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Development of small lakes in Estonia: paleolimnological studies

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Abstract

In this paper we give an brief overview of the paleolimnological studies revealing the development of Estonian lakes and their surrounding landscapes during the Holocene. The paper is mostly focused on the studies carried out in the Institute of Ecology (IoE) at Tallinn University. Development of lakes and their ecological environment can be roughly divided into two major periods: natural stage from emergence of lakes after withdrawal of continental ice sheet to signs of first anthropogenic impacts and the period where the human activity has clearly influenced the lake and its environment.

Key words

Paleolimnological methods, lake sediments, organic sediments, water-level fluctuations, climate change, human impact, vegetation succession, pollen, grain size, macrofossils, lake ecosystem, eutrophication, lake deterioration.

1 meter long lake sediment core (retrieved with belarusian borer) with markings at every 1 cm (photo: T. Vaasma) .

Introduction

Lake sediments are one of the most complete stratigraphic records that can be used to extract information on past climate, vegetation and hydro-ecological processes. Lake sediments in Estonia are rich in organic material and are fairly thick (5-7 meters) making it possible to study past processes in high temporal resolution. In Estonia lake sediments are commonly extracted during the winter when the lakes are covered with sturdy ice-cover (figure 1) or during the summer using a raft (figure 2), providing a stable surface on which to operate on. Sediments are extracted using mainly two different borers: Livingstone-Vallentyne borer (figures 3 and 4) for more watery surface sediments (up to 1 meter) and Belarusian peat borer (figure 5) for deeper sediments up to minerogenic lake basin. Depending on the aim of the studies, sediments are commonly subsampled to 1-5 cm thick samples (figure 6), giving an average time resolution of 10 to 100 years per sample. Sediments covering the whole Holocene (current geological epoch that began after the last Ice Age approximately 11 700 cal yr BP) are dated with AMS (accelerator mass spectrometry) method using ^{14}C radiocarbon from organic compounds extracted from the sediment samples.

Figure 1. Lake sediment extraction during the winter from the ice-cover (photo: T.Koff) (p. 194).

Figure 2. Lake sediment extraction during the summer from the raft (photo: J. Terasmaa) (p. 194).

Figure 3. Lake sediment extraction with Livingstone-Vallentyne borer (photo: J. Terasmaa) (p. 195).

Figure 4. Lake sediment slicing/sub-sampling (photo: J. Terasmaa) (p. 195).

Figure 5. A section of lake sediment core extracted with Belarusian peat borer (photo: J. Terasmaa) (p. 196).

Figure 6. 1 meter long lake sediment core (retrieved with belarusian borer) with markings at every 1 cm (photo: T. Vaasma) (p. 196).

In Institute of Ecology we apply multi-proxy approach when investigating the lakes, meaning a series of different analyses and methods are done in parallel: lithology of sediments, grain-size of mineral matter, macrofossils, pollen, diatoms etc. The methods cover processes in the lake as well as on the catchment, providing a thorough overview of the lake ecosystem. For example, macrofossils give information on the vegetation growing in the lake as well in the close proximity of the lake, making it also possible to reconstruct past lake-level changes as different aquatic plants grow in different water depths. Pollen analysis provides us with information on the vegetation of catchment and surrounding areas, allowing to draw conclusions on the succession of vegetation and therefore on climate conditions, but also on openness of catchment and onset of human activities (presence of cereal pollen). Combining the information from these various analyses makes it possible to draw conclusions on the changes in the environment on local as well as on regional scale.

In order to understand the past we have to understand the present situation. Paleoecological reconstructions are based on principle of actualism/uniformism (initially defined by Hutton, 1788), meaning that we assume that the processes in nature taking place today functioned in the same way in the past. For this reason we have had several projects to clarifying sedimentation patterns and processes in lakes. For example, when reconstructing lake-level changes using macrofossils, it is also important to understand how far the macrofossils can be distributed from the source plants. While macrofossils from some species tend to be distributed all over the lake (e.g. seed fragments of European white water lily), other settle close to the habitat areas thus being more suitable for past lake-level reconstructions (Koff & Vandel, 2008). We have also sampled lake surface sediments for diatoms for mapping diatom assemblages in different lake types (Punning & Puusepp, 2007; Puusepp & Punning, 2011). Various diatom species can have very specific requirements for certain physical or chemical properties such as pH, salinity, trophic status etc. Data on the ecology of the modern biota enables to create a calibration data-set, and once the fossil diatoms have been determined, modern environmental attributes of the species can be used to infer past environmental conditions (Gasse et al., 1995; Ramstack et al., 2003).

The history of IoE reaches back to beginning of the 1990s whence the paleolimnological studies have been one of the main topics among several environmental researches carried out in the institute. Actually, already in the 1980s the systematic paleolimnological researches started in North Eastern Estonia in Kurtna lake district where our colleagues measured biological, physical and chemical properties of various lakes (Punning & Toots, 1987; Punning & Punning, 1987; Punning et al., 1989; Ilomets, 1987; 1989). Investigations continued also in 1990s (Punning & Sargis, 1993; Punning & Varvas, 1993; Varvas & Punning, 1993). These studies resulted in IoE receiving the Science award of the Estonian

Republic in bio-, geo and agricultural sciences in 1995. Since then we have run several projects clarifying sedimentation patterns and processes in lakes.

The aim of the paper is to give an overview on the paleolimnological studies carried out in the IoE. Our studies focus mainly on the development of the lakes and environmental change in the region driven by natural processes and anthropogenic stressors.

Paleolimnological studies

Lakes (figures 7 and 8; table 1) studied by IoE (and a lot more in the area, see p.358-367) started to form at the end of the last Ice Age ca 11000-13000 years ago when the continental ice sheet was retreating and melting. The ground, released from the weight of the ice cover (more than 1 km thick), started to rise. The ice was melting unevenly and some of the ice blocks were covered with outwash (till) of ice sheet. After the ice blocks melted, the kettle holes formed and were filled with water (if a waterproof bottom was formed), providing an ideal environment for preservation of organic material (e.g. paleoecological material).

Figure 7. Location of Estonia and the studied lakes (Lake Lohja, Viitna, Martiska, Nõmmejärv, Verevi, Juusa and Kõži) (p. 197).

Figure 8. A typical view of Estonian lake (photo: J. Terasmaa) (p. 198).

Table 1. Main parameters of the studied lakes (p. 198).

In the beginning of the lake formation (ca 11000 cal yr BP) the water level of Lake Juusa was higher than today. Intensive meltwater infiltration followed leading to the lake level drop of ca 10 m resulting in the lowest water level around 8500 cal yr BP (Punning et al., 2005; Terasmaa, 2011; Puusepp 2011). In Lake Juusa the water-level started to rise again since 8500 cal yr BP (Punning et al.,

2005; Terasmaa, 2011) and also in some other lakes of Baltic region and Sweden (Saarse & Harrison, 1992) caused by the humid conditions during that period (Saarse & Harrison 1992; Yu & Harrison 1995; Dearing 1997; Eronen et al. 1999; Ojala & Saarinen 2002). At the same time several papers (Seppä & Poska, 2004; Antonsson et al., 2008; Seppä et al., 2009) describe the climate in ca 8000-4000 cal yr BP as warm and dry. Also Stansell et al. (2017) argue about the wetter and dry conditions of that time period in the Baltic region based on the stable isotope records of Lake Nuudsaku (South Estonia). They suggest that there was spatial and seasonal heterogeneity in precipitation patterns. However our research in Latvia in Lake Kõži (Vidzeme Heights, Central Latvia) show the lake water-level rise in the early Holocene (11700-8200 cal yr BP) reaching its maximum between 8000-7000 cal yr BP and being stable after that for several millennia (Terasmaa et al., 2013). Also in Northern Estonia in Lake Viitna the water level rose 6-7 m in the early Holocene (Punning et al., 2003). In Lake Juusa small water-level lowering occurred 3300 years ago when according to Saarse & Harrison (1992) and Yu & Harrison (1995) the climate was drier. In Lake Kõži the water-level lowering started ca 2000 cal yr BP when also the clear human impact is detected (Terasmaa et al., 2013). In Lake Viitna the water level has fluctuated extensively and several times during the last 8000 years with the maximum level in ca 3300 cal yr BP (Punning et al., 2003).

When comparing the pollen diagrams of Lake Viitna (North Estonia), Lake Juusa (South Estonia) and Lake Kõži (Central Latvia) (Koff & Kangur, 2003; Kangur, 2005; Terasmaa et al., 2016) we can conclude that in the period ca 11 000-10 000 cal yr BP *Betula*, *Pinus* and *Poaceae* species were dominating, referring to a semi-opened landscapes. During that period the climate was very variable with warmer and colder periods. Afterwards the landscapes became more forested as proportions of *Corylus*, *Ulmus* and *Alnus* rose. While in the southern study sites (Juusa in South

Estonia and Kõži in Central Latvia) (Kangur, 2005; Terasmaa et al., 2016) the *Picea* pollen was already represented around 10 000 years ago, in Northern Estonia (Lake Viitna) it appears not until 6000 years ago (Koff & Kangur, 2003). The percentage of pollen of the *Tilia* has significant rise in 8300 cal yr BP in all three study sites. While the pollen of *Quercus* appears in Lake Juusa and Lake Kõži lake sediments at almost the same time as *Tilia* pollen, in Lake Viitna the *Quercus* pollen appears with a 2000 year delay (ca 6300 cal yr BP) (Koff & Kangur, 2003). During the last 10 000 years the mean annual and summer temperatures were highest in the middle Holocene (middle Holocene is defined as period between 8200-4200 cal yr BP) (Antonsson & Seppä, 2007; Heikkilä & Seppä, 2010). After the thermal maximum (since ca 5000-6000 cal yr BP) the cooling started and lasted to recent centuries. Since 3000 cal yr BP the *Picea*, *Pinus* and *Betula* are the dominating tree species (Koff & Kangur, 2003; Kangur, 2005; Terasmaa et al., 2016). About 2000 cal yr BP in the southern areas and around 1000 cal yr BP in the Northern Estonia we can detect the human impact indicated by the rise in the proportion of *Secale* and *Poaceae* pollen (Koff & Kangur, 2003; Kangur, 2005; Terasmaa et al., 2016). This implies more exposed catchment areas as agricultural landscapes, which in turn can cause the disturbances and erosion on the catchment and hence affect also the lake ecosystems. According to the results of diatom analysis and sediment lithological composition analysis we can roughly say that during the Holocene the trophicity of the lakes tend to change from the state of low productivity to higher productivity. One indicator of human activity e.g. landscape openness is also charcoal particles representing a clear sign of forest clearance by fire. In Lake Kõži the charcoal particles are found in some sediment layers since 2000 cal yr BP (Terasmaa et al., 2016) and in Lake Juusa already since ca 6000 cal yr BP (more abundant between 1500-3000 cal yr BP) (Kangur, 2005).

Period of intense anthropogenic impact

Along with the industrial revolution the capability of humans to affect the natural environment has increased exponentially. The intense mechanised agriculture, introduction of various chemical compounds and increased consumption of natural resources (Puusepp et al., 2015; Vaasma et al., 2015a) has taken its toll on the Estonian lakes as well. Several of our studies have focused on the lakes which have gone through shifts in their ecological state due to human impact. These studies serve several purposes. For one, to establish the consequences and mechanisms how the human activity has influenced the lake ecosystems. Secondly, to understand how the human stressor and shifts in the lake ecosystems are stored in the sediments as paleoecological information, enabling us to estimate the extent of pre-historical events. Furthermore, to determine the pre-stressed ecological status of lake ecosystem and to evaluate if the shift back to the natural state would be possible. Hereafter we give an overview on four case studies. Each of the studied lakes have a different background of anthropogenic impact varying from oil-shale mining to a faulty lake-management measures.

Lake Verevi, effect of urban wastewaters

Lake Verevi is a small lake located in southern Estonia alongside town Elva. It is an example of impact of increasing population to lake ecosystem due to urban waste waters and intensive recreational activities. The region around the lake was sparsely populated until the opening of the railway in the 1880s and establishment of the town Elva. Since the beginning of 20th century the lake monitoring has shown a steady increase in trophic status. During the 1970s and 1990s, the lake was contaminated by irregular discharge of urban wastewaters, resulting in hypertrophic state in 2000s characterised by significant increase in algal productivity and strong cyanobacterial blooms (Kangro et al., 2005). In be-

ginning of the 2000s several lake remediation measures were applied.

The paleolimnological studies give us further insight to the processes taken place in the lake ecosystem. Cladocera remains (water fleas), green algae remains, oxygen isotopes and fossil pigment indicators of total productivity and of cyanobacteria reveal that the lake experienced a period of eutrophication already in the 19th century, prior the historically recorded changes (Koff et al., 2016; Mikomägi et al., 2016). Fossil pigment concentrations and number of Cladocera species indicative of eutrophication remained relatively high during the whole interval from the 1880s until the late 1970s. This may imply that the historical monitoring data may have underrepresented the anthropogenic eutrophication. Starting from 1970s the concentration of fossil pigments rise abruptly peaking around 1990s, corresponding to the hypertrophic state of the lake. The increased productivity also resulted in the authigenic precipitation of lake marl due to the intensive photosynthesis (Vandel & Koff, 2011). The sediment records also reveal the first signs of possible recovery after the remediation measures in 2000s. The concentration of fossil pigments and Cladocera species indicative of eutrophication show decreasing trends (Koff et al., 2016). But as the period of improved ecological conditions has been relatively short in lake Verevi, it is too early to give any thorough evaluation on the possible recovery of the lake ecosystem.

Lake Lohja, effect of an unsuccessful lake management

Lake Lohja, located in the northern Estonia, is an cautionary example of lake mismanagement. Initially a clear- and soft-water small lake featuring rare *Lobelia dortmanna* L. (figure 9) has gone through a shift in ecological status towards worsening. In the late 1960s the lake rapidly transitioned to an algal dominated turbid state (low water transparency). Changes occurred shortly after the lake management measures were carried out

in 1963–64 when toxic pesticide (bicyclic terpene) and liming with oil-shale ash was applied to turn the lake conditions suitable for sea trout farming. The experiment was deemed unsuccessful as the introduced trouts did not adapt and the initial fish population perished and was replaced by carp. Strong cyanobacterial blooms and fish decimation followed (Mäemets 1968).

Figure 9. *Lobelia dortmanna* L., water lobelia. A rare oligotrophic lake species, left on a dry land after a water level drop in lake Valgejärv, Kurtna Lake District area. (photo: J. Terasmaa) (p. 201).

The paleolimnological studies were carried out in order to test the hypothesis that the unsuccessful lake management measures caused the deterioration of lake ecosystem. Surprisingly, the palaeoecological data revealed that the shift towards higher trophic state started considerably earlier (Koff et al., 2016; Marzecová et al., 2017). Pigment and Cladocera indicators show ecological deterioration already in the late 1930s, referring to an abrupt transition to eutrophic and algal-dominated ecological state (Koff et al., 2016). Simultaneously, the increase in titanium indicates an increase in soil erosion (Marzecová et al., 2017). This gives the basis to impeach possible changes in the catchment. The cartographic analysis of the historical maps of the catchment area reveal various land-use changes in the 20th century: intensification of the drainage system (1930s and 1980s), deforestation (in the 1940s) and the opening of the clay quarry with an inflow to Lake Lohja (mid-20th century–1990) (Koff et al., 2016). Evidence at hand suggests that although poor lake management might have worsened the ecological status of the lake, the primary drivers for the eutrophication and algal blooms have been the land-use changes in the catchment, which have been a constant source of nutrients and turbidity from eroded particles. The gradual loss of wetlands and increase of ditches in the catchment have had a more significant effect on

the lake ecosystem compared to the direct, but brief impact of chemical lake manipulation. The study highlights the importance of catchment land-use and disturbance by ditches in changing the ecology of small lakes (Marzecová et al., 2017). The paleolimnological data shows no signs of recovery back to the earlier natural stable state in case of lake Lohja.

Lake Martiska - effect of extensive groundwater extraction

Lake Martiska is located in eastern Estonia in a controversial area where pristine lake district with several Natura 2000 Habitat lakes is surrounded by heavy industry ranging from oil-shale mining and peat excavation to ground-water extraction (detailed information in chapter/article ...). Latter is considered as the main factor affecting the lake Martiska. The groundwater extraction (intake wells established in 1970s) led to a huge water-level drop up to 3.8 meters meaning a 80 % loss in lake-water volume. This lead to a loss in rare macrophyte species characteristic for oligotrophic lakes: *Isoëtes lacustris* L., *Sparganium angustifolium* Michx and *Lobelia dortmanna* L. (Vandel et al., 2016).

The severe ecological consequences left aside, the water-level lowering and latter partial recovery offered an ideal opportunity to study if the event was recorded as paleoecological markers in the lake sediments. We tested two methods: mineral grain-size distribution and macrofossil analyses. In case of mineral grain-size distribution the water-level fluctuation left clear signals to the lake sediment: water-level drop caused the transportation of coarser material to the deeper areas of the lake. With the restoration of water-level finer materials started to accumulate again (Punning et al., 2006, 2007; Vaasma et al., 2015b). The macrofossil analysis did not prove to be as informative. The overall number of macrofossils were low and mainly of terrestrial origin. No detectable shifts in macrofossil assemblages were present in the four sediment cores that were analysed

(Kaljuvee, 2015). As the population of aquatic macrophytes is abundant in lake Martiska (Vandel et al., 2016), the reason for low number of macrofossils can be the intense decomposition processes that can also continue after sedimentation of organic material (Vandel, 2010). When it comes to possible restoration of previous lake ecosystem with the recovering water-level there are no positive signs so far. The rare oligotrophic species have until now not yet re-appeared (Vandel et al., 2016).

Lake Nõmmejärv - effect of oil-shale mining discharge water

Lake Nõmmejärv is situated in the Kurtna Kame Field, eastern Estonia, in the Kurtna landscape conservation area and is one of the NATURA 2000 habitat lakes (longer description of the area and historical situation is presented in article/chapter ...). It is a small hard-water lake with a complicated history in terms of ecology: heavily influenced by discharges of alkaline oil-shale mine waters through an artificial Raudi channel since 1972. Slight anthropogenic impact had already started earlier: an army camp was founded in the vicinity of the lake around 1930s (Marzecová et al. 2011). To date, the overall ecological status of the lake has been evaluated as good.

The signal representing the inflow of mining water from Raudi channel is represented clearly in the lake sediment as an abrupt increase in minerogenic material (Koff et al., 2016). Major shifts in sediment chemistry and pigments point to alterations in the sedimentation regime as well as in the ecological status. The increased pigment concentrations during the 1980s suggest temporary peaks in total productivity. Paleoecological data suggest that prior the artificial inflow, the overall lake productivity has been lower, although there are some indications of cyanobacterial groups (Koff et al., 2016). Starting from the 1990s paleodata shows an steady increase in lake productivity. The artificial inflow and increase in lake productivity has also lead

to the authigenic precipitation of carbonates showing an abrupt increase since 1970s. Recently the amount of artificial inflow has decreased and is estimated to decrease even more due to closing of some parts of oil-shale mines (Terasmaa et al., 2014). Sedimentary analysis have shown a high amount of phosphorus (an essential and limiting nutrient for primary production) in the lake sediments while the concentration in the water is low (unpublished data). With the decreasing through-flow of water and increased primary production there is a slight risk that the lake can become periodically anoxic leading to release of phosphorus from the sediment, which in turn leads to higher lake productivity. Therefore, even though the lake monitoring shows good ecological status, the paleolimnological data advise caution, by pushing the limits of lake ecosystem a shift in the stable-state can occur.

Conclusion

The paleolimnological studies carried out in the Institute of Ecology at Tallinn University have provided insight on the development of

the small lakes and environmental changes in the Baltic region. During the Holocene the lake levels have been fluctuating widely. It is hard to point out certain pattern for all studied lakes. This suggests the importance of local conditions. After the retreat of continental ice sheet, *Betula*, *Pinus* and *Poaceae* species were the first to dominate. Afterwards, the proportion of other deciduous trees like *Alnus*, *Ulmus* and *Tilia* etc increased. During the last millennia intensified deforestation and agriculture have left their mark on the landscapes. In the last few centuries, the human impact on the lakes has become even more severe. Several lakes, once inhabited by rare oligotrophic macrophytes, have gone through changes in their ecological status. The loss of rare species and deterioration of lakes ecology may be irreversible as the lakes have shifted to different stable states. Still, in some cases, paleolimnological data shows signs of recovery as the anthropogenic stress has decreased during recent decades.

References (p. 204)