Palaeolimnological assessment of the reference conditions and ecological status of lakes in Estonia – implications for the European Union Water Framework Directive

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Abstract. The European Union Water Framework Directive (WFD) requires an assessment of reference conditions for lakes, i.e. the conditions expected with only minimal human impact on water bodies. Limnological monitoring records seldom go back more than a few decades and so rarely document the onset of human impact on lakes. Methods of palaeolimnological approaches especially fitted for the purposes of the WFD are described and two case studies, on lakes Rõuge Tõugjärv and Pappjärv, are presented. The palaeolimnological study of Rõuge Tõugjärv demonstrated that a commonly held belief that man-made eutrophication of Estonian lakes is a relatively modern matter of concern and is related to post-industrial population growth and intensification of agriculture is a misconception. The lakes, particularly those in rich soil areas, have been mediated by human impact over millennial time-scales. In many European countries it has been agreed that AD 1850 approximately represents the reference conditions for lakes. Our observations in Rõuge Tõugjärv showed that during that period anthropogenic disturbance on the lake was the greatest. Lake Pappjärv is an example of recent human influence on the aquatic ecosystem that has undergone severe degradation due to infiltration into the ground of a variety of substances from the local bitumen plant, mineral fertilizer storage tanks, and road service sand and salt mixing-grounds that have been accumulating in the lake since the 1950s.

Key words: Water Framework Directive, reference conditions, lake sediment, diatoms, Estonia.

INTRODUCTION

Eutrophication of aquatic ecosystems, principally induced by nutrients from agricultural sources, industrial waste, and domestic sewage, has been recognized as a global unresolved environmental problem threatening the quality of surface waters (Smol 2002). The efforts made to manage and restore anthropogenically disturbed lakes better have increased over the last decades, and range from reductions in nutrient loading (e.g. Jeppesen et al. 2005) to lake restoration projects (e.g. Cooke et al. 2005). As a result, now numerous examples of lakes are in recovery (e.g. Anderson et al. 2005). Successful management requires a skilful understanding of ecosystem processes in lakes and knowledge of pre-disturbance conditions to set realistic restoration goals (Battarbee 1999).

The Water Framework Directive (WFD) of the European Union, which will drive the management of surface waters throughout Europe for the next decades, aims at achieving 'good status' for all relevant waters within the European Union by 2015 (EU 2000). The WFD sets environmental objectives, which involve all the individual aspects of an aquatic ecosystem and require the prevention of its further deterioration, reduction of polluting sources, improvement of water status, and finally the promotion of balanced and sustainable water uses. To achieve this goal, water bodies are identified and typified by each member state. For instance, in Estonia, lakes are divided into eight types according to their limnological parameters (Ott 2006). Two large lakes (Peipsi and Võrtsjärv) are treated as separate types and small lakes are split into six types. The ecological quality of lakes should be assessed with focusing primarily on biological quality criteria, while the traditional chemical standards have become only supporting elements. The assessment should answer the decisive question to which degree the present-day conditions deviate from those expected in the absence of significant human impact, i.e. reference conditions (high-quality ecological status). In this manner the reference conditions may be interpreted as the environmental conditions existing before intensive rural activities, or before the onset of large-scale industrial impairments. For that purpose the establishment of type-specific reference conditions for all different water body types is required. In Estonia it is an almost impossible task to find lakes with reference conditions for each lake type, particularly as the catchments and lakes are culturally impacted. Moreover, in Estonia as in many other countries very little, if any, long-term and pre-impact monitoring data are available from lakes and the onset of man-induced deterioration is usually undocumented. Fortunately, natural archives of environmental change, i.e. lake sediment records, can be used to reconstruct these missing data sets.

According to the WFD, palaeolimnological techniques can be utilized for identification of pre-disturbed ecological conditions in lakes, as well as for assessing environmental change, identifying causes of change, and also determining the current ecological status of aquatic ecosystems of lakes (Bennion & Battarbee 2007). Palaeolimnology is a multidisciplinary science that uses the physical, chemical, and biological information preserved in sediment profiles to reconstruct past environmental conditions in inland aquatic systems. With the palaeolimnological approach water quality can be examined in a longer time-scale, enabling looking back in time for hundreds or thousands of years.

During the last years we have implemented palaeolimnological methods to be fit especially for the WFD purposes in Estonia. We have investigated five different types of lakes altogether with 13 case studies (Table 1), however as alkalitrophic lakes, dark soft-water lakes as well as coastal lakes are relatively few, these water body types have not been studied so far. In this paper we focus upon the methods applied to determination of reference conditions for Estonian lakes and introduce some examples of the current research.

METHODS

Short subsurface cores with unconsolidated sediment were collected through the lake ice from or near the deepest place of the study basins using a cable-operated Willner-type gravity corer or a freeze corer. Deeper sediments were recovered with a Russian peat corer.

As accurate dating of sediments constitutes an essential part of palaeolimnological studies, the chronology was established and evaluated by a combination of different independent approaches (see details of the methods in Last & Smol 2001a, 2001b): (1) ^{210}Pb dating; (2) ^{137}Cs and ^{241}Am reference horizons; (3) the spheroidal fly-ash particle distribution in sediment profiles; (4) ^{14}C dating; and if annual layers of the sediment were observed in the sequences, then by (5) counting of varves (lakes Pikajärv, Rõuge Tõugjärv, Pappjärv, Kooraste Linajärv, and Verevi).

Table 1. The list of the studied Estonian lakes for the WFD, their typology, trophic status, and location of the coring site. HY, hypereutrophic; E, eutrophic; M, mesotrophic; O, oligotrophic

Lake	Estonian WFD typology	Lake trophy	Max. depth, m	Location	Reference
Peipsi	Lake Peipsi	M/E	15.3	58°47′15″N 27°19′20″E	Heinsalu et al. 2007
Võrtsjärv	Lake Võrtsjärv	E	6.0	58°09′40″N 26°04′10″E	Heinsalu et al. 2008
Harku	Shallow, light, medium alkalinity	HY	2.5	59°25′10″N 24°36′40″E	Leeben et al. 2008
Kaiavere	Shallow, light, medium alkalinity	E	5.0	58°36′00″N 26°40′30″E	Alliksaar & Heinsalu 2005
Nohipalu Valgjärv	Light, softwater	O	11.7	57°56′30″N 27°20′50″E	Heinsalu & Alliksaar 2009
Pikajärv	Deep, light, medium alkalinity	HY	23.0	58°04′05″N 26°35′10″E	Leeben et al. 2005
Rõuge Tõugjärv	Deep, light, medium alkalinity	M	17.0	57°44′30″N 26°54′20″E	Alliksaar et al. 2005
Verevi	Deep, light, medium alkalinity	HY	11.0	58°13′55″N 26°24′15″E	Heinsalu & Alliksaar 2005
Pappjärv	Deep, light, medium alkalinity	HY	16.9	57°49′00″N 27°01′55″E	Heinsalu & Alliksaar 2005
Kooraste Kõverjärv	Deep, light, medium alkalinity	M	10.1	57°57′55″N 26°39′45″E	Heinsalu & Alliksaar 2005
Kooraste Linajärv	Deep, light, medium alkalinity	HY	14.0	57°57′45″N 26°39′50″E	Unpublished
Saadjärv	Deep, light, medium alkalinity	M	25.0	58°32′15″N 26°39′00″E	Heinsalu & Alliksaar 2007
Tollari	Deep, light, medium alkalinity	E	10.5	57°45′10″N 26°20′30″E	Unpublished

Subfossil diatoms are well preserved within lake sediments because of siliceous cell walls that are very resistant to decay. Moreover, individual diatom species have well-defined ecological optimum values and tolerance ranges for many limnological variables including phosphorus concentration (Hall & Smol 1999). Therefore we applied diatom-based reconstruction for defining reference conditions in Estonian lakes. Diatoms have been used for establishment of background baseline conditions for lakes in many EU states like Great Britain (Bennion et al. 2004), Ireland (Leira et al. 2006), Denmark (Bjerring et al. 2008), Sweden (Norberg et al. 2008), and Finland (Räsänen et al. 2006).

The diatoms in the subsamples of the sediment profile were counted and identified using standard techniques (Battarbee et al. 2001). The relative abundance (percentage values) of species was calculated and those taxa that reached at least 1% relative abundance in at least one sample were used in the statistical treatment of the data. The statistical stratigraphic zonation and correspondence analysis were applied to assess the floristic changes occurring at each dated sediment record. When the diatom assemblage for the bottommost part of the sediment section implied stable composition with insignificant floristic change, the average of these samples was regarded to represent reference conditions. In some case studies additional aquatic fossil indicator groups were implemented (green algae, cladocerans, pigments) for the reconstruction and assessment of the ecological change and furthermore, pollen evidence was applied to tracking human agricultural activity in the lake catchment (e.g. Alliksaar et al. 2005).

For each lake sediment profile, the Bray–Curtis dissimilarity coefficient (Michelutti et al. 2001) was used as a measure giving the degree of floristic change based on diatom species composition between sediment subsamples. The values of the Bray–Curtis coefficient range from 0 to 100, where 0 indicates that two samples are identical and 100 indicates that they are completely different. The mean diatom composition was calculated for the subsamples representing reference conditions and the floristic distances of temporally younger subsamples were computed. The surface sediment subsample (uppermost 1 cm) of each lake was taken to represent the current ecological conditions of the lake. The WFD requires that the ecological quality needs to be determined for individual lake types and that all relevant lakes should be assigned to one of the five ecological quality classes: 1 – high, 2 – good, 3 – moderate, 4 – poor, 5 – bad. The Bray–Curtis index values were attached arbitrarily with the WFD ecological quality classes in the way that 0–20 were assessed to be high diatom-based water quality, and 20–40 represented good, 40–60 moderate, 60–80 poor, and 80–100 bad water quality conditions.

The development of weighted–averaging-based regression and calibration tools has become a widely used and reliable means of quantitative reconstruction of environmental change from the composition of fossil diatom assemblages. These mathematical models describe the relationships between diatom composition and lake environmental variables. Diatom-inferred lake epilimnetic total phosphorus concentrations (DI-TP) were reconstructed online (http://craticula.ncl.ac.uk/Eddi/jsp), using the northwestern European total phosphorus dataset of the European Diatom Database calibration training set and weighted averaging partial least-squares regression (WAPLS; ter Braak & Juggins 1993) model for Lake Rõuge Tõugjärv and the locally-weighted weighted averaging regression (LWWA; Juggins 2001) model for Lake Pappjärv. The resultant DI-TP estimation LWWA model ($r^2 = 0.75$) generated a root mean squared error of prediction (RMSEP) of 0.25 log µg TP L^{-1} and WAPLS model ($r^2 = 0.73$) generated an RMSEP of 0.27 log µg TP L^{-1}.

CASE STUDIES

Lake Rõuge Tõugjärv

Rõuge Tõugjärv is a small (surface area 4.2 ha), deep (maximum depth 17.0 m), stratified hard-water meso-trophic lake located in a kettle-hole depression in the 75 m deep primeval valley in southern Estonia. A small stream flows through the lake, causing a rapid rate of water exchange. The Rõuge area is situated in a dense prehistoric setting, e.g. archaeological evidence of the settlement and hillfort date back to AD 800–1100. The lake was chosen for investigation because of its annually laminated sediment sequence (Veski et al. 2005), which provides accurate chronological control necessary for high-resolution palaeolimnological study.

During the 15th century *Cyclotella* species (*C. comensis* and *C. comta*), diatoms that are tolerant to low-nutrient waters, showed high values, while reconstructed DI-TP concentrations were low, in the range 20–40 µg L^{-1} (Fig. 1), i.e. reflected the mesotrophic status of the lake. Since the 16th century significant changes in the diatom composition have taken place. *Cyclotella* spp. declined and the proportion of eutrophic and hypereutrophic taxa, e.g. *Stephanodiscus parvus*, *Cyclostephanos dubius*, *Aulacoseira granulata* var. *angustissima*, *Asterionella formosa*, and *Fragilaria crotonensis*, increased. Moreover, DI-TP concentrations increased and showed maximum values over 100 µg L^{-1} in the mid-19th century, indicating that the lake itself

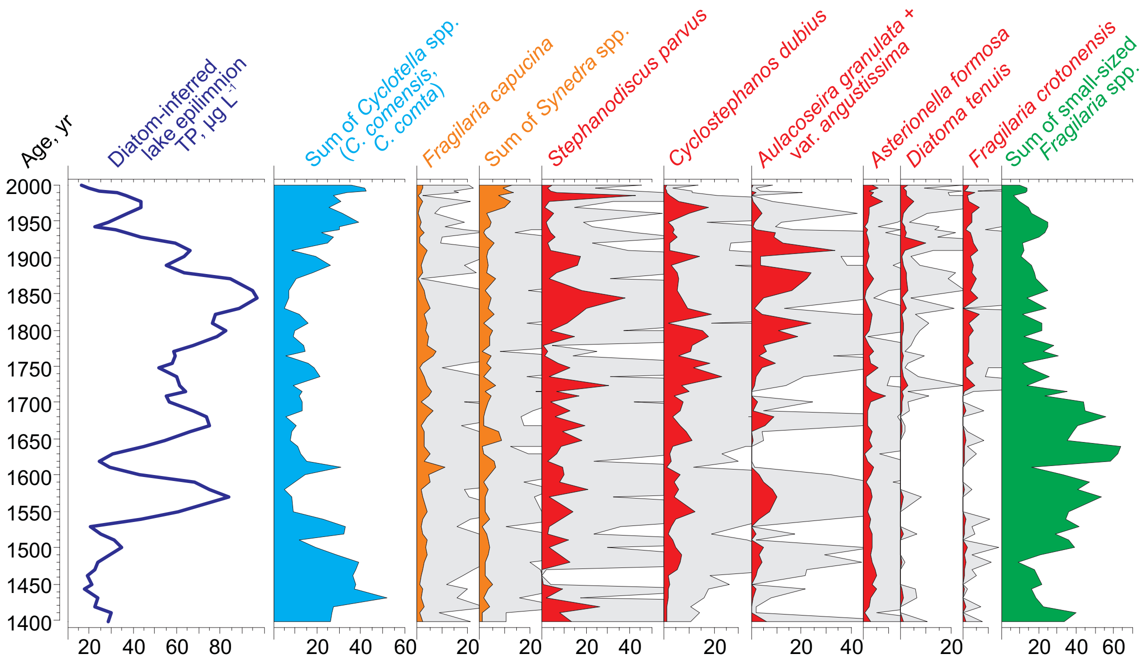

Fig. 1. Diatom-inferred lake surface water total phosphorus concentration and relative abundance (%) of the most common diatom taxa plotted against sediment age of Lake Rõuge Tõugjärv for the time period of AD 1400–2000. Diatom-inferred lake surface water total phosphorus concentration is represented as a 3-sample moving average curve. The grey curves show 10× exaggeration of the percentage values. Sediment chronology is based on counting annual laminae of the sediment record.

underwent rapid eutrophication. However, according to diatom stratigraphy and DI-TP reconstruction, the aquatic ecosystem of Rõuge Tõugjärv recovered at the onset of the 20th century and the modern lake has the water quality similar to that of the 15th century.

For many EU countries it is generally agreed that ca AD 1850 is a suitable time against which to assess human impact on lakes, as this exemplifies a time period prior to major industrialization and agricultural intensification (Battarbee 1999). However, the palaeolimnological case study of Rõuge Tõugjärv showed that implementation of ca AD 1850 as a benchmark for lake reference conditions in Estonia is not valid and due to long-term agricultural impact on many lakes, determination of the 'natural reference conditions' is a complicated task and requires consideration of a much longer time period. Some lakes, particularly those in rich soil areas may have been mediated by human impact over hundreds to thousands of years in response to the start and development of primitive agriculture following forest clearance.

Palaeolimnological evidence of permanent rural land-use around Rõuge Tõugjärv appears from the onset of the Bronze Age, around 1800 BC, marked by the appearance of cereal pollen grains, contemporarily with an increase in other pollen-based human indicators, such as ruderal plants (Poska et al. 2008). Simultaneously, the diatom composition data and the DI-TP values suggest that the lake was contemporarily sensitive to this early major catchment disturbance phase, influential change occurred in lake water quality, in-lake nutrient concentrations increased and the lake switched from mesotrophic to eutrophic state, and there was no lag between the external man-made catchment forcing and the lake response (Heinsalu & Veski 2007).

The post-1500s expansion of farming is visible in both pollen and loss-on-ignition data as high non-tree and cereal pollen percentages and high minerogenic material input into the lake as a result of the increasing area of arable and grassland. In addition, pollen evidence suggests that the maximum extension of both arable and pastoral farming activities in the area was reached during the mid-19th century (Veski et al. 2005). Thus the major eutrophication of Rõuge Tõugjärv occurred contemporarily with human-induced catchment disturbances and rural activities had a major role in shaping the water quality of the lake. In addition, the pollen data covering the last one hundred years showed a decrease in arable land and reforestation of the area due to the consolidation of farmsteads and more efficient land-use practices (Alliksaar et al. 2005). As a result, the lake responded rapidly to diminishing catchment activities and external loading reductions, as seen from diatom composition and the DI-TP data (Fig. 1).

The palaeolimnological study of Lake Rõuge Tõugjärv pointed out that the implementation of the simplified top/bottom palaeolimnological sampling approach is not an appropriate method for sampling strategy for WFD purposes in Estonia. This approach involves the analysis of only two samples per sediment sequence of the lake, whereas a top surface sample represents present-day environmental conditions and a sample from deeper sediment represents material that deposited before the marked anthropogenic impact (Smol 2002). Thus, to define true natural reference conditions for many Estonian lakes, a much longer temporal sequence should be considered and preferably a high-resolution palaeolimnological study with a good chronological control is required.

Lake Pappjärv

Pappjärv is a small (surface area 4.8 ha), deep (mean depth 6.1 m, maximum depth 16.9 m), stratified hyper-eutrophic hard-water lake, located in the town of Võru, southern Estonia. During the last 50 years the human footprint on the lake ecosystem has been harmful, namely the escape of oil products during incidents from a local bitumen plant, the leakage of nutrients from mineral fertilizer storage tanks, as well as chloride runoff from the mixing-ground of sand and salt for winter road service. The regular limnological monitoring of the lake since the 1970s has recorded very high concentrations of phosphorus, nitrogen, chlorides, and organic compounds. Due to massive blooming of phytoplankton, water transparency has been only a few centimetres, indicating that the lake is strongly affected by man-induced pollution.

An 80 cm long sediment core was obtained for palaeolimnological investigations in order to track the environmental history of Pappjärv. The freeze core recovered from the central part of the lake indicated that the uppermost part of the sediment sequence was composed of a regularly repeated pattern of annual laminations. A detailed chronological scale for the core was established by varve-counting of the upper part of the core and by a series of radiometric (^{210}Pb, ^{137}Cs, and ^{241}Am) measurements. According to the dating results, the core was covering the period from ca AD 1700 to 2005.

The base of the studied core section, covering the period from AD 1700 to the 1950s was dominated by planktonic *Cyclotella* species (notably *C. comensis* and *C. comta*) tolerant to waters with low nutrient content (Fig. 2). The DI-TP concentration estimates were low and very stable during that long period and ranged between 7 and 8 µg L^{-1}. From the beginning of the 18th

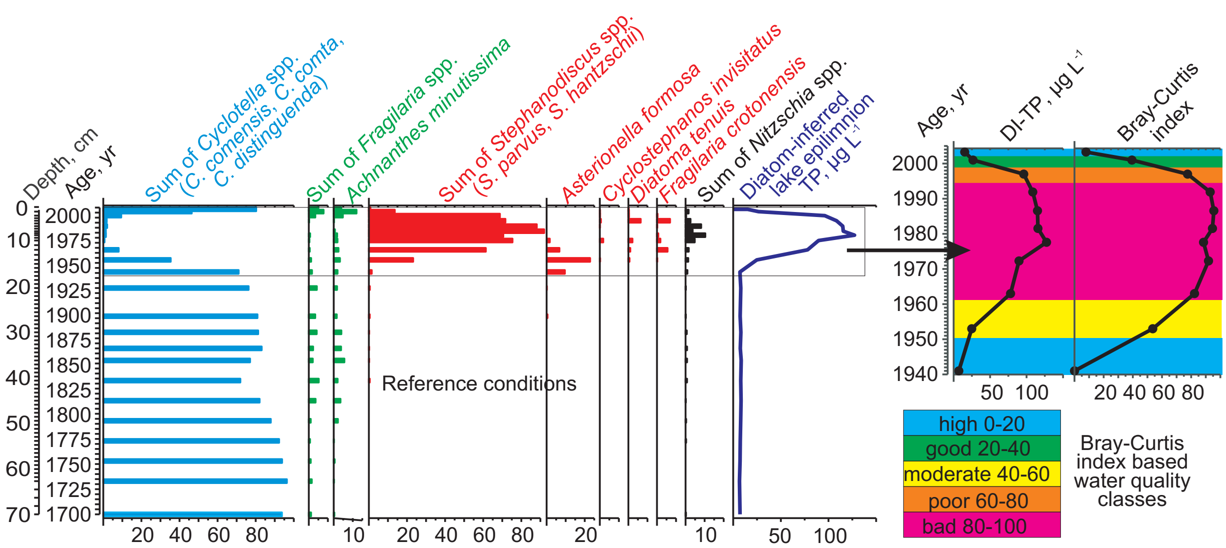

Fig. 2. Relative abundance (%) of selected diatom taxa and diatom-inferred lake surface water total phosphorus (DI-TP) concentration for sediments of Lake Pappjärv for the time period of AD 1700–2005. In a separate window the DI-TP content and Bray–Curtis index as an estimate of diatom-based lake water quality class for the time period of AD 1940–2005 is shown.

century until the middle of the 20th century, the ecosystem of Pappjärv was stable and typical of a stratified hard-water lake with a well-illuminated water column and nutrient-poor conditions, which presumably represents natural reference status of this lake. According to Lake Pappjärv sediment study and our earlier observations (e.g. Heinsalu et al. 2003; Heinsalu & Alliksaar 2005), the natural reference diatom flora of deep stratified lakes with clear water and intermediate alkalinity is characterized by planktonic *Cyclotella* taxa, such as *C. comensis*, *C. comta*, and *C. distinguenda*. These lakes have DI-TP reference values <20 μg L^{-1}.

Changes in the composition of diatoms started in the 1950s contemporarily with the establishment of the bitumen plant in the vicinity of Pappjärv. *Cyclotella* spp. decreased and were replaced by eutrophic planktonic diatoms like *Stephanodiscus parvus* and *Asterionella formosa*. The DI-TP concentration suddenly increased threefold to 25 μg L^{-1}. According to Bray–Curtis index values calculated between average diatom assemblages, the lake had turned to the moderate diatom-based water quality class (Fig. 2).

Significant changes in diatom composition took place between the 1960s and early 1990s: eutrophic *Stephanodiscus* spp. became a dominant taxa, *Cyclotella* spp. declined, and *Nitzschia* spp., diatoms often tolerant to organic pollution, appeared. In accordance with dramatic changes in the diatom assemblage, the DI-TP content increased above 100 μg L^{-1} in the late 1970s and stayed at constant high levels, after which there was a temporary decline in the mid-1990s. The diatom composition likely reflected both the high productivity and very low transparency of the water column and DI-TP values implied hypereutrophic conditions. The Bray–Curtis index values suggest that the diatom-based ecological status of the lake was bad. The marked shift in the deterioration of the water quality of the lake was a consequence of local industrial runoff of polluting compounds.

In the last ten years the diatom assemblage has again changed considerably. *Cyclotella* spp. has recovered, and, respectively, the proportion of eutrophic planktonic diatoms has decreased. In addition, DI-TP values have declined to 15 μg L^{-1}. Sediment diatom data suggest that the quality of epilimnetic waters has improved step by step during the last decade and recovered from the anthropogenic perturbations. Furthermore, the Bray–Curtis index as an estimate of lake water ecological quality class showed a change from poor to high status. However, the improvement of the lake ecosystem concerns only the surface layer. The limnological survey of Lake Pappjärv during summer 2005 (http://eelis.ic.envir.ee:88/seireveeb/) indicated that deep layers were anoxic and hypolimnetic nutrient concentrations were extremely high (e.g. TP value of 4700 μg L^{-1}), implying that bottom layers were still saturated with nutrients and possibly with hazardous organic compounds posing a risk for the lake ecosystem.

The study of the Pappjärv sediment record suggests that in certain deep stratified lakes palaeolimnologists should track past changes in the separate layers of the water column using multiple indicators. For example, in addition to diatoms as good indicators of the lake epilimnetic processes, analyses of profundal chironomids as a proxy for hypolimnetic water quality should be included.

CONCLUSIONS

Limnological monitoring records seldom go back for more than a few decades and so rarely document the onset of human impact on lakes. Our study demonstrated that biostratigraphic analyses of sediment records enable reconstruction of the history of both individual lakes as well as their surroundings including ecosystem reference conditions, the status of the lakes under minimum human influence. We have developed, according to WFD requirements, robust tools for the assessment from the lake sediment record of both biological and chemical qualities of lake water prior to human impact. This kind of information is essential for setting realistic lake management and restoration targets.

Our palaeolimnological study of Lake Rõuge Tõugjärv demonstrated that the commonly held belief that man-induced eutrophication of Estonian lakes is a relatively modern phenomenon related to post-industrial population growth and intensification of agriculture is a misconception. Some lakes, particularly those in rich soil areas, have been affected by human activities over longer time-scales for hundreds to thousands of years, from the start and development of primitive agriculture following forest clearance. It has been agreed in many European countries that approximately AD 1850 represents the reference conditions for lakes as it corresponds to the period before industrialization and agricultural intensification. Our observations showed that during that period anthropogenic disturbance on Rõuge Tõugjärv was the greatest.

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Järvede foonitingimuste ja ökoloogilise seisundi hindamine paleolimnoloogiliste uuringute abil – rakendus Euroopa Liidu veepoliitika raamdirektiivile

Atko Heinsalu ja Tiiu Alliksaar

Euroopa Liidu veepoliitika raamdirektiivi (VRD) nõuete kohaselt on järvede seisundi määratlemise aluseks eri tüüpi veekogude nüüdisolukorra võrdlemine foonitingimustega, st looduslähedase intensiivsest inimmõjust veel puutumatu seisundiga. Et olemasolevad instrumentaalsed andmeread Eestis tavaliselt nii kaugele minevikku ei ulatu, kui veekogud olid veel looduslikus seisundis, tuleb VRD kohaselt järvede foonitingimuste väljaselgitamiseks kasutada paleolimnoloogilisi mudeluuringuid. Artiklis on antud lühiülevaade setteuuringute metodoloogiast, mida on viimastel aastatel TTÜ Geoloogia Instituudis järvede foonitingimuste uuringutes kasutatud, ja uurimistulemusi on kajastatud Rõuge Tõugjärve ning Võru Pappjärve näitel.