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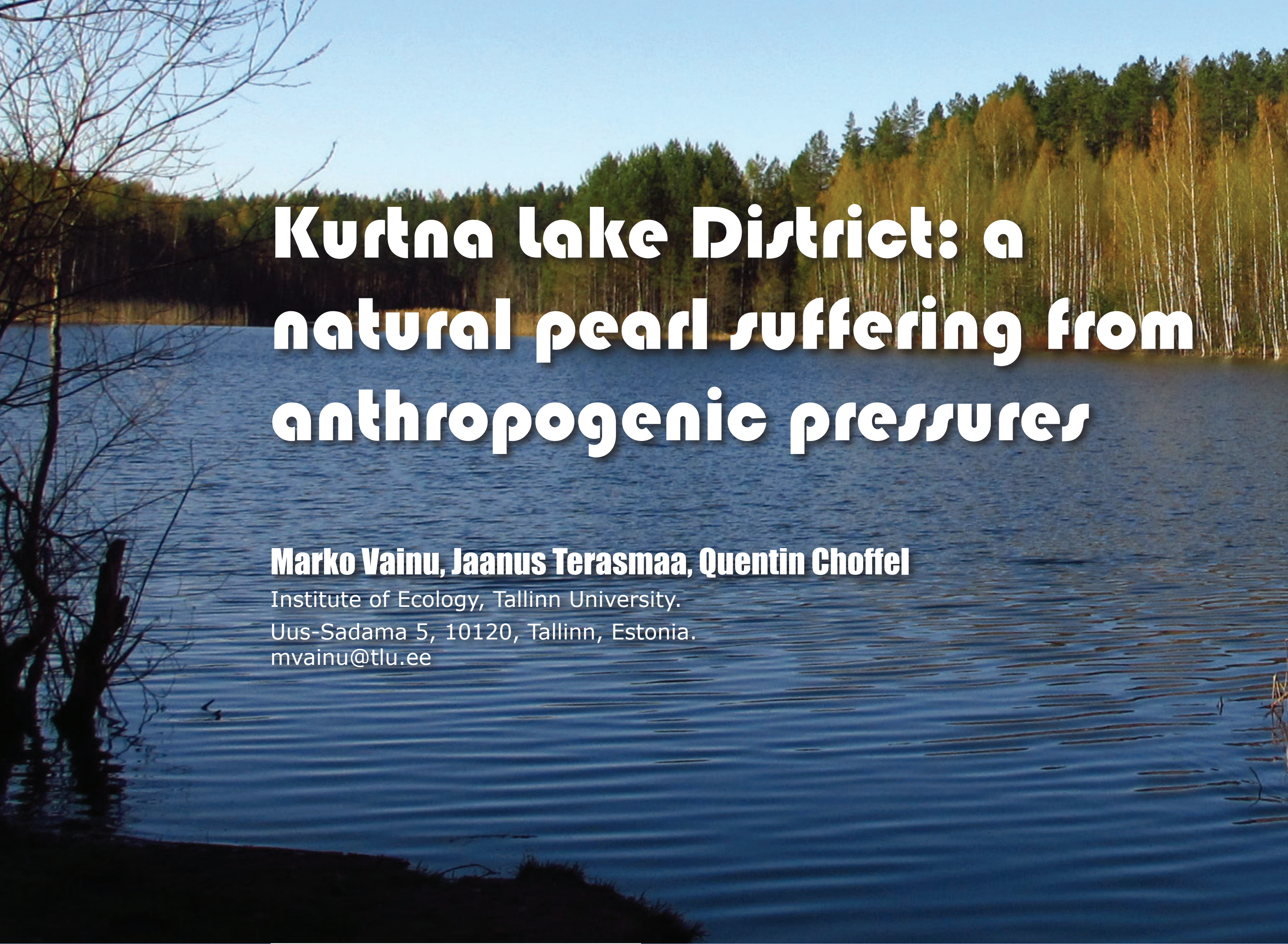

Kurtna Lake District: a natural pearl suffering from anthropogenic pressures

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Version française p. 208

Abstract

The Kurtna Lake District, situated in the northeastern part of Estonia, contains the largest number of lakes per km2 in the country – 38 natural lakes in a 30 km^2 area. The unique area fell under severe anthropogenic influence in the middle of the 20^{th} century and the influence has continued until the present day. Oil-shale, sand and peat mining, groundwater and surface water abstraction – all have been affecting the lakes in the district. Lake water levels have dropped, lake chemistries and consequently lake ecosystems have changed. For some lakes the effects have been larger, but some lakes have remained mostly unchanged. In 1987 a landscape protection area was formed, but that has not solved the problems. The lake district used to contain five rare clear water lakes with low nutrient and mineral content (L. Valgejärv, L. Liivjärv, L. Ahnejärv, L. Martiska, L. Kuradijärv). Nowadays, most of them have become significantly more eutrophic, because of water level decrease, but L. Valgejärv, with its preserved unique plant communities, is still considered to be one of the ecologically most valuable lakes in

A view of Lake Ahnejärv from the north (photo by Marko Vainu)

Estonia. The lake district also contains the only siderotrophic (iron rich) lake in Estonia – Lake Räätsma. Lakes Nõmmejärv and Konsu have had their water regime changed considerably. Lake Nõmmejärv accepts the inflow of sulphate-rich mine water and Lake Konsu has been turned into a surface water reservoir for an oil-shale processing factory. Lake Kihljärv on the other hand has effectively dried out in the recent years. At the same time, the picturesque Lake Saarejärv has remained largely unaffected. Therefore, the Kurtna Lake District is an area of great contrasts, partly it still resembles the pristine nature it used to be, and partly it is a sad monument for an overly eager consumption of natural resources.

Key words

Estonia, lakes, anthropogenic influence, Habitats Directive, water-level changes, groundwater abstraction, oli-shale mining, peat cutting, mine-water inflow, *Isoetes lacustris*, *Lobelia dortmanna*, sulphide formation.

Kurtna Lake District

In Estonia, the land rich of lakes, one of the most spectacular lacustrine landscapes is located in its northeastern part. The Kurtna Lake District is the largest lake district in Estonia. It consists of 38 natural lakes in a 30 km^2 area. The lakes range from very small (0.1 ha) to medium (146 ha) and are both hydrologically and limnologically very diverse. Most of the lake district is included to a national landscape protection area and part of it is also included to a European Union Special Area of Conservation (formed in accordance with the EU Habitats Directive – 92/43/EEC). Therefore it would seem that the unique landscape is well protected from any human-induced harm. The reality is unfortunately quite different. The lake district is surrounded and also penetrated by areas where various natural resources are utilised. That has a direct negative effect on the ecosystem of the lakes.

The lake district is situated in and around the Kurtna Kame Field, which consists of hillocks (kames) and small ridges that range from 40 to 70 m a.s.l and kettle holes between them (figure 1). Most of the landscape is covered with Scots pine forests with occasional birch groves in dry kettle holes and near the lake shores. The landscape was formed over the ancient Vasavere valley by a retreating ice sheet during the end of last (Weichselian) glaciation around 12 200 to 12 300 years ago (Karukäpp 1987). The kames consist of glaciolacustrine and glaciofluvial sands and gravel. The kettle holes between them have a glaciokarstic origin and were formed after partially buried ice blocks, left behind by the glacier, melted. Groundwater level rise caused many of the kettle holes to fill with water and the lakes were formed. The Kame Field is surrounded by paludified plains from the north, east and west and the Kuremäe terminal moraine from the south.

Figure 1. Morphology of the Kurtna Lake District, its anthropogenic influencers, and lake habitat types according to the Habitats Directive – 92/43/EEC (p. 211).

(p. 211)

The ancient Vasavere valley is an up to 80 m deep geological formation in sedimentary rocks. The crystalline basement in the area lies around 220-240 m below sea level and is covered by Ediacaran and Cambrian terrigeneous rocks and Ordovician carbonaceous rocks (Puura et al. 1987). The Vasavere valley cuts through the Ordovician rocks. The Ordovician limestone and oil-shale layers are separated from the sands and gravel by a discontinuous layer of till. The highly permeable sediments in the valley contain an unconfined Quaternary groundwater aquifer, which is partly separated from the Ordovician aquifer by the low-permeability till layer. The oil-shale layer in the Ordovician sediments is the main power source in Estonia, as more than 80% of the electricity is produced from oil-shale.

In addition to being the most lake-rich area of Estonia, the uniqueness of that specific lake district lies in the limnological types of lakes it contains or has contained. In the 1960s it was considered that five of the total of nine oligotrophic lakes in Estonia were in Kurtna (Mäemets 1966). Oligotrophic lakes contain very little nutrients, mineral and humic substances. That makes them very rare and also vulnerable to natural and, especially, anthropogenic stressors. In the present day, 18 of the nearly 40 lakes in the district are considered to be especially valuable and have been listed as important habitats according to the EU Habitats Directive (figure 1). Nine belong to the habitat type 3110 – Oligotrophic lakes containing very few minerals of sandy plains; two to the type 3130 – Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*; and seven to the type 3140 – Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. Some type 3110 lakes host plant species that are rare and under protection in Estonia – *Lobelia dortmanna, Sparganium angustifolium* and *Isoetes lacustris*.

Most of the lakes in the district are closed-basin lakes with no surface water inflow nor outflow. Lakes that have either surface water outflow or through-flow have been mostly modified by humans and were closed-basin lakes in their natural state as well.

History of human influence

Human influence in the lake district can be traced back to the middle of the 19th century, when some of the lakes were connected with ditches (Punning et al. 1997; Kivioja 2017). In the 1920s and 1930s an army camp operated near Lake Nõmmejärv and during World War II the pine forests in the central part of the Kame Field were burnt. Despite that, the lakes were more or less in a natural state until the 1940s.

In 1946 the first underground oil shale mine "Ahtme" was established northwest of the lake district (figure 1). As the oil-shale layer lies below the groundwater table, then in order to excavate it, the excess water has to be pumped out. Therefore the establishment of the Ahtme mine was the first action that affected natural groundwater levels and flow directions in the surroundings of the Kurtna Lake District. The closest the mine border was to the lake district was 400 m. In 2002 it was closed and refilled with groundwater.

In 1962, an open-cast oil-shale mine "Sirgala" was established east of the lake district (figure 1). It is still operating and has reached the distance of 500 m from the closest lake. The water level in that mine has been lowered more than 20 m (figure 2). Since the 1990s, the mining company is obliged to protect the lake district from draining into the mine by maintaining filtration ditches on the western border of the mine and by shielding the western slope of the mine with an infiltration barrier. The mining company has had trouble providing water for the filtration ditches during drier and, therefore, most important periods, though. For example, in the autumn of 2015 and spring of 2018 the filtration ditch was completely dry (figure 3).

Figure 2. Groundwater flowing into the Sirgala mine (photo by Marko Vainu) (p. 213).

Figure 3. Dry filtration ditch on the western border of Sirgala mine in May 2018 (photo by Marko Vainu) (p. 213).

In 1973, another underground oil-shale mine, called "Estonia", was opened southwest of the district. That mine is also operating nowadays. but currently the groundwater level lowering, caused by that mine, does not reach the lakes in Kurtna.

In 1948, an industrial surface water intake was established in Lake Konsu to supply a nearby oil-shale chemistry factory with technological water. To sustain the required amount of water in Lake Konsu, a channel system that connects 11 lakes was constructed from 1953 to 1963. Since 1970, mine water from "Viru" oil-shale mine, further in the west, was diverted into the main channel in the system – the Raudi channel (figure 4). Later water from the "Estonia" oli-shale mine was added as well. In the present day, nine lakes are connected to the channel system (figure 1) and only water from the "Estonia" mine is pumped into the Raudi channel. The average pumping rate in 2016 and 2017 was 550 l/s. Part of the water flows to Lake Konsu, but part of it passes the lake district, exits it in the eastern border and flows on through the open-cast mines in the east. The creation of the channel system caused a decrease of lake levels in all of the connected lakes and changed their water chemistry considerably. Most affected has been Lake Nõmmejärv, as it is the first to receive the mine water. Before sedimentation basins were built in the 1990s near the outflows of Viru and Estonia mines, Lake Nõmmejärv basically acted as a natural sedimentation basin. In addition to suspended matter, the mine water is also rich in sulphates. These could be reduced to sulphides in the pore water of the sediments and form toxic hydrogen sulphide or release phosphorus bound into sediments. Mine water inflow has already affected the functioning of Lake Nõmmejärv, but could potentially affect more significantly if conditions change (read further under the description of Lake Nõmmejärv).

Figure 4. Mine water flowing in the Raudi channel (photo by Marko Vainu) (p. 214).

In 1964 a peat milling field "Oru" was established east of the lake district (figures 1 & 5). Its main purpose was to make effective use of the resource before it was lost to the oil-shale mine. The drainage system of the milling field also lowered the level of nearby lakes. For example, the level of Lake Liivjärv dropped by 2 m from 1960 to 1975. Peat milling has continued and there are plans to speed it up. That way it would also be possible to mine the underlying oil-shale layer more quickly, let the groundwater table restore to its natural level and to finally end the decade-long consistent pressure from the lowered groundwater table on the lakes in the eastern part of the district.

Figure 5. Abandoned section of the peat milling field in the northern part of the district (photo by Marko Vainu) (p. 214).

Also in 1964, a sand quarry (Pannjärve) started operating in the centre of the Kame Field. It was established in the topographically most diverse part of the Kame Field. At first, the excavation took place above the groundwater table. Therefore it did not have any effect on the lakes, but since 1979 sand has been excavated below the water table with the use of hydropumping. The mining has continued and an artificial lake with the area of 45 ha has formed in the quarry (figure 6). The quarry has had some effect on the groundwater level and thus on the lake levels of the central part of the lake district. During the years of most active mining, considerable amounts of groundwater seeped into the quarry and more importantly, the large open water area of the artificial lake induces larger evaporation. On average 800 m^3/day of water evaporates from the surface of the artificial lake, which otherwise would remain as groundwater.

Figure 6. The artificial lake in the Pannjärve sand quarry (photo by Marko Vainu) (p. 215).

The latest and arguably the most problematic facility for utilising natural resources was built to the centre of the lake district in 1972. It is the Vasavere groundwater intake. The intake consists of 14 wells, from where drinking water for the nearby town of Jõhvi and some districts of Kohtla-Järve is being pumped. Currently, the maximum allowed pumping rate is 8000 m^3/day. The actual pumping rate has ranged from 4000 m^3/day at the end of 1970s and at the beginning of 2000s to 10 000 m^3/day at the beginning of 1990s (figure 7). Vainu (2018) has shown that the pumping has considerably affected the water-balance and water levels of the nearby lakes – especially lakes Martiska, Kuradijärv and Ahnejärv (read further under the description of the specific lakes).

Figure 7. Average annual pumping rates from the Vasavere groundwater intake (p. 216).

The rising conflict between the preservation of the natural landscape and the expanding utilisation of natural resources was first addressed in the 1970s, when limnologists started to demand taking the lake district under strict protection and banning all excavation and water abstraction activities in the vicinity of the district (Mäemets 1977). In 1977 a project was compiled to construct a system of infiltration basins, which would provide additional water for the groundwater abstraction plant (Metslang & Metslang 1977). It was planned to pump water from Lake Suurjärv into these infiltration basins. The project was not carried out, though.

In the middle of 1980s a thorough scientific investigation of various landscape elements of the lake district was completed and based on its results, the landscape protection area was established in 1987 (Ilomets 1987; 1989). Nevertheless, it did not stop any of the previously described activities affecting the lake district. Its most significant effect was that plans to excavate oil-shale even closer to the district, or even under it, or to pump even more water from the groundwater aquifer were put on hold.

In the first half of the 1990s a new environmental assessment on the effects of industrial production of the lake district was performed (Põder et al.... 1996). The assessment was co-financed by the USA Environmental Protection Agency. It gave suggestions for establishing monitoring networks and proposed measures for decreasing the anthropogenic pressures on the lake district. Again, most of the suggested measures stayed only on paper, largely because of the economical crisis that struck Estonia in the end of the 1990s.

In 2018 another research project was launched, which has to give the ecologically acceptable rate of human induced water-level fluctuations in the most valuable lakes in the district and the hydrogeological conditions (groundwater level and pumping rates) that have to be met in order to maintain these lake levels. It remains to be seen if the results of that study will finally be implemented and the degradation of the valuable natural gem will eventually be ended (figure 8).

Figure 8. Timeline of negative and positive milestones in the Kurtna Lake District related to anthropogenic influence (timeline by Jaanus Terasmaa, modified by Marko Vainu) (p. 217).

Ten most significant lakes in the district

In the following section ten selected lakes in the district are introduced. The selection was based on the ecological and/or scientific value of the lakes and the scale of anthropogenic influence. Five of the once oligotrophic lakes (Valgejärv, Liivjärv, Martiska, Kuradijärv and Ahnejärv) are introduced, Lake Nõmmejärv is most heavily affected by mine water, Lake Konsu has been turned into a water reservoir, Lake Räätsma is a limnological rarity, being the only siderotrophic lake in Estonia, Lake Saarejärv is the the best-preserved lake in Kurtna and Lake Kihljärv has effectively ceased to exist.

Lake Valgejärv

Lake Valgejärv (White Lake) is the ecologically most valuable lake in the district at the present day (figure 9). Its area is 8.5 ha and maximum depth in the spring of 2014 was 10.5 m. That makes it the shared deepest lake in the district. It is a closed-basin semidystrophic[1] or – according to some older surveys – oligotrophic[2] lake, with no surface water inflows nor outflows. It receives its water from precipitation, an adjacent peatland and groundwater. According to the EU Habitats Directive, it has been listed as habitat type 3110. It is the only lake in the district where all the three characteristic rare and protected plants *Lobelia dortmanna, Isoetes lacustris* and *Sparganium angustifolium* are still growing and the bottom of the lake is covered by mosses up to the depth of 4.5 m.

Figure 9. A view of Lake Valgejärv (photo by Marko Vainu) (p. 218).

Groundwater level drawdown because of the nearby open-cast oil-shale mine is the most important anthropogenic pressure affecting the lake. The direct influence of the mine on the water level of the lake has not been proven yet, although the water level of the lake has historically been fluctuating in a one meter range. Most recently it dropped 80 cm from May 2012 to November 2015

1. Semidystrophic – with low level of mineral substances and medium level of humic substances and nutrients.
2. Oligotrophic – with low level of nutrients and mineral and humic substances.

and recovered 70 cm by May 2018. In the autumn of 2015, lower than average water levels were recorded in many of the lakes in the district. These were partially caused by relatively dry weather in 2014 and exceptionally dry weather during the summer and autumn of 2015. In 2014, the sum of precipitation in the Kurtna region was 591 mm and in 2015, only 471 mm, while the long-term average is 736 mm. In addition to the natural decrease of the groundwater level because of lower precipitation, the effect of drought was probably amplified in the case of L. Valgejärv. It did not enable the mining company to pump enough water into the filtration channel between the lake and the Sirgala mine. As the lake is relatively close to the mine, then that could have allowed for a more pronounced groundwater level drop than would have occurred in natural conditions. Previously, water for extinguishing forest fires has been taken from the lake, causing abrupt water-level changes as well.

All these large lake-level fluctuations are threatening the lake's valuable plant communities. Especially *Lobelia dortmanna*, because it grows only in shallow near-shore water and the plants are left to dry land and subsequently die during periods of lower water level (figure 10). The population of *Lobelia* is also affected by swimmers, because the lake with its partly sandy and well approachable shore is popular among them, although there are no official camping sites nor beaches at the lake.

Figure 10. Exposed plants of Lobelia dortmanna on the shore of Lake Valgejärv (photo by Marko Vainu) ***(p. 218).***

Concerning nutrients, the amount of total nitrogen in the surface layer has stayed low, in 1987 it was 0.4 mg/l (Mäemets et al... 1989) and in May 2018 it was 0.35 mg/l. The content of total phosphorus has increased, though. While in 1987 it was below the detection limit (Mäemets et al... 1989), then in May 2018 it was 0.02 mg/l. Also water transparency has deteriorated through time – in 1954 it was 4.4 m (Ott 2001), but in May 2018 it was only 1.5 m. The water transparency is low because of the high content of humic substances in the water. The decrease in water transparency could indicate that the role of the adjacent peatland in providing water for the lake has increased in time, as the groundwater level and consequently its share in the lake's water balance has dropped. On a positive note, the lake water was oxygenated until the ninth meter in May 2018. Therefore, even though the lake is not as pristine as it used to be decades ago, it is still the shiniest pearl among the lakes of Kurtna Lake District and also outstanding among Estonian lakes in general.

Lake Liivjärv

Lake Liivjärv (Sand Lake) is one of the northernmost lakes in the district. Its area is 4.5 ha and maximum depth in the spring of 2014 was 8 m. It is considered to be an oligotrophic lake. It has no surface water inflows nor outflows. It receives its water from precipitation and groundwater. According to the EU Habitats Directive, it has been listed as habitat type 3110. Historically, both *Sparganium angustifolium* and *Isoetes lacustris* have grown in the lake. *Isoetes lacustris* became extinct in the lake already in the 1980s (Mäemets & Teder 1987), but few plants of *Sparganium angustifolium* still grow in its northern part (figure 11). The lake has suffered the largest known water-level drop in the whole lake district. In 1929 its water level was 46.4 m a.s.l., but in the summer of 2006 and in the autumn of 2015 its level was down to 42.2 m a.s.l (figure 12). So the lake has lost more than four meters on extreme occasions.

Figure 11. Sparganium angustifolium blooming in Lake Liivjärv (photo by Marko Vainu) ***(p. 220).***

Figure 12. Recorded lake levels in the five once oligotrophic lakes in the Kurtna Lake District ***(p. 220).***

Figure 13. A view of Lake Liivjärv from the eastern shore. In the foreground the drained peatland is visible (photo by Marko Vainu) ***(p. 220).***

The most important anthropogenic pressures that have affected the lake's water level have been groundwater level drawdown, caused by the drainage of the adjacent peatland (figure 13) and the nearby open-cast oil shale mine. The majority of the water level drop occurred in the 1960s and 1970s after the establishment of the drainage network for the peat milling field. The dramatic water level drop has significantly affected the status of the lake. The lake had a very low level of nutrients and subsequently very sparse vegetation and low plankton biomass in the 1950s. Also, the water transparency was very high – 6.6 m (highest in Kurtna) (Mäemets 1977). By 1987 the level of nutrients in the surface layer had risen (total nitrogen – 0.7 mg/l, total phosphorus – 0.003 mg/l) and, though, plankton biomass was still low, vegetation had started to flourish in the lake (Mäemets et al... 1989). Water transparency had dropped to 4 m. In May 2018 the water transparency was only 1.6 m and the water became anoxic from the depth of 3 m. Content of total nitrogen in the surface layer was 0.52 mg/l and total phosphorus 0.023 mg/l. Therefore the status of the lake has been continuously deteriorating and the lake is going through the process of eutrophication caused by a too low volume of water.

In addition to the increased trophic level and the consequent bloom of biomass, the water transparency of the lake has also likely reduced because of changes in its water budget. The high content of yellow matter in water (16.3 mg/l) in May 2018 suggests that a similar process, as described in the case of Lake Valgejärv, is happening at Lake Liivjärv as well. Caused by the drop in the underlying groundwater level, the lake has started to receive relatively more darker water from the peatland, compared to the clearer groundwater from the sand layers. Consequently, the lake water has become darker. Groundwater seepage measurements in L. Liivjärv from May 2018 also support that hypothesis. Therefore, the lake has effectively changed from oligotrophic to semidystrophic, because of human influence.

The lake is very popular among local people, because of the official sandy beach on the southern shore of the lake.

Lake Martiska

Lake Martiska is the most researched lake in the lake district. It has been one of the ecologically most valuable soft and clear-water oligotrophic lakes in Kurtna, but it has suffered from huge water level fluctuations that have considerably reduced its value (figure 14). It is a closed-basin groundwater dependent lake. Its water level difference in 1946 (before anthropogenic disturbance) and 1987 (during highest anthropogenic disturbance) was 3.4 m (figure 12). By the beginning of the 21st century, the water level of the lake restored to a certain extent, but at its maximum level was still 1.3 m below the level of 1946. Since the summer of 2012 until the end of 2015, the water level dropped again almost to the level of the historical minimum, but started to rise after that. For that reason, the area and the maximum depth of the lake has been changing as well. For example, in May 2012 the area of the lake was 2.7 ha and maximum depth was 8 m. In 1946 the lake area had been 4.4 ha (known maximum) and in 1987 it was 1.3 ha (known minimum).

Figure 14. A view of Lake Martiska from the north (photo by Marko Vainu) ***(p. 222).***

Studies have shown that the most important driver for the fluctuations has been groundwater abstraction from the Vasavere groundwater intake since 1972 (Vainu 2018). The closest well of the intake is only 200 m from the lake. Before 1972, the water level could also have been affected by changing evapotranspiration caused by the reforestation of the catchment of the lake. The forest had died there in a huge fire during the World War II. Additionally, sand mining below the water table in the Pannjärve quarry has affected the local groundwater level.

Before the utilisation of natural resources started in the centre of the lake district, the natural groundwater flow direction was from west to east. Groundwater abstraction from the intake lowered the groundwater level around the intake and formed a cone of depression, which in turn diverted the natural groundwater flow direction. Water from the lake started seeping towards the intake and caused the lake level to drop. In general, the lake level has been lower during periods of higher groundwater abstraction and vice versa. The measured lake levels were the lowest in the end of the 1980, when the abstraction was high. The abstraction was the highest in the 1990s, but unfortunately, there are no lake level measurements from that period. The abstraction dropped considerably in the end of the 1990s and stayed low in the beginning of the 21st century. That allowed the lake level to restore. In the first half of 2012, the wells and other intake facilities were renovated and since August 2012, the abstraction was increased to the upper level of the permitted rate (8000 m^3/d). The level of Lake Martiska started to decrease immediately and continued to drop until the end of 2015. The continuous drop of the lake level was supported by two consequent very dry years. In 2014 and 2015 the sum of potential evapotranspiration exceeded the sum of precipitation. Hence, the rate of groundwater recharge was low or nonexistent. Years 2016 and 2017 were wetter and the rate of groundwater abstraction was reduced as well. That allowed the lake level to restore by a certain extent.

Before the 1970s the lake and its shores were largely plant free. Only large nearshore areas were inhabited by the characteristic species for oligotrophic lakes: *Lobelia dortmanna*, *Isoetes lacustris* and *Sparganium angustifolium*. But 1981 was the last time the first two species were encountered (Mäemets & Teder, 1987). *Sparganium* was present later as well, but only as hybridised specimens (Ott et al.... 1995). When the water level dropped, the habitats of *Lobelia dortmanna* and *Isoetes lacustris* became dry and were inhabited by reeds, grasses and even tree seedlings. Once the water level restored, these areas were flooded, the new vegetation died and started decomposing. As the above-mentioned plant species require clear sandy bottoms for growing, then the newly submerged shore areas were unsuitable for recolonisation. While the characteristic species have disappeared, other vegetation, indicative of eutrophication, has increased. Reed beds almost fully encircle the lake and in the water *Potamogeton*, *Nymphaea* and *Nuphar* species are thriving (figure 15). In 1957 the water transparency was as high as 5.4 m, but by 2001 it had dropped to 3 m (Ott 2001). In May 2018 it was a bit higher – 3.2 m. It is still considered to be good transparency, but taking into account the decrease, the situation has clearly worsened. In the summer of 1957, the enrichment with oxygen was high both at the surface and at the bottom (Mäemets 1968), but in the summer of 2001, the bottom was anoxic (Ott 2001). In May 2018 there was no oxygen from the fourth meter onwards. At the same time, the average content of total nitrogen was 0.78 mg/l (0.60 mg/l in 2006) and total phosphorus 0.026 mg/l (0.018 mg/l in 2006) (data from 2006 in Ott (2006)). The national threshold for a good ecological status regarding total nitrogen and total phosphorus content in lakes with clear and soft water is <0.50 mg/l and <0.02 mg/l, respectively. Therefore, the lake has largely lost its limnological uniqueness, but is still listed as habitat type 3110 according to the EU Habitats Directive. The lake is popular among holidaymakers, as there are sandy sections along its shoreline. The high recreational load has put an even bigger stress on the lake, both by littering and by addition of non-natural substances to the water.

Figure 15. Nymphaea in L. Martiska (p. 222).

Lake Kuradijärv

Lake Kuradijärv (Devil's Lake) is a small and mysterious lake in the centre of the lake district. It is also a closed-basin groundwater-dependent lake located close to the Vasavere groundwater intake and, thus, has suffered similar faith to Lake Martiska. As it is even closer to the intake, its water level fluctuations have also been higher. Its water level dropped 3.8 m from 1946 to 1987 (figure 12). The water level increase in the beginning of the 21st century, the decrease from 2012 to 2015, and the subsequent increase have followed a similar pattern to Lake Martiska. In May 2012, the area of the lake was 1.5 ha and maximum depth 8 m. In 1946 the area had been 2 ha (known maximum) and in 1987 it was 0.9 ha (known minimum). According to historical data, Lake Kuradijärv was the deepest lake in the district (11.5 m) before the large water level drop and the eutrophication and sediment accumulation that followed. Lake Kuradijärv has also been one of the characteristic oligotrophic lakes in Kurtna and is still listed as habitat type 3110 according to the EU Habitats Directive. In addition to being the deepest lake, its distinctive character was being basically free of vegetation. Only *Sphagnum* mosses grew in the bottom of the lake as lately as in 1950s (Mäemets 1977). The dark plant-free body of water in forest was probably the reason why the lake was once given such a gloomy name. After the water level drop submerged vegetation inhabited the lake, but even in the present day the amount of vegetation is limited. Also, in contrary to Lake Martiska, only few patches of reed are growing in the littoral zone of the lake. Another visual characteristic of the lake is the presence of dead treetrunks in the nearshore water. These are the remnants of the lowest water levels in the 1970s to 1990s, when the shore area was inhabited by terrestrial vegetation. After the water level rose, the trees died, but the trunks remained standing, adding to the devilish presence of the lake (figure 16).

Figure 16. A view of Lake Kuradijärv and the dead trunks of trees on its shore (photo by Marko Vainu) (p. 224).

In May 2018, the water transparency of Lake Kuradijärv was 1.4 m. It had been 2.6 m in 2006 (Ott 2006), but 1.4 m in 1987 (Mäemets et al... 1989). Although the level of nutrients has risen in that lake compared to, for example, 1987 as well, the situation seems to have improved in the recent decade. In May 2018 the content of total nitrogen was 0.89 mg/l, while in 2006 it had been 1.82 mg/l (Ott 2006) and the content total phosphorus was 0.027 mg/l in May 2018, but had been 0.031 mg/l in 2006 (Ott 2006). The reasons, why the relatively high trophic level has not resulted in similar expansion of vegetation as in Lake Martiska, still remain unclear.

Lake Ahnejärv

Lake Ahnejärv (Greedy Lake) is the third closed-basin lake in the centre of the lake district (figure 17), which has been affected by the Vasavere groundwater intake. Lake Ahnejärv is the farthest of three from the intake and for that reason, its water-level fluctuations have been milder – maximum 2.9 m (figure 12). It is also the largest and deepest of the three. In May 2012 its area was 5.7 ha and maximum depth 9 m. In 1946 its area was 7.5 ha (known maximum) and in the autumn of 2015 it was 4.7 ha (known minimum). The lake was one of the five unique oligotrophic lakes of Kurtna as listed in 1966 (Mäemets 1966). As the two previous lakes, it has also been nominated to habitat type 3110 according to the EU Habitats Directive. The lake has a more complex shape than the other two lakes. There is a peninsula in the southeastern part of the lake that was an island before the large water level drop in the 1970s. All the three characteristic plants for oligotrophic lakes *Lobelia dortmanna*, *Isoetes lacustris* and *Sparganium angustifolium* have inhabited the lake. Here they survived longer than in Lake Martiska, and they were also found in the middle of the 1990s. But by

2011 all of them had disappeared. Controversially, the cause for it could have been the water level rise, because the plants that had moved lakewards during the low water level, found themselves in too deep water after the lake-level rise and could not survive there. Before the water-level drop, Lake Ahnejärv had one of the the highest water transparencies in Kurtna – 6 m (Mäemets 1977). By 1987 it had dropped to 4.8 m (Mäemets et al... 1989), but then it was the highest measured transparency in the district. Unfortunately, more recent transparency as well as trophic level measurements are lacking.

Figure 17. A view of Lake Ahnejärv from the north (photo by Marko Vainu) (p. 224).

Lake Konsu

Lake Konsu is by far the largest lake in the district (figure 18). Its area is 140 ha and the maximum depth is 10 m. It is a dyseutrophic[3] lake with surface water throughflow. According to the EU Habitats Directive, it has been listed as habitat type 3140. The lake's natural water regime has been changed considerably and it is basically functioning as a reservoir.

In 1948, a pipeline from the lake to a nearby town of Kohtla-Järve was constructed to provide technological water for an oil-shale processing factory. As mentioned before, the lake itself could not provide the requested amount of water, therefore in the 1950s and 1960s, the Raudi channel system was constructed to provide additional water from nearby lakes and underground oil-shale mines. In that way, the catchment of the lake was increased to 120 km^2. In 2017 5 million cubic meters of water was taken from the lake. That is 3.5 times less than the amount of mine water that was pumped into the channel system in 2016 and 2017. The lake level is regulated with a weir on its southeastern side (figure 19). Thus, all the excess water that is not used by the surface water intake either flows from the lake to the east via the Konsu ditch through the oil-shale mine area, or will not reach the lake at all and passes via the Raudi channel through lakes Peen-Kirjakjärv and Kirjakjärv.

On the northern shore of the lake, there is the only official camping site of the Kurtna region.

Figure 18. A view of Lake Konsu from the north (photo by Marko Vainu) (p. 226).

Figure 19. A weir on the southeastern side of Lake Konsu, used for regulating the lake level (photo by Marko Vainu) (p. 227).

Lake Nõmmejärv

Lake Nõmmejärv (Heathland Lake) is the first lake on the Raudi channel that receives the mine water pumped there to increase the supply in the Konsu surface water intake. It is an alkaline eutrophic[4] lake (figure 20). Its area is ~11 ha and maximum depth in the autumn of 2017 was 5.8 m. In recent times, its volume has varied between 226 000 and 290 000 m^3, depending on its water level, which in turn depends largely on the amount of mine water. According to the EU Habitats Directive, it has been listed as habitat type 3140. Originally, it was a closed-basin lake, but already in the end of the 19th century, outflow towards L. Särgjärv was constructed. At the same time, the Raudi stream, which had been flowing towards Lake Suurjärv, was diverted into Lake Nõmmejärv as well. So it was turned into a flow-through lake. In 1953, that channel was connected with Lake Konsu and in 1963 additional inflow from Lake Suurjärv via Lakes Niinsaare and Mustjärv was constructed and the existing channels were dredged. Consequently, the water level of lake Nõmmejärv dropped by 80 cm. In 1970, pumping of mine water into the Raudi channel was started. Eventually, only water

3. Dyseutrophic – with high level of nutrients and humic substances and low level of mineral substances.

4. Eutrophic – with high level of nutrients and low level of humic substances.

from the Viru mine was pumped into the lake, later the water from the Estonia mine was added and since 2013, after the closure of the Viru mine, only water from the Estonia mine reaches the lake. In 2017, altogether 17 mln m^3 of mine water was pumped into the lake.

Figure 20. A view of Lake Nõmmejärv from the east (photo by Marko Vainu) (p. 228).

Mine water from the oil-shale mines is rich in mineral (especially sulphates – SO_4^{2-}, bicarbonates – HCO_3^- and calcium – Ca^{2+}) and suspended matter, and is much more alkaline than the near surface groundwater of the region. For twenty years, until the beginning of 1990s, the lake functioned basically as the sedimentation basin for mine water, and only then sedimentation basins were built at the mine water outflows. During these years the sediment layer increased by 25 cm (Kõiv & Ott 2011). While the problem of suspended matter was largely solved, the issue with high load of sulphate is still active. In 2017–2018, the average sulphate content in the inflowing water was 265 mg/l. Sulphate itself will not do any harm to the lake's ecosystem, but after being diffused into the pores of the topmost sediment layer, it could be used as an oxygen source by bacteria and be reduced to sulphide (S^-). Preconditions for the reduction are sufficient amount of organic matter and anoxia, which is always present in the sediments, but not on top of the sediment layer in well oxygenated lakes. Sulphides could form hydrogen sulphide (H_2S) that is poisonous for wildlife or react with iron and form iron sulphide (FeS). As FeS, the sulphides are trapped in the sediments and can do no harm to the ecosystem. But if the sulphides take iron from iron phosphates, then it triggers phosphate release from the sediments and thereby fosters the eutrophication of the lake. Currently some sulphate reduction is taking place in the sediments of Lake Nõmmejärv, but it has not had a measurable negative effect on the ecosystem. The water replacement rate is high enough to guarantee well oxygenated conditions in the bottom of the lake and therefore the sulphate reduction rate is kept under control. There has been a sufficient amount of iron to bind both the phosphates and sulphides that have formed. Additionally, the pH of the lake is high (~8) that keeps ~90% of the unbound hydrogen sulphide in nontoxic dissociated form (HS^-).

Lake Nõmmejärv had the highest content of mineral matter, including calcium and bicarbonates (210 mg/l) among the Kurtna lakes already way before there was any mine water inflow back in 1937 (Riikoja 1940). Although, the mine water increased the alkalinity of the lake (in 2017–2018 the average content of bicarbonates was 290 mg/l), its communities remained largely unaffected, as they had been adapted to alkaline water before. For example, *Chara* species were dominant among inlake vegetation before the mine water inflow and they are dominant in the present day as well. The most recent assessment of the status of the lake in 2006 reached the conclusion that the lake is in good state. Hence, it can be concluded that even though the change in the hydrological budget of the lake was enormous, its ecosystem has not suffered from it, yet. Right now the most visible effect of the decades-long mine water inflow are some plant-free areas in the near-shore regions of the lake. There, under the greyish layer of settled calcite, a very soft and amorphous layer of sediments, enriched with iron sulphide, are present. That substrate is largely uninhabitable for aquatic plants and therefore these areas form dead patches in the lake bottom (figure 21).

Figure 21. A thin layer of calcite underlain by a layer of sediments, enriched with iron sulphide (FeS), in the near-shore area of the lake. Photographed during low water level, when that area was exposed (photo by Marko Vainu) (p. 229).

Controversially, stopping the mine water inflow now could trigger a series events that are detrimental for the lake's ecosystem. If the water replacement rate of the lake would become too low, anoxic conditions could develop in the bottom of the lake, reduction of the sulphide that is left in the water and especially in the sediment pore water could intensify and both of its negative effects (toxicity and phosphorus release) could become more pronounced. Recent measurements have shown that the danger of the fulfilment of that scenario is fortunately quite low, as the water replacement rate of the lake would stay sufficiently high (>20 times a year) even if the mine water inflow was completely stopped. Despite that, it could still be necessary to add iron to the lake, if mine water inflow is stopped, in order to completely avoid any negative effects.

Therefore, Lake Nõmmejärv is an example of an ecosystem that has become dependent on the anthropogenic influence and might not be successful sustaining itself if it is abruptly left on its own again.

Lake Räätsma

Lake Räätsma is a narrow and elongated lake in the southern part of the lake district. Its area is 15.5 ha and in the spring of 2014 it shared the honours of the deepest lake (10.5 m) in Kurtna with Lake Valgejärv. It is a closed-basin lake with no surface water inflows nor outflows. It receives its water from precipitation and groundwater. According to the EU Habitats Directive, it has been listed as habitat type 3140. The significance of the lake lies in the fact that it is considered to be the only siderotrophic lake in Estonia. Siderotrophic lakes have a high concentration of iron in the water of the bottom layer. In Lake Räätsma 9 mg/l of iron has been measured in the bottom (Mäemets 1987). It is believed that the iron originates from groundwater and it is brought to the lake through springs. The level of that lake has not fluctuated significantly in the recent past as it is not in the direct area of influence of the anthropogenic pressures. Though, its water level dropped around a meter in the 1960s because of unknown reasons. The lake is not very popular among holidaymakers because of its high shores that make the lake difficult to approach.

Figure 22. Northern shore of Lake Räätsma in winter (photo by Marko Vainu) (p. 230).

Lake Saarejärv

Lake Saarejärv (Island Lake) is the best-preserved lake in the lake district, because its water level has been stable throughout the last seventy years. It is also the only lake in the district that has an island (figure 23). Its ecological value, though, is not as high as in the case of some other previously described lakes, because it has never hosted rare plant species. Its area is 6.5 ha and maximum depth in the autumn of 2014 was 8.2 m. It is a closed-basin semidystrophic lake, with no surface water inflows nor outflows. It receives its water from precipitation, an adjacent peatland and groundwater. According to the EU Habitats Directive, it has been listed as habitat type 3110. The lake is not popular among holidaymakers because it does not have an open beach area, but as its shore has not been disturbed by water level fluctuations, it is surrounded by undisturbed coniferous forests and contains a picturesque island, then it is a visually very pleasing lake for environmentally aware tourists.

Figure 23. A view of Lake Saarejärv and its island from the south (photo by Marko Vainu) (p. 230).

Lake Kihljärv

Lake Kihljärv is the lake with the worst destiny in the lake district, because it has effectively dried out in recent years. Altogether it is the second lake in Kurtna to disappear, as a small lake – Vasavere Mustjärv – dried already in 1980s. Lake Kihljärv has never been ecologically very valuable and it has received very little scientific attention. It is known that in 1987 its water transparency was 2 m, but already then there was a significant amount of vegetation in the lake. While in the spring of 2013 there was still sufficient amount of water in the lake and it covered an area of 2 ha, then by the end of the very dry autumn of 2015, the lake had completely dried out (figure 24). The lake was still dry in the spring of 2016. It is the closest lake to the Sirgala open-cast mine – there is only 500 m between the mine border and the lake, and the mine bottom is more than 20 m lower than the former lake level. As there is no evidence that the lake has dried out ever before, then it is a strong argument for assuming that the filtration ditch and the infiltration barrier, which should protect the groundwater level from dropping too low under the surface adjacent to the mine, do not function properly. In May 2018 the lake was still effectively dry, only a narrow crescent-shaped strip of water was visible in the northeastern part of the former lake basin (figure 25).

Figure 24. Lake Kihljärv in the spring of 2013 (left) and in the spring of 2016 (right). (Orthophotos from the Estonian Land Board) (p. 231).

Figure 25. The bottom of the former Lake Kihljärv in May 2018 (photo by Marko Vainu) (p. 231).

Conclusions

The Kurtna Lake District is an area where the mostly abstract value of nature collides with the more material value of natural resources. Until the present day, decisions based on the material value have prevailed, but the situation is not hopeless. It needs a joint effort from the representatives of both mindsets to reach a situation where the lakes will preserve for the generations to come, side-by-side with reasonable economic activities. Right now the Kurtna Lake District is an area of great contrasts, partly it still resembles the pristine nature it used to be, and partly it is a sad monument for an overly eager consumption of natural resources.

References (p. 234)