Palaeolimnological assessment of environmental change over the last two centuries in oligotrophic Lake Nohipalu Valgjärv, southern Estonia

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Abstract. The main objectives of this study were to reconstruct the environmental conditions for a small oligotrophic lake during the last two centuries, to determine if the environment of the lake was anthropogenically mediated, and to assess the pre-impact reference conditions with palaeolimnological techniques. A short sediment core from Lake Nohipalu Valgjärv was analysed in detail for diatom assemblages as well as for loss-on-ignition measurements. Accurate chronology of the sediment core was established and evaluated by different independent approaches – ^{210}Pb, ^{137}Cs, and ^{241}Am dating, and the distribution of spheroidal fly-ash particles in sediments. Quantitative inference models based on sedimentary diatoms were applied to reconstruct changes in past lake water pH. Before the mid-19th century, Nohipalu Valgjärv was an oligotrophic lake with clear water continuously transparent down to the bottom and with rich benthic diatom flora. Since the early second half of the 19th century, presumably as a result of forest logging around the lake, water transparency decreased and benthic diatom productivity diminished, and the lake did not recover any more to natural baseline conditions. Due to peat mining activities in the Meenikunno bog, the quality of lake water has changed during the last two decades. The lowered lake level, deteriorated light climate, and decreased pH are the most important environmental variables that have influenced the lake ecosystem.

Key words: lake sediment, diatoms, ^{210}Pb chronology, reference conditions, Lake Nohipalu Valgjärv, Estonia.

INTRODUCTION

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 a ‘good status’ for all relevant waters within the European Union by 2015 (EC 2000). The ecological quality of lakes should be assessed by the degree to which present-day conditions deviate from those expected in the absence of significant anthropogenic impact, termed ‘reference conditions’. For that purpose the establishment of type-specific reference conditions for different water body types is required. 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-made deterioration is usually undocumented. According to the WFD, palaeolimnological techniques can be utilized for the identification of pre-disturbed ecological conditions in lakes, as well as for assessing an environmental change, identifying causes of the change and also for 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.

In the frame of the Viru–Peipsi CAMP project, which elaborated a water management plan for the Viru County and Lake Peipsi Basin region according to the requirements of the WFD (www.envir.ee/viru.peipsi/eng/index.php), a short lake sediment core from a small lake, Nohipalu Valgjärv, was investigated. The aim of the study was to reconstruct environmental changes in this particular lake during the last few centuries, reveal the onset of the man-made disturbances, and establish reference conditions in this water body. Diatoms, microscopic algae that are common in all kinds of water, are very good indicators of pH in softwater lakes, and methods of inferring past pH conditions from fossil diatom assemblages are well established (Battarbee et al. 1999). In the present project we tried to date the sediment core accurately, establish changes in the floristic composition of the lake using microfossil diatom assemblages, and reconstruct quantitatively past changes in lake water variables, namely pH, using primarily lake sediment diatom-based transfer functions (e.g. Birks et al. 1990).

STUDY AREA

Nohipalu Valgjärv is a small (7 ha) oval-shaped softwater oligotrophic lake, located in a glaciokarstic hollow in the

Meenikunno Landscape Reserve in southern Estonia (57°56′30″N; 27°20′50″E). The deepest part of the lake (11.7 m) is situated westwards from the centre. Sporadic limnological samplings have been carried out in the lake since the end of the 1950s, many of which are characterized in Mäemets (1977). Since 1991, the lake has been surveyed annually during summer months as a part of the Estonian national monitoring programme (http://eelis.ic.envir.ee:88/seireveeb/). Nohipalu Valgjärv has neither inlet nor outlet and the water table is controlled by groundwater. Water in the lake is slightly acidic and the water column is strongly stratified. During the last years the water transparency has been 3.5–6 m. The lake's watershed with an area of 91.4 ha consists of sandy sediments covered with coniferous (pine) forest, and quite outstanding limnoglacial landforms, kames, lie north of the lake. The large Meenikunno bog, the ditching of which for peat mining had caused the lowering of the lake water level, is located westwards.

METHODS

A short sediment core from the ice-covered Nohipalu Valgjärv was taken with a Willner sampler from the deepest part of the lake in March 2003. The core was sectioned at 1 cm intervals in the field and placed into plastic bags, transported to the laboratory, and stored at 4 °C prior to the analyses.

The chronology of the sediment core is based on ^{210}Pb radiometric dating verified by the sediment distribution of the artificial radionuclides – ^{137}Cs and ^{241}Am, and spheroidal fly-ash particles (SFAP). The sediment activity of ^{210}Pb, ^{226}Ra, ^{137}Cs, and ^{241}Am was analysed in the Radiometric Laboratory of the Ukrainian Hydrometeorological Research Institute by gamma spectrometry with a low background germanium detector (Appleby et al. 1986). Spheroidal fly-ash particles, products of high-temperature combustion of fossil fuels, were counted at ×250 magnification under a light microscope after the sequential treatment of sediment subsamples by 30% H_2O_2, 2.7 M HCl, and 0.3 M NaOH to remove organic, calcareous, and biogenic siliceous material (Rose 1990).

The organic matter and carbonate content was measured as loss on ignition after heating dried samples at 550 °C for 4 h and at 950 °C for 2 h, respectively (Heiri et al. 2001). The residue remaining after combustion is regarded as sediment terrigenous matter.

For diatom analysis the pre-weighted samples were treated with 30% H_2O_2 to remove organic material (Battarbee et al. 2001). Diatom concentrations were determined by adding a known number of commercially available *Lycopodium* spores to the cleaned sediment slurry. Slides were mounted with Naphrax and analysed for microfossils using a Zeiss Axiolab microscope (oil immersion, phase contrast, ×1000 magnification, numerical aperature – 1.30). Chrysophyte cysts were enumerated as separate categories during microscopy and the ratio comparing cysts and all microfossils was calculated. At least 400 diatom valves were counted from each sediment sample. The taxonomy and nomenclature of diatoms follow the Surface Water Acidification Programme guidelines (Stevenson et al. 1991).

Diatom-inferred lake surface water pH was reconstructed using weighted averaging partial least-squares regression (ter Braak & Juggins 1993) and the European Diatom Database (Battarbee et al. 2000) as a regional calibration dataset. The modelling was performed online (http://craticula.ncl.ac.uk/Eddi/jsp/).

RESULTS

Sediment description, chronology, and accumulation rate

A 38 cm long sediment core recovered consisted of homogeneous brownish coarse detritus gyttja. The 10 cm top section of the core was unconsolidated and overlain by a 0.5 cm thick green-coloured layer of algal debris.

Radioisotope analyses showed that the ^{210}Pb concentration in the lake sediment had a distinctive decreasing gradient up to a depth of ca 15 cm and decreased even more dramatically to a depth of 20 cm (Fig. 1). Down the core this gradient changed to almost zero, keeping the ^{210}Pb concentration well in excess of the supported ^{226}Ra level at 7–8 Bq kg^{-1}. At a depth of 20–25 cm equilibrium between ^{210}Pb and ^{226}Ra occurred, corresponding to about 150 years of sediment accumulation. Irregular decline in the ^{210}Pb concentration profile refers to changing intensity of the sedimentation rate. Therefore the constant initial concentration approach, which considers that different parts of the sediment profile have different rates of accumulation (Appleby & Oldfield 1978), was applied to the calculation of ^{210}Pb age of sediments.

From the artificial radionuclides the ^{137}Cs activity had a strong subsurface peak with a maximum at a ca 2–3 cm depth (Fig. 1). The presence of the radionuclide ^{241}Am in the sediment profile was confidently detected at a depth of 0–9 cm. This radionuclide is a clear indicator of the nuclear weapons test fallout in the 1960s and its first appearance in the sediments could record this event. Apparently the ^{137}Cs peak at 2–3 cm in the lake sediments corresponds to the impact of the Chernobyl radioactive cloud of 1986. The study of the ^{137}Cs distribution on subsurface soils in Estonia

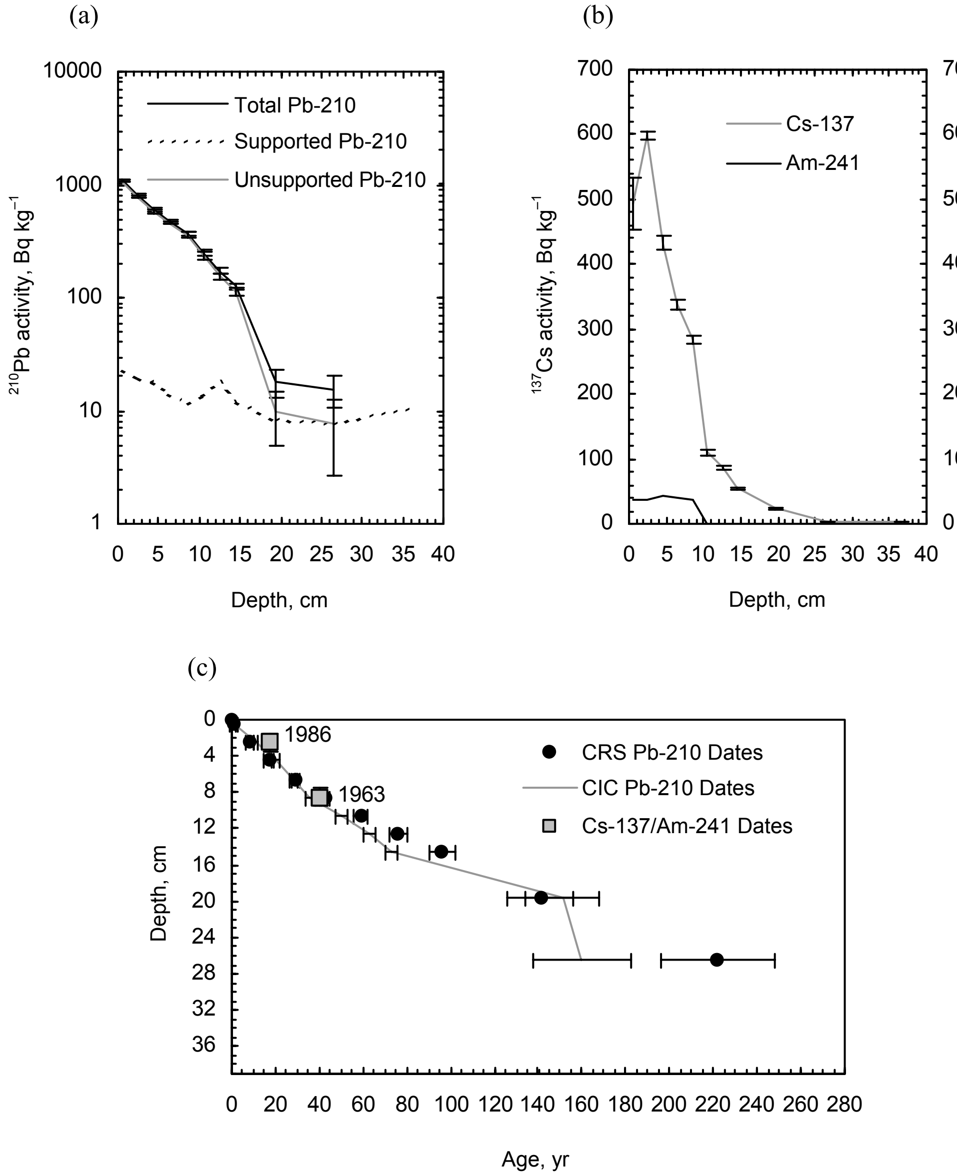

Fig. 1. Distribution of total, supported, and unsupported ^{210}Pb activities (a) as well as ^{137}Cs and ^{241}Am activities (b) in the studied sediment core. (c) The age–depth profile from the radiometric chronology together with error margins of the ^{210}Pb dates. CRS (constant rate of supply) and CIC (constant initial concentration) are ^{210}Pb dating models; in our study the CIC model was applied to age calculations of the sediment record of Nohipalu Valgjärv.

(Realo et al. 1995) has shown that in the region of Nohipalu Valgjärv the estimated Chernobyl-derived contribution to the radiocaesium inventory in natural soils was about 10–30% above the nuclear weapon tests fallout deposition in the early 1960s. Both these periods, determined from the ^{137}Cs and ^{241}Am records, coincide well with the calculated ^{210}Pb dates (Fig. 1).

The down-core distribution of SFAP supported the reliability of the obtained ^{210}Pb age–depth curve. This independent chronological method is based on the fact that the SFAP distribution profile in the sediment core follows the historical record of fossil fuel consumption of the study area and, fortunately for Estonia, the history of fuel combustion and fly-ash emissions is very well documented (Nõges et al. 2006). Comparison of the SFAP concentration in the Nohipalu Valgjärv sediment core with the data on fossil fuel consumption in Estonia (Fig. 2) revealed specific features in the SFAP distribution

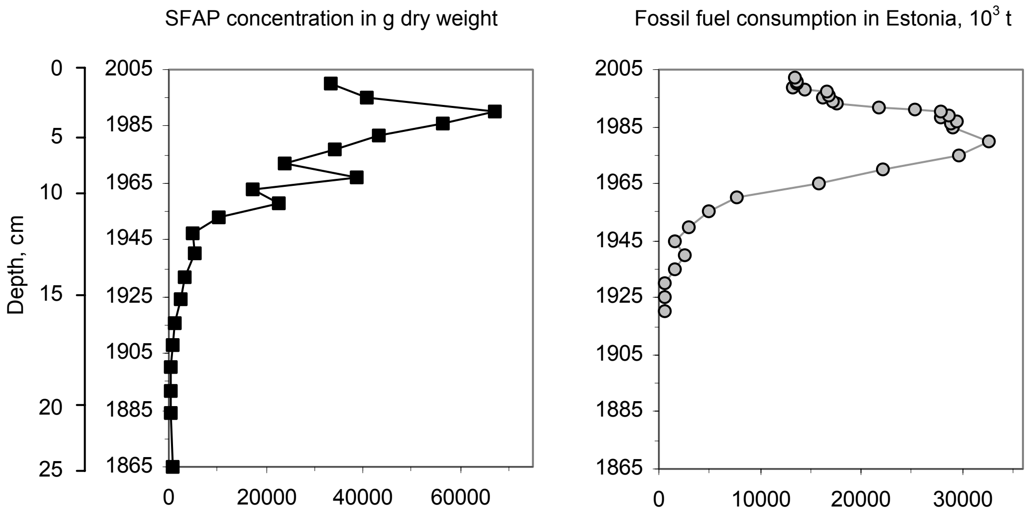

Fig. 2. (a) The temporal distribution of spheroidal fly-ash particles (SFAP) in the sediment sequence of Nohipalu Valgjärv; (b) fossil fuel consumption history in Estonia.

curve, which can be used as reference layers for dating. For example, a sharp increase in particle concentration due to a considerable rise in total energy demand after World War II and the peak in the SFAP record at 2–3 cm depth were followed by decline in subsurface values. The decline was caused by two main factors – the increase in particle emissions removal efficiency and the decrease in energy production since the 1980s (Heinsalu et al. 2007). These features in the SFAP distribution profile agree well with the radiometric dates: according to the ^{210}Pb age-scale, the sharp rise in particle concentration is dated to the end of the 1940s and the subsurface maximum to the middle of the 1980s; the latter is well supported by the ^{137}Cs record.

From the end of the 18th century the initial sedimentation rate in Nohipalu Valgjärv was very low, with the mass accumulation rate being below 0.006 g cm^{-2} yr^{-1} (Fig. 3). A sharp peak in sediment accumulation occurred in the middle of the 19th century when it rose almost 10-fold to about 0.05 g cm^{-2} yr^{-1}. After that the former low sedimentation rate was achieved again, which stayed fairly uniform until the 1960s. The following 20–30 years showed an increasing tendency in the deposition rate to approximately 0.012 g cm^{-2} yr^{-1} with a slight decrease during the 1990s–2000s.

Physical and chemical properties of sediments

The particulate matter of sediments consisted mainly of organic matter, the proportion of which fluctuated between 60% and 80%. The carbonate content in sediment dry weight was very low, only about 2%. Organic and terrigenous matter showed quite distinctive changes in their profiles (Fig. 3). Stable values (organic matter 76%, terrigenous matter 22%) at the beginning of the 19th century started to change gradually towards higher mineral matter input until its sharp peak of 35% in ca the 1860s. These changes resulted in a dramatic drop in the organic matter content and a simultaneous very high sediment accumulation rate. During the following years the previous sediment composition was attained again. From the second half of the 19th century, the inorganic matter content showed a gradual continuous increase, while the share of organic matter decreased steadily. In the 1980s, however, the organic matter content of sediments started to rise.

Diatoms

Diatom analyses were carried out from 15 samples within the 0–35 cm core depth representing the time-span of ca AD 1800–2002. A total of 93 diatom taxa of 18 genera were identified. Diatoms preserved in sediments showed nutrient-poor conditions. Littoral diatoms living unattached on lake sediment (epipelic diatoms) and those living attached to water plants (epiphytic diatoms) were abundant, whereas planktonic diatoms floating in the open water were almost absent. Diatom stratigraphy (Fig. 4) was divided into three diatom assemblage zones (DAZ).

The species composition of diatoms in the sediments that accumulated between ca AD 1800 and 1870 (DAZ 1)

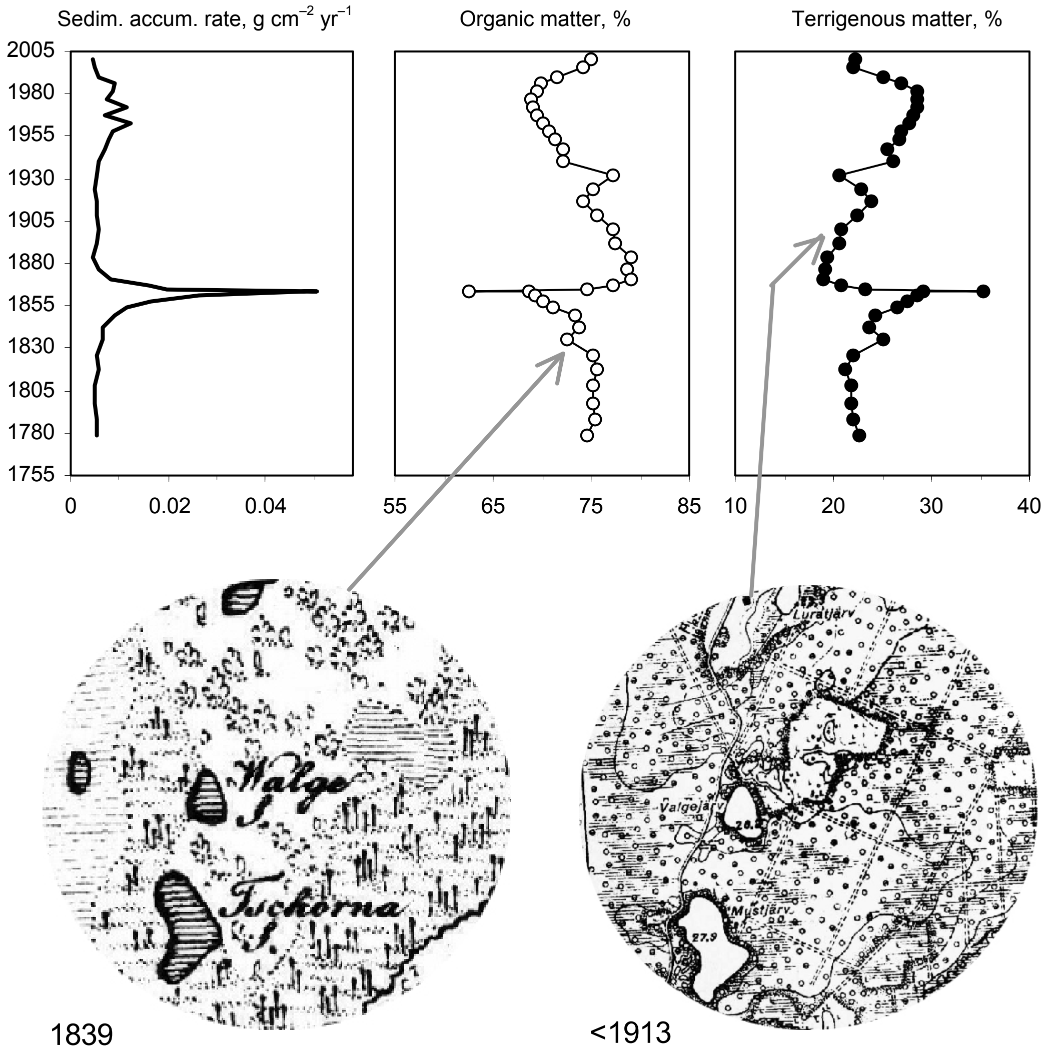

Fig. 3. The sediment accumulation rate, and contents of organic and terrigenous matter in the sediments of Nohipalu Valgjärv estimated by loss on ignition. The map of the Livonia province by C. G. Rücker from 1839 at a scale of 1 : 185 200 does not show any evidence of forest clearance; the Russian verst-map at a scale of 1 : 42 000, compiled earlier than 1913, shows that forest logging north-eastwards of the lake has occurred.

was dominated by benthic *Pinnularia interrupta*. Diverse taxa belonging to the genera *Navicula* (*N. arvensis* and *N. submuralis*), *Eunotia* (*E. minima* and *E. pectinalis* var. *minor*), and *Stauroneis* (*S. anceps* and *S. anceps* f. *hyalina*) were also common. The diatom concentration was relatively high, reaching up to 1500×10^6 valves g^{-1} dry sediment. Diatom-inferred pH values oscillated between 6.2 and 6.4 in that time period, but increased in about the 1860s (Fig. 5).

In the sediments that accumulated between AD 1870 and the 1980s (DAZ 2), the diatom composition remained similar, however, the relative frequency of the dominant species *Pinnularia interrupta* decreased. The epiphytic taxa of the genera *Achnanthes*, *Cymbella*, and *Eunotia*, as well as *Tabellaria flocculosa* and epipelic *Brachysira neoexilis* became more important. In addition, diatom concentration decreased to about 50×10^6 to 300×10^6 valves g^{-1} dry sediment. The number of chrysophyte cysts in the sediment increased largely. The diatom-inferred pH declined to the pre-1860s values and did not show notable changes afterwards.

The diatom composition changed distinctly in the sediment that deposited since the 1980s (DAZ 3). *Pinnularia interrupta* almost disappeared and was replaced by epiphytic species of the genus *Eunotia*, notably by *E. incisa* and *E. rhomboidea*. The diatom concentration decreased continuously. Diatom-inferred pH dropped by one unit from 6 to 5.

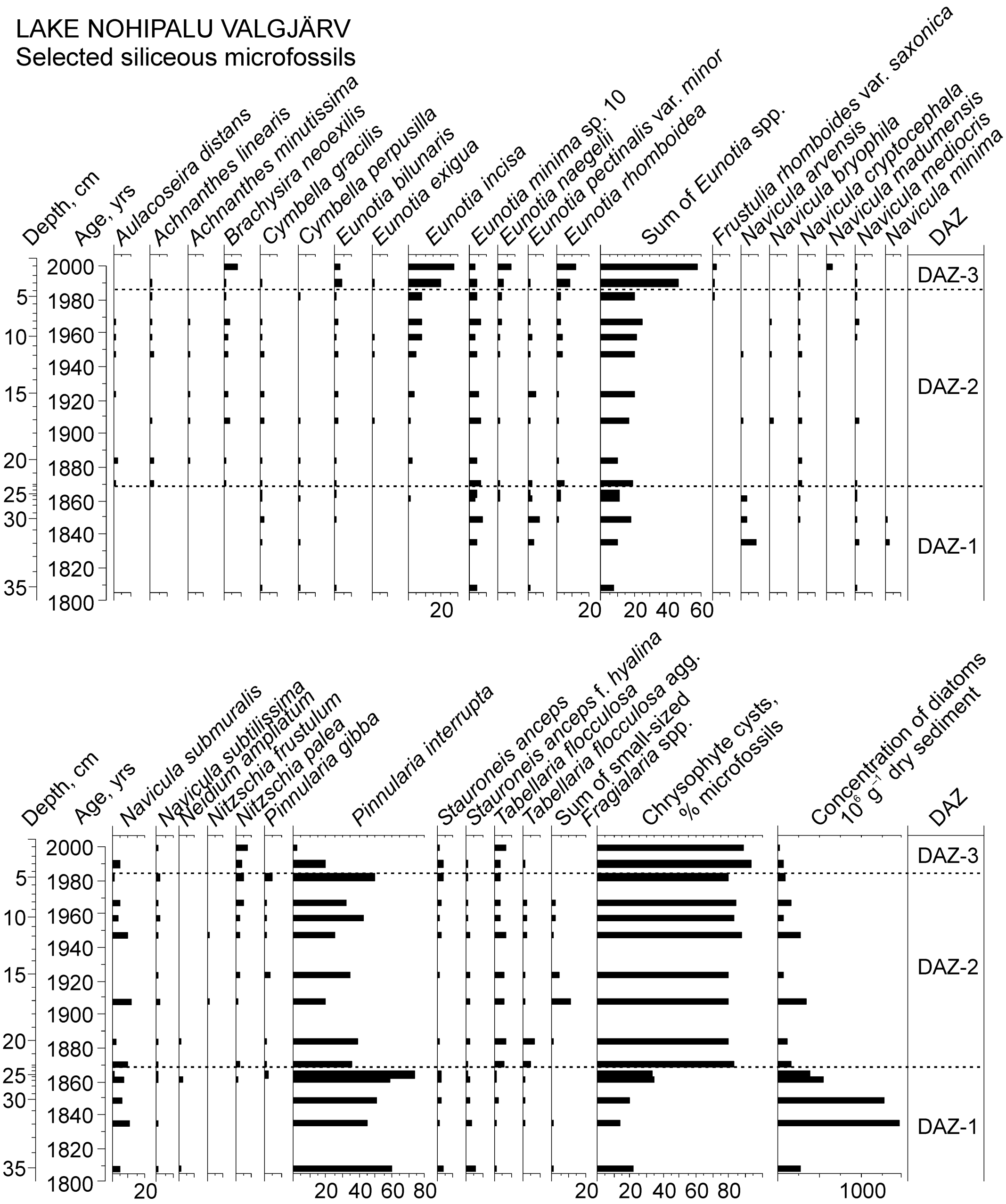

Fig. 4. Diatom stratigraphy of Nohipalu Valgjärv. Relative frequency of the most abundant diatom taxa, ratio of chrysophyte cysts to all siliceous microfossils, and concentration of diatoms are shown. DAZ – diatom assemblage zone.

DISCUSSION

According to the requirements of the WFD, Estonian small lakes are divided into 5 types (Ott 2005). Following this typology, Nohipalu Valgjärv belongs to type 5, i.e. to the category of light- and soft-water lakes (Tamre 2006). Based on a more traditional typology, these lakes are known as clear-water oligotrophic lakes, and Nohipalu Valgjärv is a very typical example of these lakes (Mäemets 1974). Oligotrophic lakes are not common in Estonia. They constitute about 8% of the Estonian lakes (Ott 2006) and strictly typical representatives are absent at all nowadays (Ott & Kõiv 1999). Most of the Estonian oligotrophic lakes have become eutrophicated during the last decades and have already reached the mesotrophic state. These lakes that were typical oligotrophic water bodies in the 1950s, have, however, maintained a part of their characteristic biota and, therefore, are still regarded as oligotrophic (Ott & Kõiv 1999).

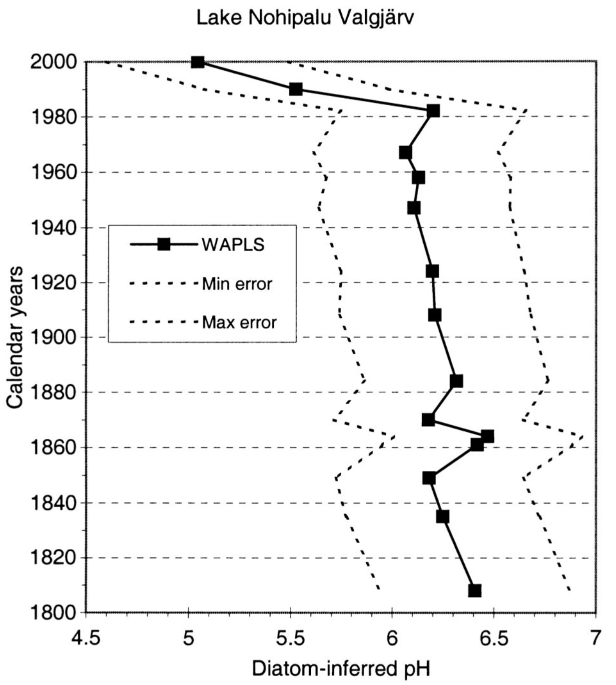

Fig. 5. Diatom-based reconstruction of lake surface water pH for Nohipalu Valgjärv. The quantitative transfer function was developed using weighted averaging partial least-squares regression (WAPLS). Error margins are shown as broken lines. The combined pH dataset of the European Diatom Database was used as a calibration set.

Studies on the environmental history of oligotrophic lakes, based on palaeolimnological techniques, primarily diatom-based reconstruction, have so far been lacking in Estonia. In general, we identified three periods in the development of Nohipalu Valgjärv within the timespan of about 200 years.

About 200 years ago Nohipalu Valgjärv had a diatom assemblage of acidophilous *Pinnularia*, *Navicula*, *Eunotia*, and *Stauroneis* species. These diatoms prefer oligotrophic, slightly acid or circumneutral, soft- and clear-water lakes. Also diatom-based reconstruction of pH suggested slightly acid lake water with values around 6.2 and 6.4. The diatom concentration indicated rather high productivity of benthic diatom species. Thus, the lake had definitely better light climate conditions 200 years ago and the water column was perhaps transparent down to the bottom, as indicated by rich benthic communities. In addition, very high and stable organic matter values in the sediment suggest the existence of a forested catchment with stabilized vegetation and topsoil cover around this seepage lake without any permanent surface inflow. Therefore we assume that such diatom assemblages represent the natural reference conditions for the lake.

The change in the diatom flora in the mid-19th century was inferred as a decrease in the epipelic *Pinnularia interrupta* and a corresponding increase in epiphytic diatoms. The modification of the diatom flora could be attributed to a peak in the accumulation of mineral matter (Fig. 3). In a lake without any considerable allochthonous input of inorganic matter, the minerogenic component of the sediments calculated from loss on ignition reflects the intensity of erosion in the catchment. The reason for the sudden erosion event might be connected to forest clearance around the lake. The specific changes in the landscape documented in early historic records and maps allow comparison with palaeoecological data and have been profitably applied to validate the past environmental and land-use reconstructions (Veski et al. 2005; Poska et al. 2008). The historical scheme of the Nohipalu area originating from 1897 (map preserved in the Estonian Historical Archives – EAA 2072-4-64, Kristina Teral pers. comm. 2008), as well as the Russian verst-map at a scale of 1 : 42 000 compiled before 1913 (Fig. 3), show large-scale forest clearance northeastwards of the lake. The logging must have taken place sometime during the middle or second half of the 19th century, as the map of the Livonia province by C. G. Rücker from 1839 (scale 1 : 185 200) shows no evidence of the forest lot (Fig. 3).

However, despite the deforestation and soil erosion, the diatom flora in the lake retained many of its previous characteristics and the diatom-based reconstruction of lake water pH indicated a short-term and slight increase possibly due to mobilization of major ions from topsoil and transport together with clastic erosional material into the lake. The lower number of benthic diatoms living on the lake bottom suggests decreased water transparency as a result of soil erosion creating turbidity, which also had a negative effect on the overall diatom productivity. The increased number of chrysophyte cysts compared to diatoms strongly supports the change in the lake environment and might also be related to reduced light availability. This large-scale forest clearance in the vicinity of the lake had a persistent impact on the ecology of the lake as the previous diatom composition did not recover even after the reforestation of the catchment. Examples of similar impact of forest clearance and/or forest fires have also been documented from other small lakes (e.g. Renberg et al. 1993; Korhola et al. 1996).

During the 1990s–2000s, sediment diatom composition and habitat variation have changed to the assemblage dominated by more acid-tolerant and epiphytic *Eunotia* spp. These diatoms, e.g. *E. incisa* and *E. rhomboidea*, grow on water plants in the littoral area of the lake. Overall decrease in diatom concentration indicates that the area of the euphotic lake bottom has diminished markedly. In the late 1950s and early 1960s the registered Secchi depth was more than 8 m and in summertime the water above the lake bottom was supersaturated with oxygen (Mäemets 1968), however, at the present time the water transparency of the lake has been 3.5–6 m with poor oxygen conditions of the bottom layers. Still, in the early 1960s, a limnological survey registered submerged macrophytes reaching a depth of 12 m in Nohipalu Valgjärv (Mäemets & Freiberg 2007). During the last decade the plant growth has been limited to 5–6 m. The onset of changes in light conditions took place already in the mid-1960s when, as a result of ditching and draining of the Meenikunno peat bog for peat mining, the natural lake level was lowered by more than 1 m (Mäemets 1977). Possibly these events can be attributed to the increased sediment accumulation rate in the lake (Fig. 3). The sediment diatom-inferred pH reconstruction suggests that pH declined by more than 1 pH unit by the 1980s. The seepage of acidic water rich in humic substances from the peatland to the lake, presumably as a result of the lowered groundwater table, had affected lake water quality. The lowered lake level, deteriorated light climate, and decreased lake surface water pH are the most important environmental variables that have influenced modern diatom composition in the lake.

CONCLUSIONS

Palaeolimnological analyses of a 38 cm sediment core from the middle part of Nohipalu Valgjärv covering about 200 years of sediment accumulation provided important insights into the history of this lake, especially outside the instrumentally documented range, and for evaluating natural baseline conditions. The study was mainly based on diatom and loss-on-ignition analyses. A chronology of the core, established on the basis of ^{210}Pb, ^{137}Cs, and ^{241}Am measurements and cross-checked by SFAP counting, showed a good agreement and suggested that the age–depth model for the core was reliable. The diatom-based pH reconstruction suggests slightly acid conditions during the first half of the 19th century. The diatom composition and concentration indicates an oligotrophic, continuously transparent water column down to the bottom with rich benthic diatom flora and a stable aquatic ecosystem similar to natural reference conditions. In the second half of the 19th century, probably in connection with forest clearance around the lake, water transparency decreased and benthic diatom productivity diminished. This logging event caused an irreversible change in the ecology of the lake, showing the very sensitive nature of this type of lake ecosystem that can be easily thrown out of its balance. Due to peat mining activities in the surrounding bog since the mid-1960s, the water quality of the lake has changed markedly during the 1990s and 2000s. The lowered lake level, deteriorated light climate, and decreased pH are the most important environmental variables that have influenced the lake ecosystem with poor buffering capacity vulnerable to the changes in the catchment.

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Nohipalu Valgjärve kahesaja-aastase perioodi keskkonnaseisundi muutuste paleolimnoloogiline hindamine

Atko Heinsalu ja Tiiu Alliksaar

Setete ränivetikakoosluse põhjal oli Nohipalu Valgjärv 19. sajandi algupoolel oligotroofne, nõrgalt happelise keskkonnaga, põhjani läbipaistev ja rikkaliku bentilise diatomeeflooraga järv. 19. sajandi keskpaiku toimus ulatusliku metsaraie tõttu järve seisundis pöördumatu muutus: vähenes vee läbipaistvus ja langes bentiliste diatomeede arvukus. Viimase 20 aasta jooksul on turbatootmine naabruses asuvast Meenikunno rabast muutnud järve veekvaliteeti: kõige enam on järve ökosüsteemi mõjutanud vee läbipaistvuse vähenemine ja järvevee pH langus.