 1960-2010, the modelled concentrations oscillate between ~30 mg TP m^{-3} in April-May to almost 60 mg TP m^{-3} in autumn. The model, however, underestimates this seasonality, as measured peaks in autumn were more pronounced. Nevertheless, average modelled values for 1985 to 2010 were close to those measured.

External and internal TP loadings alternated since 1950. From 1950 to 1955, external loading from river inflow was 0.4 mg m^{-2} day^{-1} while resuspension plus diffusion balanced sedimentation (both ~ 30 mg m^{-2} day^{-1}). From mid 1950s inflow loadings increased to 0.9 mg

m^{-2} day^{-1}. This increase enhanced the TP circulation: resuspension plus diffusion increased to 46.7 mg m^{-2} day^{-1} and sedimentation to 47.4 mg m^{-2} day^{-1}. TP accumulated in the sediment storage. As a result of the drop in nutrient pollution in the 1990s, TP loadings from inflows decreased to 0.2 mg m^{-2} day^{-1} and TP storage in the sediments started to shrink. Today, the resuspension plus diffusion of TP from the sediment is higher than sedimentation, which confirms that high TP concentrations in the lake are governed by internal loading. However, external loading from cities (e.g. Pskov city) and agriculture areas is still high.

Retention, defined as R [-] = $(L_{TP,in} – L_{TP,out}) L_{TP,in}^{-1}$ (where $L_{TP,in}$ [mg TP m^{-2} day^{-1}] and $L_{TP,out}$ [mg TP m^{-2} day^{-1}] are TP loadings in lake inflow and outflow), changed from positive (lake is a P sink) to negative (lake is a P source). R was about 0.03 in the years 1951-1955, on average, increasing to 0.4 in the years 1956-1990. Since the 1990s, R is close to -1.5. This value indicates that the lake releases 1.5 times more phosphorus in the outflow than it receives from tributaries, on average. However, retention is seasonally high in autumn, winter and spring, and low in summer. The model results show that the lake was already a seasonal phosphorus source (negative retention) in summer in the 1950s and in the period of high pollution from (1960-1990). Since the 1990s, the modelled retention was never positive at monthly temporal resolution, and, on average, in summer the lake released up to 5 times more TP through the Narva River than it receives from all inflows combined.

4.2 Phytoplankton dynamics

No clear trends in either lake median concentration or the 5^{th} and 90^{th} percentiles were observed in satellite-derived Chl-a time-series of the period between 2002 and 2012. Short-lived, high-biomass phytoplankton occurrences were observed yearly, with peak biomass in the 100-350 mg m^{-3} range and associated with prevalence of OWTs 8 and 2. The fractional cover of each OWT showed an annual seasonal succession over the observed period. The typology of L. Peipsi *s.l.* included (fractional cover, and OWT descriptions in parentheses): OWT2 (10.0 %, marginal dominance of pigments and CDOM over inorganic suspended particles), OWT4 (11.3 %, turbid waters with high organic content), OWT6 (2.3 %, balanced influence of optically active components at shorter wavelengths), OWT8 (12.5 %, strong cyanobacteria presence and clear reflectance peak near 700 nm), OWT9 (12.9%, similar to OWT2 waters but with higher reflectance at shorter wavelengths), and OWT12 (1.1 %, turbid, moderately productive waters with possible cyanobacteria presence). In 49% of observed pixels no OWT (and no corresponding Chl-*a*) could be mapped. This category includes the winter period influenced by ice and snow cover, but could also include water types that are not yet mapped by the processor.

The spatial distribution of phytoplankton blooms is shown per year in Fig. 2 as a series of 90th percentile (p90) maps of Chl-*a* for the period 2003-2011 during which the whole ice-free season was observed by MERIS. Contrasting concentrations are consistently found between L. Peipsi *s.s.* and L. Pihkva/Pskov, with L. Peipsi *s.s.* in the north showing p90 rarely above 40 mg Chl-*a* m^{-3} and L. Pihkva/Pskov rarely below 80 mg Chl-*a* m^{-3}. The number of times each pixel was observed shows a gradual increase of observational cover in the first years of MERIS (as data throughput gradually improved).

4.3 Future scenarios

Reduction of TP pollution will shorten the duration of recovery (the period until the sediment TP storage is empty). This is indicated by the five scenarios of TP pollution calculated with WaterGAP3.2 for the period 2011 to 2050: (1) current state (pollution and hydrology equal the average conditions in the period 2006-2010), (2) no TP pollution (only background loadings but hydrology characteristic of 2006-2010), (3) no TP loadings at all (this unrealistic scenario describes the lower bound of P loading), and (4) half and (5) doubled TP pollution (based on 2006-2010 pollution and hydrology). WaterGAP3.2 calculations show, that the duration of recovery and the timing of drop in TP concentrations after recovery differs by a few years between these scenarios. At current pollution level, the model indicates sediment P depletion around the beginning of the 2020s. With no pollution or even no TP loadings at all, this drop starts now. Doubled pollution (considered unrealistic) would add up to half a decade to sediment recovery.

Reduction in TP pollution has significant effects on the calculated TP concentrations if there is no TP in the sediments (recovered situation). The average TP concentration in the modelled Lake Peipsi drops to ~15 mg TP m^{-3} (current pollution level), ~5 mg TP m^{-3} (no pollution), ~0 mg TP m^{-3} (no P nutrient and, therefore, no production in the lake), ~10 mg TP m^{-3} (half pollution), or ~25 mg TP m^{-3} for doubled pollution. These are rough estimates and average concentrations in a simple lake model that smooths out spatial and temporal variations (seasonality). Recovery periods might be different for specific parts of the lake, e.g. recovery is expected to take longer in L. Pihkva/Pskov. Furthermore, results do not include climate change effects.

Pollution from the surrounding catchment is a major factor in controlling nutrient loads to Lake Peipsi. Strategies for nutrient load reduction should mainly focus on agricultural nutrient runoff and (according to Piirimäe et al. 2015) municipal and industrial waste water treatment, especially in the Russian part of the drainage basin, where past, present and future pollution data are not available. The WaterWorld Policy Support System was used to construct a number of scenarios for land and water management options: changes in agriculture eco-efficiency and upgrading livestock waste management capacity.

WaterWorld scenarios for agriculture eco-efficiency (Mulligan and Clifford 2015) allow the reduction or increase in unit area inputs of pesticides, fertilisers and other potential pollutants. WaterWorld calculates the water quality metric HFWQ by cumulating upstream influences from a range of land uses. The footprint of each land use category, combined with the distribution of land uses and of water, produces the overall footprint. The parameter "Fraction of water exposed to contamination" can be used to scale the contribution of all land uses, representing more or less polluting conditions or specific contaminant loadings. The baseline value of 'fraction of water exposed to contamination' is 0.1. This fraction was reduced to 5% of the baseline value for the 'eco-efficient scenario', and increased to 100% (0.2 fraction exposure) for 'doubling inputs scenario'.

L. Pihkva/Pskov, due to larger extent of croplands in this part of the catchment, showed the greatest changes in agricultural eco-efficiency, resulting in a decrease in HFWQ and increased contamination downstream (Table 1). These changes are low as they are catchment averages and lake averages, and croplands are present in only 35% of the catchment. Although the catchment and lake average changes are low, the changes in HFWQ for both scenarios are significant in areas within or just downstream from croplands. However these effects are diluted downstream in cleaner waters, and so the impact on the lake is reduced.
Similarly, the impact of scenarios where livestock waste capacity was installed or upgraded was investigated. These scenarios change the outflows of livestock related effluents. A 100% increase in waste management capacity resulted in a reduced HFWQ (Table 1), but this is particularly focussed in L. Pihkva/Pskov where the extensive pasturelands are located.

5 Discussion

In this paper, we present the abilities of complementary practises for eutrophication monitoring that are based on large scale and data-rich modelling and satellite data. In general, the presented methods show a high potential to (i) complement in situ measurements, (ii) better understand relevant processes, and (iii) support stakeholders in making pollution and land management related decisions. This potential becomes particularly apparent when focussing on lake phosphorus balance, phytoplankton dynamics, and the management-dependent future of eutrophication. Lake managers in other regions experiencing similar problems, as well as data scarcity, can benefit from this approach: using remotely sensed data to evaluate the spatial and temporal patterns of eutrophication, and using process-based global water quality models to elucidate eutrophication relevant processes.

As a data-rich methodology, WaterGAP3.2 provides detailed information about the history, current situation and lake management dependent future of the lake phosphorus balance. For example TP concentrations which increased from mesotrophic in the 1950s to its present average values were well captured, and the model demonstrates that these are now insensitive to external loading due to dominating resuspension and diffusion from a huge TP storage in the sediments. The model then indicates that internal loading from sediments and the TP concentration in the lake water will decline to the level of the early 1950s and Lake Peipsi will return to acting as a phosphorus sink. For eutrophication analysis, a large benefit of WaterGAP3.2 is that it provides insights into specific components of the P balance that could not be measured with regular in situ monitoring (for instance TP storage in sediments).

Satellite data add significant monitoring value by providing spatial as well as temporal phytoplankton dynamics, to complement in situ data, and to validate or calibrate models. As demonstrated in this paper, MERIS satellite imagery and *Calimnos* provided realistic time series of Chl-*a* with adequate spatio-temporal resolution. These provide the spatial distribution of phytoplankton blooms, which could not be captured by in situ monitoring or accurately captured by watershed models. These data particularly demonstrate the differences between L. Peipsi *s.s.* and L. Pihkva/Pskov and a tendency of higher Chl-*a* concentration closer to the shores, which is also apparent from in situ measurements (e.g. Kangur et al. 2005). While MERIS observations ended in 2012, the Sentinel-3 series in the Copernicus programme provide guaranteed and continuous observation with the OLCI instrument over the next two decades, thus covering the period in which further changes in the lake nutrient regime are expected to show.

We have further shown that WaterWorld is a useful tool to inform policy decisions by showing possible impacts of changes in land management on water quality. WaterWorld results point out that land management changes in areas where there are significant croplands particularly affect water quality downstream, although dilution effects from clean water entering from the landscape downstream from can produce a rapid downstream decay of influence of pollution sources.

Although in this paper modelling results and satellite data analysis were primarily presented to give an impression on their respective methodological capabilities in the case of Lake Peipsi, the modelling and EO results, shown in section 4, already highlight key elements of a preferred management strategy for a clean lake:

- Significant change of TP pollution from the catchment does not change present average TP concentrations in the lake. Consequently, pollution reduction efforts do not have immediate effects, but significant effects in future.
- Chl-*a* and TP concentrations in the southern part (L. Pihkva/Pskov) are approximately twice as high as in the northern part (L. Peipsi *s.s.*). Therefore, restoration efforts should focus on L. Pihkva/Pskov. As long as water quality of the southern tributaries (primarily the Velikaya River on Russian territory) and some polluted Russian inflows

to L. Peipsi *s.s.* do not change, efforts in the catchment of northern, Estonian tributaries (e.g. Emajõgi River) will not likely solve eutrophication issues.

- Nutrients in sediment are the main cause of the continued eutrophic status of the lake as a whole (current conditions characterize L. Peipsi *s.s.* eutrophic, while the trophic status of Lake Lämmijärv is close to hypertrophic and Lake Pihkva is a hypertrophic basin). However, this pool in the sediment is slowly depleted by resuspension and diffusion. The lower the external pollution from e.g. the agriculture and municipal sectors, the faster the lake should recover. After recovery, concentrations in tributaries will again govern lake TP concentrations.
- Strategies of nutrient load reduction should focus on agricultural nutrient runoff as well as municipal and industrial waste water treatment in the Russian part of the drainage basin. Agricultural management measures should prioritize a reduction of diffuse emissions from agriculture. WaterWorld identifies those areas that have most impact on lake water quality.

All methods have their limitations. For example, WaterGAP3.2 works on average loadings from the drainage basins, averages of concentrations in inflows, and, based on that input, it estimates the length of recovery periods. This simplification through averages provides only a rough direction of change. In reality, there is a variation of concentrations in time and space, which cannot be captured by the presented models, and ideally, management of the watershed will be based on the complementary use of large scale modelling, remote and in situ observations.

6 Conclusion

This study is the first large-scale model based system analysis of the nutrient fluxes and balances of Lake Peipsi. The study covers the complementary modelling and observation practises and their potential for eutrophication monitoring at Lake Peipsi, based on complementary hydrological models and satellite data. The results show that recent external pollution reduction efforts have a delayed (several decades or longer) effect on average TP concentrations in Lake Peipsi, which is large and has long residence times. Therefore, eutrophication phenomena (algal blooms, oxygen deficit, cyanotoxins) still persist. Spatial analysis shows that Estonia and Russia must work together to solve the current eutrophication issue of the transboundary lake. Water quality of Lake Peipsi will improve only with significant decreasing nutrient load from the Velikaya River catchment, but such an improvement is achievable.

Conflict of Interest – None

7 References

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8 Figures

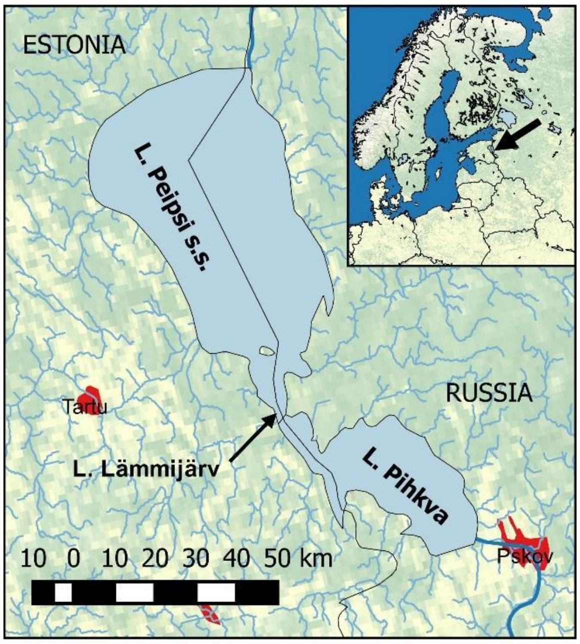

Fig. 1 Location of L. Peipsi *sensu lato* (*s.l.*) comprising L. Peipsi *sensu stricto (s.s.)*, L. Lämmijarv, and L. Pihkva.

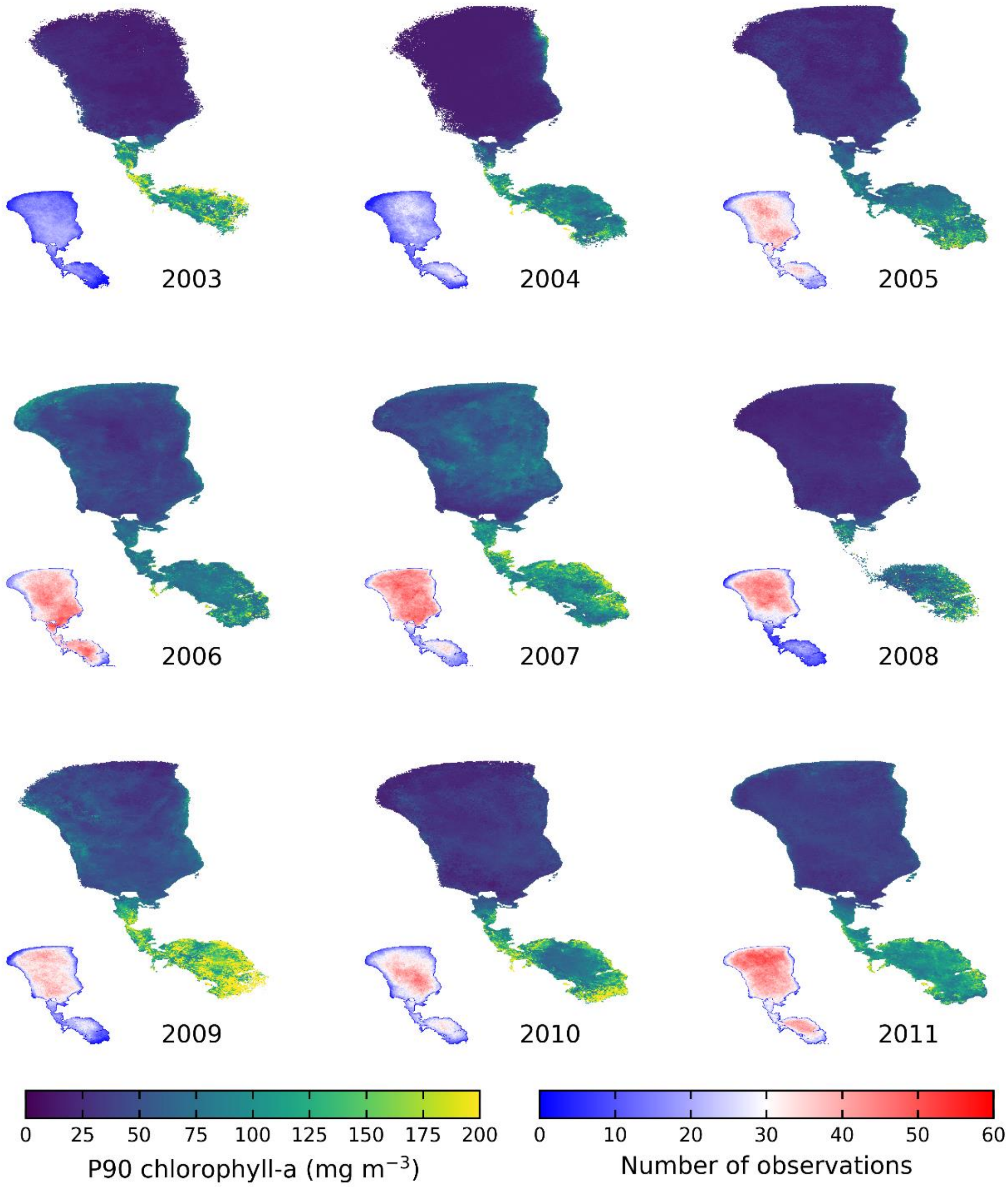

Fig. 2 90th percentile Chl-a concentrations. Each year for which the full ice-free season was observed by MERIS is shown. The number of times each pixel was observed is shown in the inset to each panel.

9 Tables

Table 1 Impact of changes in Eco-efficiency and livestock waste management capacity on lake contamination.

Change in HFWQ	Eco-efficient scenario	Doubling inputs scenario	Increasing waste management capacity 100%	Decreasing waste management capacity 100%
Water in Lake Peipsi	-0.14%	+0.13%	-0.19%	+0.05%
Water in L. Pihkva/Pskov(west):	-0.69%	+0.53%	-0.39%	+0.13%
Water in L. Pihkva/Pskov(east):	-0.50%	+0.49%	-0.33%	+0.12%