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Estonia, the land of lakes

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Version française p. 176

Abstract

Around 4.8% of the territory of Estonia is covered with standing water bodies - in total over 110 000 objects. Natural lakes are one of the smallest group (1 562), exceed by ponds (51 780) and bog pools (45 309) by order of magnitudes. Same time only 51 on of standing water bodies are bigger than 1 000 000 m² (100 ha), most of those are natural lakes, and only seven are man-made. Distribution of standing water bodies are not spatial even – normally uplands have more lakes and ponds, in the lower part of the country bog pools are more abundant. In Estonian natural lakes are formed during the retreat of the continental ice, are mostly of thermokarstic origin and offering valuable material for paleolimnological reconstructions. During the Holocene, lakes have gone through very different water-level and development stages (varying characteristics of the basin, sedimentation dynamics and ecosystem properties) and as a result, those stages could be considered and compared as of entirely different water bodies. For understanding the current status of the standing water body, we must know the development scenario. In landscape, small water bodies are forming a network, that plays an important role in the human well-being and providing ecosystem services. Collectively, most of the terrestrial-aquatic interface is in small standing water bodies. This zone is considered as

Dynamiques Environnementales 42

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Lake nearby Vihula (Photo: Teddy Auly).

one of the most productive habitats. Numerous authors have been demonstrated, that small standing water bodies combined support more freshwater species than rivers or big lakes. Lake Peipsi is 4th largest in Europe, but as its shoreline length is only 800 km, it takes around 23 000 smallest Estonian standing water bodies to exceed this number. That means that it is essential to start valuing small water bodies.

Key words

Standing water body, natural lake, pond, bog pool, lake development.

Introduction

Estonia is often described as the land of lakes and water bodies are considered one of the country's most valuable natural resources. There are natural lakes in different types and sizes scattered all over the country from coastal lakes to lakes in small forest hollows in our heights in Southern Estonia. As lakes vary by genesis and development, they have several categories and classes, many of them quite rare and valuable in European level. Natural lakes are not the only

type of standing water bodies in Estonia - in fact, if we consider the abundance of water bodies, natural lakes are forming one of the smallest group. There are numerous bog-pools and different kind of man-made water bodies, which numbers are exceeding the natural lakes by two orders of magnitudes. As typology of different standing water bodies are internationally quite confusing and every country has their approach, it is quite often not directly comparable in EU or global level. One thing is clear - standing water bodies are important and valuable not only as ecosystems, freshwater reservoirs and carbon sinks, but they have also been part of everyday life and culture already very long time, offering for us number of vital ecosystem services.

Why Estonia has natural lakes and how we know it?

The territory of Estonia is 45 339 sq km², of which around 4.8% is standing water bodies. Estonia belongs to the Boreal region and is characterised by a flat surface topography: over 60% of the country's territory lies at an absolute height of 0 to 50 metres (Raukas and Teedumäe 1997). The majority of Estonian natural lake basins formed during the retreat of the continental ice and are of thermokarstic (/glaciokarstic) origin. It means that the subglacial interhill depression isolated an ice-block, which became covered with sediments.

At the beginning of the Holocene warmer climate gradually melted the buried ice-block and formed depression, quite often covered with the peat layer, upon which the lake sediments began to accumulate after sinking of the surface (Terasmaa et al. 2014). Thermokarst lakes are widespread across circumpolar regions and are generally shallow, not deeper than 10 m (Bouchard, 2016). As numerous studies have shown (e.g. Andreev et al. 2005; Kabailiene 2006; Terasmaa, 2014), as thermokarstic lakes are formed gradually over a long period, the process may be bidirectional - the depth of

the lake basin is a function of sinking bottom and rising water-level. Nowadays Estonian lake basin is half-filled with lake sediments and are rather shallow, ca 75% of them have a water depth of less than 10 m (Ott and Kõiv 1999).

Despite their relative shallowness, sediments of Estonian lakes are rich sources of paleoenvironmental information. Lakes are dynamically responsive systems that can integrate environmental and climatic changes into a continuous, high-resolution sedimentary archive of the local and regional level (Terasmaa, 2005). Every particle that has reaches the lake and accumulates into the sediment can be regarded as a carrier of information about its origin and pathways. As to its source, the material deposited in lakes is either autochthonous (formed in situ) or allochthonous (transported into the lake from outside) (Håkanson & Jansson, 1983). The amount of matter accumulated yearly depends on water depth – the deeper an area is located, the higher the amount of deposited matter usually is. However, this information is available only from a certain level of generalisation. As it has been shown by Terasmaa et al. (2013) the main factors affecting the development of the lake and sedimentary signals throughout the Holocene can change in time. With time the general role of the climate can decrease (the role of environmental influences is rising). Changes in sedimentary signals are caused by local factors (morphologic structure of the catchment area, lithology of the bedrocks, genesis and shape of lake depressions, the intensity of the water cycle, the position of the subsoil water level, etc.) and during the last millennias by human activities.

For formation of the lake, not only suitable basin but also water is needed. From the ecosystem point of view, water is the most crucial part of the lake. Without the water or under significant lake-level changes gaining the stable and healthy lake ecosystem is not possible, so the mechanisms affecting the formation of the amount of water in

lakes have to be well understood (Vainu, 2018). In stable conditions (climatic and hydrogeological) the water volume in the lake should be in an equilibrium state (Street-Perrott & Harrison 1985) - it may fluctuate annually, but the long-term average volume must be stable. Numerous palaeostudies (e.g. Digerfeldt 1986; Yu & Harrison 1995; Korhola et al. 2002; Punning et al. 2005; Terasmaa et al. 2013; Stansell et al. 2017) indicate that lakes have gone through significant lake-level changes in the past. The long-term average (equilibrium) volume of a lake may fluctuate because of changes in catchment properties (vegetation, soil, topography), climatic or hydrogeological conditions (Vainu, 2018). When the main impact factor stabilises, the lake volume reaches a new equilibrium state. The amount of water in a lake is determined by the balance of water inputs and outputs. Inputs are all related to the precipitation (on the lake surface or the lake catchment), runoff from the catchment and seepage from groundwater. Of course, not all of the precipitation falling on the lake catchment reaches the lake, as it is reduced by canopy interception, storage in the soil, evapotranspiration from the vegetation and evaporation from bare soil (Vassiljev, 2007; Vainu, 2018). Water output is surface water discharge, evaporation from the lake surface and seepage into groundwater. Surface water outflow depends on the shape of the lake basin; evaporation depends on climatic parameters and groundwater seepage on the groundwater level around the lake and lake basin hydrogeological properties (Vainu, 2018).

Reconstructed development of Lake Väike Juusa (southern Estonia) during the Holocene with the help of 3D digital elevation models for the paleolake stages (at 9000 BP, 8000 BP, 6000 BP, 4000 BP, 2000 BP and the present) suggested that during the different water-level stages lakes must be considered as entirely different water bodies with varying characteristics of basin, sedimentation dynamics and ecosystem properties (figure 1; table 1) (Terasmaa, 2011; Terasmaa, 2013).

Figure 1. Reconstructed palaeobasins of Lake Juusa (at 9000 BP, 8000 BP, 6000 BP 4000 BP, 2000 BP and present) (after Terasmaa 2011, Terasmaa 2013) (p. 180).

Table 1. Characteristics of the reconstructed phases of the lake basin (after Terasmaa 2011, 2013) (p. 181).

At the beginning of the Holocene (10000–9500 years before present (BP)), the water level was highest, flooding surrounding lowland in the southwest. Around 8000 BP lake level was fell to its known minimum. A similar pattern in water-level changes is noted in other lakes in northern Europe and in the territory of former Soviet Union (Yu and Harrison, 1995; Yu, 1998). Since that time, the level of L. Juusa has increased continuously to the present level, the settling of fine-grained matter sealed the basin and sediment layer started to grow. The lake level reached its first peak at 4000 BP. Based on the composition of basal sediments, it seems that evaporation and infiltration might have exceeded precipitation at that time, leading to a negative hydrological balance in the lake and a reduced water level. Another slight increase in the lake level took place between 3000 and 2000 BP when lake level reached its maximum, followed by a sharp decrease and continuous increase, which brought the lake level up to the current state (Terasmaa, 2011).

As data on figure 1 and in table 1 affirms, during every development state Lake Juusa was the utterly different living environment, as lake depth, size, basin morphometry and every other parameter differed. It means that same time area of the littoral zone, nutrient budget (due to a reworking of sediments), stratification and mixing pattern etc. was probably also different.

How to understand lake development and status?

Thus, for an understanding of the lake ecosystem development and reasons behind the current status, we must take into account a large number of variables and their interaction, in different spatial-temporal scales. One way to describe the palaeogeographical approach is to use the so-called Doctrine of Uniformity (uniformitarianism). Uniformitarianism was first considered by the British geologist James Hutton, who formulated the general idea of this principle as early as 1788: "No vestige of a beginning, no prospect of an end" (Hutton, 1788). The idea of James Hutton was made popular by the book "Illustrations of the Huttonian Theory of the Earth", published by the Scottish mathematician and geologist John Playfair in 1802, which, in turn, was picked up and further developed by the British geologist Charles Lyell in his three-volume essay *Principles of Geology* (Lyell, 1830, 1832, 1833). That the reason why he is sometimes wrongly considered to be the founder of uniformitarianism. Formulations of the principle in its most famous form were made by his student, British geologist Archibald Geikie, as follows: "The present is the key to the past" (Geikie, 1905; Oldroyd, 1980). To understand the complexity of this doctrine we can break it down to the four principles (figure 2).

The principle of cause-consequence adequacy means that for understanding differences between at first sight similar lake ecosystems (lake 1 (L1) and lake 2 (L2) in figure 2a) interrelationships between causes and consequences of possible events (f1-f4) should be described and the dominant influence factor (F2, F3) defined. Only in this way it is possible to understand changes in the past and predict the further development of the lakes. Different ecosystems can achieve a very close state as a result of various influencing (f1-f4) - this is referred to as the principle of hierarchic correspondence of external factors (figure 2b). The number and significance of the external or internal

factors can differ, therefore the development history of the lake also. This phenomenon can be described with the concept of similarities - systems with common characteristics will have more likely similar features (even identical development history), than systems without any similarities. For a direct comparison of the different system, there must be similarities in the development of the system - this follows the principle of similarity of development paths (figure 2c). Even if at a current moment ecosystems are with equivalent energy flow and matter cycle, it is essential to know the development path (hence $L1! = L2 = L3$, since L1 has had more development stages). This leads to the principle of similar natural conditions (figure 2d). Causal correlation is transferable only if the energy flow (E1, E2) and the matter cycles (C1, C2) have been similar. Therefore, to apply the known relationships of one ecosystem for describing processes or relations in another ecosystem, the knowledge about both system functions and development paths has to be available (Punning, 1991, Terasmaa, 2013).

Figure 2. Principles used in palaeolimnology (after Punning, 1991 and Terasmaa, 2013). The principle of cause-consequence adequacy (a), the principle of hierarchic correspondence of external factors (b), the principle of similarity of development paths (c), the principle of similar natural conditions (d). L1, L2, L3 are hypothetical lakes and their development stages, f1-f4 are the impact factors (F - main impact factor), E1-E2 are energy flows, C1-C2 are matter cycles (p. 181).

Natural lakes in Estonia

In the territory of Estonia, there is a total of 1562 natural lakes, of which 1238 are bigger than 10 000 m² (1 ha) (ETD2017). The largest lake in Estonia is Lake Peipsi (354307 ha, shared with Russia, 4th biggest in Europe), followed by Lake Võrtsjärv (26919 ha) in central Estonia. Those two lakes make up around 95% of the total area of Estonian

natural lakes, which means that most of the lakes are very small.

As the majority of lake basins is formed during the end of ice-age, they are more abundant on uplands, especially in southern Estonia (Haanja, Otepää, Sakala, and Karula Heights), but also in Vooremaa (figure 3). Pandivere Heights is different and has only a few lakes. One of the highest density of lakes are in a North-Eastern part of Estonia (Kurtina Lake District), but also North-Kõrvemaa has many lakes in rather a small territory (Aegviidu and Jussi lakes). On West-Estonian low coasts of mainland and islands are numerous coastal lakes formed due to land uplift and sediment transportation (former bays).

Figure 3. Natural lakes. Every dot represents one lake (ETD2017) (p. 183).

Estonian lakes are mostly shallow (only 20 of them are deeper than 20 m). Deepest lake is Lake Rõuge Suurjärv (38 m), followed by Lake Väike-Palkna (31.9 m) and Lake Udsu (30.2 m) (EELIS, 2018).

The fauna of Estonian lakes is rich, especially among invertebrates - about 2000 species are described. Most species-rich invertebrate groups are insects (~750 species), crustaceans (~233 species) and arachnids (~210 species). About 50 species of fish are known to live in Estonian lakes, in Lake Peipsi alone 36 species are described. There are 11 species of amphibians in Estonia, the common frog is the most common Estonian amphibian, but crested newt, smooth newt, common toad and moor frog live almost everywhere in Estonia also. Over 100 species of birds are seen on lakes, around 40 of them are nesting birds. Most common mammals are beaver, otter and water vole. Over 100 species of vascular plants, tens of water mosses and various algae species are described in Estonian lakes. According to the status of the aquatic biota, hydromorphology and water quality lake's

ecological status is assessed. In Estonia 90 lakes are defined as bodies of surface water and are under continuous monitoring. One of the goals of the Water Framework Directive is to achieve for all lakes good status, but unfortunately, it is not so. In 2016 only 45% of the monitored lakes were in very good or good ecological state. The status of water bodies is assessed based on monitoring data which is usually carried out with a six-year rotation cycle. This means that most of the bodies of water are observed every six years. Only a small proportion, so-called reference water bodies, are observed every year or with a three-year rotation cycle (EEA 2018).

Standing water bodies of Estonia - not only lakes

Estonia has not only natural lakes but several other types of standing water bodies: bog pools (formed in the surface depressions of raised bogs), man-made reservoirs, farm ponds, fish ponds and so on (figure 4).

Figure 4. Standing water bodies in Estonia (ETD 21017) (p. 184).

The problem is, that definition of the different types of water bodies in smaller size-classes (e.g., is it a lake, pond, or kettle hole?) tends to be country-specific with no universal definition of the size or even genesis. The term "pond" is often used in a more general sense and could describe both natural and artificial SWBs (Pätzig et al. 2012), or as in Estonia, strictly meaning only artificially made small standing water bodies. Different authors have set various lower and upper limits for the surface area of ponds. Lower limits range from 1 m² to 1 000 m² (Biggs et al. 2005; Oertli 2013; Bartout 2015) and upper limits from 10 000 m² to 2 000 000 m² (Jedicke 1989; Céréghino et al. 2008; Oertli et al. 2009). In EU level, the small standing water bodies have been disregarded in the environmental protection policies and are even absent from state-level inventories. The border between small and "mentioning-worth" standing water bodies is

quite hazy - it can be $<100\,000\text{ m}^2$ (Meybeck, 1995), $<10\,000\text{ m}^2$ (Ryanzhin, 2005), or even $<500\text{ m}^2$ (Kuusisto and Raatikainen, 1988). According to the analysis of the OpenStreetMap (OSM) database by Bartout et al. (2015), the total number of standing water bodies in all EU countries is estimated to be ca. 1 million. At the same time, they concluded that to achieve genuinely reliable estimates, each geographical region requires a specific function adapted to its hydrological characteristics. The problem is that models for large-scale and global inventories are not designed for estimating the relative abundance of small SWBs, mainly because of technical limitations. In example detection limit using LIDAR-based methodologies is $\sim 2\,000\text{ m}^2$ (Toscano et al. 2014) or even higher ($8\,000\text{ m}^2$ according to the USGS (Heidemann 2012)) and same goes with other recent attempts to count all standing water bodies (detection limit was $2\,000\text{ m}^2$ in Verpoorter et al. (2014) and $5\,000\text{ m}^2$ in Feng et al. (2016)).

Estonian Topographic Database by the Estonian Environmental Agency is based on the topographic and orthophoto maps and contains over 111 000 standing water bodies (table 2).

Table 2. Standing water bodies (SWBs) in Estonia (statistics without Lake Peipsi) according to the Estonian Topographic Database (ETD2017) (p. 185).

Estonian database distinguishes between lakes, reservoirs and artificial lakes, bog pools, ponds and bioponds, but there are also two less clear categories - "unspecified" and "other". The current minimum mapping size is considered to be 20 m^2 (100 m^2 for bog pools), but it also contains smaller objects.

Table 3. Categories of standing water bodies in Estonia (without L. Peipsi, L. Võrtsjärv and Narva reservoir) (ETD2017) (p. 185).

As data shows (figure 5; table 3), Estonian standing water bodies are strongly dominated by tiny ones. Small size does not mean, that they are not important - quite the other way around. Small standing water bodies (below 0.01 km^2) are more heterogenic than large water bodies when it comes to the surface area, and they are forming an essential element for landscape biodiversity. Small water bodies are forming a network, that plays a vital role in providing major ecosystem services (flood prevention, water storage, carbon sequestration etc.); but also improved well-being for humans (Hill et al. 2018). Even bog pools, which are less diverse, often support rare plant and animal assemblages. It has been demonstrated, that small standing water bodies combined support more freshwater species than rivers or big lakes (Biggs et al. 2005; Oertli et al. 2009). Collectively, most of the terrestrial-aquatic interface (perimeter) - some of the most productive habitat - is in small SWBs (Verpoorter et al. 2014). This is clear also in Estonian case (figure 5, table 3) - ponds and bog pools are dominating in the database if we look the perimeter.

Figure 5. Categories of standing water bodies in Estonia (without L. Peipsi, L. Võrtsjärv and Narva reservoir) by total count, area (m^2) and perimeter (m) (ETD2017) (p. 186).

Distribution of bog pools, reservoirs, artificial lakes and ponds (figure 6) reveals that they are spatially heterogeneous because different types have a different origin. Bog pools are numerous (45 309), but this significant number is not visible on the map - markers are stacked as they are very close to each other on small territories. Still, bog pools are underrepresented in the Estonian database. They are tiny (median size is 211 m^2) and disappear and appear due to natural processes faster than natural water bodies in the mineral ground. One reason behind the disappearance of bog pools can be related to the drainage of the wetlands

since the 19th century and still ongoing process, so the current bog pools are remnants of former abundance. Reservoirs, artificial lakes and ponds, as man-made water bodies, also comprise a significant proportion of the small size classes. In total, man-made water bodies are slightly exceeding the number of natural standing water bodies. Still, the natural water bodies are forming the majority of the total area (figure 6, table 3), in the example, only 8 have an area over 100 ha. It is important to note that in Estonia protected species inhabit over 2000 small standing water bodies outside of the protected areas.

There are in total 51 standing water bodies bigger than 100 ha in Estonia. Comparison of the area with perimeter (shoreline length) (figures 7; 8) shows that there is no clear relationship between those two parameters. Most of the water bodies are bunched together in the same sector (area <300 ha and perimeter <13 000 m).

Figure 6. Abundance and distribution of standing water bodies: (a) bog pools, (b) reservoirs and artificial lakes, (c) ponds and (d) uncategorised. Every dot represents a single water body. (ETD 2017) (p. 186).

Figure 7. Standing water bodies bigger than 100 ha VS their perimeter (m) (without L. Peipsi, L. Võrtsjärv and Narva reservoir). Green dots are natural lakes; yellow dots are man-made water bodies (p. 187).

Figure 8. Locations of standing water bodies bigger than 100 ha (without L. Peipsi, L. Võrtsjärv and Narva reservoir). Green dots are natural lakes; yellow dots are man-made water bodies (p. 187).

One of the biggest lakes in Estonia (after Lake Peipsi, Lake Võrtsjärv and

Narva Reservoir) - Lake Ülemiste - has average perimeter and three times smaller lake - Lake Endla - has the longest perimeter in this dataset (figure 9). As the figure shows the reason behind this is the shape of the water body and the complexity of the shoreline. If we calculate shoreline index as suggested by Hutchinson (1975), we can also see that Lake Ülemiste has one of the smallest value (1.5) and Lake Endla one of the highest (4.7).

Figure 9. Comparison of the Lake Ülemiste (a) and Lake Endla (b). Both maps are in the same scale (Estonian Land Board, 2018) (p. 188).

Conclusions

Estonia is the land of lakes, but not only - other types of small standing water bodies are significantly more numerous, forming all together density as high as 2.5 standing water bodies per km². In total Estonia has over 111 000 standing water body, only 51 on of them are bigger than

1 000 000 m² (100 ha). Median size is 266 m². The bulk of the small water bodies comes from bog pools and ponds categories. At the moment there are slightly more man-made water bodies in the database, but the balance is delicate, and bog pools seem to be underestimated because of their origin and fast rate of changes.

Nevertheless, small standing water bodies are essential at every level - as landscape elements, providers of the ecosystem services and keepers of the freshwater biodiversity. Individually they may be not species-rich, but as they are abundant and varied, the total number of species is higher than in one big lake can ever be. As they are numerous they also offering the highest amount of near-shore habitats. Lake Peipsi can be

4th largest in Europe, but with its ~800 km long shoreline, it takes only around 23 000 smallest water bodies (areas from 10 m² to 100 m²) in the database to exceed this number. That does not mean that bigger and natural lakes do not need protection, but that we should value small ones also.

Another important concept for understanding lakes (or all standing water bodies) is that they are in constant change due to a myriad of factors acting in different time-scales. Lake basins are filled with sediments over the course of time, changing the lake water volume and other properties of the lake. Water-level can change due

to the changes in climatic conditions, catchment properties or groundwater levels. The ecosystem is changing because of previously mentioned factors, but not only - human-induced changes (in hydrology, nutrients budget etc.) are quite often over-ruling the effects of natural ones and speeding up the shifts between equilibrium states. When changes are too rapid and one-directional, leading to the eutrophication, we need to take responsibility and find the way to stabilise the ecosystem to protect biodiversity and other essential ecosystem services.

References (p. 190)