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IMPACT OF WATER-LEVEL CHANGES TO AQUATIC VEGETATION IN SMALL OLIGOTROPHIC LAKES FROM ESTONIA

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Abstract

This study demonstrates the effect of drastic water-level changes to the aquatic vegetation in three small oligotrophic lakes situated in Kurtna Kame Field in north-eastern Estonia. The area holds around 40 lakes in 30 km^2 of which 18 lakes are under protection as Natura Habitat lakes (Natura 2000 network). The area is under a strong human impact as it is surrounded by oil shale mines, sand quarry, peat harvesting field etc. The most severe impact comes from the groundwater intake established in 1972 in the vicinity of three studied lakes. The exploitation of groundwater led to drastic water-level drops. In 1980s the water-level drops were measured to be up to 3 to 4 meters compared to the levels of 1946. Lake Martiska and Lake Kuradijärv were severely affected and only 29% and 45% of lake area respectively and 21% of initial volume remained. Both lakes were described as oligotrophic lakes before severe human impact and held characteristic macrophytes such as *Isoëtes lacustris* L., *Sparganium angustifolium* Michx and *Lobelia dortmanna* L. As the water level declined the lakes lost their rare characteristic species and can now be described more as a meso- or even eutrophic lakes. When the volume of groundwater abstraction decreased in the 1990s the water levels started to recover but did not reach the natural levels of pre-industrialized era. Also the vegetation did not show any signs of recovery. In 2012 the pumping rates increased again causing a new rapid decline in water levels which almost exceed the previous minimum levels. The water-level monitoring alongside with the macrophyte monitoring data gives us a good case study on how the long term abrupt water-level changes can affect the aquatic vegetation.

Keywords: water-level changes, small lakes, oligotrophic lake, eutrophication, human impact, *Lobelia dortmanna*, *Isoëtes lacustris*, *Sparganium angustifolium*

1 INTRODUCTION

Lakes are dynamic ecosystems and shift between ecological states through time due to various factors. One major factor is the water level which can fluctuate in larger and smaller scales for various reasons such as climate, sedimentation, human impact etc (Terasmaa et al., 2013). Due to climatic conditions derived from seasonal changes small-scale lake-level changes are common and natural even in lakes with most pristine state. These natural fluctuations may even have positive effects on ecological condition of the lake (Coops&Hosper, 2002) as well on macrophyte diversity (Keddy&Reznicek, 1986). In overall macrophytes are highly dependent on lake level as the water depth limits their habitat. The water-depth range at which macrophytes can grow is relatively broad for many species, but occasionally can be sufficiently narrow (Hannon&Gaillard, 1997). Therefore lake-level manipulations can in some cases be used as a control for unwanted macrophyte species (Cooke, 1980), but it can also lead to deterioration of the lake ecology. Water-level fluctuations can affect the abundance of submerged macrophytes and therefore bias the balance from clear water state towards turbid state (Blindow, 1992). Decreasing submerged vegetation stand can lead to wind driven sediment resuspension (Liu et al., 2013) limiting the photic conditions required for submerged macrophytes and therefore the turbid state can be long-termed without a natural scenario to preliminary clear water state. Also nutrients will become more available for phytoplankton with resuspended sediments, increasing their biomass and therefore reducing photic conditions in water column (Schallenberg&Burns, 2004). In case when submerged vegetation is replaced by dominating floating-leaved plants it can eventually become a stable state (Scheffer et al., 2003) as the increased floating leaved plants limit the light availability for submerged vegetation. As oligotrophic lakes have low buffering capacity they can be most vulnerable to lake-level changes. Study on Swedish small oligotrophic lakes (Lillieroth, 1950) demonstrated that water-level lowering (up to 2 m) tended to affect the lakes macrophytic and planktonic communities towards slightly more eutrophic direction. Water-level regulations led to complete disappearance of large isoetids such as *Lobelia dortmanna* and *Isoëtes lacustris* in oligotrophic lake in Finland (Hellsten, 2001). Although there are case studies showing the response (Wallsten&Forsgren, 1989) and recovery (Havens et al., 2004) of submerged vegetation to increased water levels, recovery from extremely lowered lake-level conditions are not that common.

Most changes in lake-level are usually small in both spatial as well as in temporal scale. Also cases where long term low water levels are restored are scarce. Kurtna Lake District in north-eastern Estonia offers a valuable case study where human induced lake-level lowerings are long-termed (up to several decades) and vast as only less than quarter of the lake volumes remained. Previous studies show that hydrological changes have affected the sedimentation and left paleolimnological markers in the lake sediments (Punning et al., 2007; Vaasma et al., 2015). The area has also been intensely monitored over the last 70 years including the vegetation mapping in lakes. As the lakes also had initially rare large isoetids characteristic to oligotrophic lakes: *Lobelia dortmanna* and *Isoëtes lacustris*, it provides us a chance to study their response to lake-level changes. It also presents an opportunity to observe if and to which extent the vegetation and ecological status of once oligotrophic lakes have recovered after partial water-level recovery. The aim of this study is to compare historically recorded water level and vegetation mapping data of three oligotrophic lakes in order to trace shifts in vegetation composition related to the water-level changes.

2 STUDY AREA

Kurtna Lake District is located in north-eastern Estonia, Europe (Figure 1). It resides in the Kurtna Kame Field which is also a landscape conservation area with large forests and mires and a popular recreation area for tourists and local people. Kurtna Kame Field holds approximately 40 lakes on a 30 km^2 area which is the highest density of lakes in Estonia. As 18 of these lakes are under a protection as Natura Habitat lakes (Natura 2000 network) the conservation of the area is of utmost importance. The lakes were formed during the early Holocene after the retreat of the continental ice sheet (Punning, 1994) and are kettle hole lakes. The shape, size, drainage area, hydrological regime and trophic status vary among lakes, but mostly they can be described as small (under 100 ha) and shallow (depth up to 10 m) lakes.

The Kurtna Kame Field area lies in a transitional zone between a sparsely inhabited territory with extensive forests and mires and a densely populated and heavily industrialized oil shale mining and processing region (Punning, 1994) (Figure 1). The underground oil shale mining and the abstraction of groundwater started at the end of the 1950s which more or less affected all lakes in the area through the groundwater exploitation (Punning, 1994). There was a decline in the mining volumes of oil shale after the reorganization of the local economy in the 1990s. Additionally to mining, three lakes in the centre of the Kurtna Lake District have also been affected strongly by the Vasavere groundwater intake wells established in 1972 (Punning, 1994). All 14 intake wells were established in the vicinity of Lake Martiska (hereafter L. Martiska), Lake Kuradijärv (hereafter L. Kuradijärv) and Lake Ahnejärv (hereafter L. Ahnejärv) which are all under protection as Natura Habitat lakes (Natura 2000 network) belonging to type 3110 (oligotrophic waters containing very few minerals of sandy plains). Initially the pumping rates did not exceed 6000 m^3 day^{-1} but rose significantly in 1980s and stayed high in the beginning of 1990s with around 9000 m^3 day^{-1}. Starting from the second half of the 1990s abstraction rates fell and stayed around 5000 m^3 day^{-1} until 2012 when abstraction wells were renovated and the pumping rates increased again (Vainu&Terasmaa, 2014). During the recent years abstraction rates have risen but not exceeded 8000 m^3 day^{-1}.

2.1 Lake Martiska

L. Martiska (Figure 1) is a small dimictic lake (3.0 ha) with mean water depth of 2.2 m and maximum depth of 7.8 m. L. Martiska has been described as an oligotrophic lake but its trophicity has increased in the last decades. Martiska is a closed-basin lake with steep-sloped and sandy shores in the west and peaty gentle slopes in the east. During 1946–1987 lake level dropped from 46.0 m a.s.l. to 42.6 m a.s.l. (Erg&Ilomets, 1989). Lake level was measured to be 44.7 m a.s.l. in 2009. Before the industrial impact and water-level lowering L. Martiska used to be *Lobelia-Isoëtes* lake. The vegetation was described as scarce and poor in species (Riikoja, 1940; Miljan, 1958). Helophyte zone consisted dominantly of *Carex* spp. but also *Sparganium angustifolium* was found. Majority of floating-leaved plants consisted of *Nymphaea candida* and *Nuphar lutea*, but the lake was also rich in oligotrophic species such as *Lobelia dortmanna* and *Isoëtes lacustris*. Also the phytoplankton used to be scarce in species as well as in overall biomass and algal blooms (cyanobacteria) did not occur. Both abundance and number of species of zooplankton were moderate (Mäemets, 1968).

2.2 Lake Ahnejärv

L. Ahnejärv (Figure 1) is a small dimictic lake (5.8 ha) with a mean water depth of 3.3 m and maximum water depth of 9 m. L. Ahnejärv has been described as a oligotrophic lake but its trophicity has increased in the last decades. L. Ahnejärv is a closed-basin lake with a paludified shoreline.

During 1946–1987 lake level dropped from 46.8 m a.s.l. to 43.9 m a.s.l. (Erg&Ilomets, 1989). Lake level was measured to be 44.9 m a.s.l. in 2009. Before the industrial impact and water-level lowering in 1936 rare oligotrophic species such as *Lobelia dortmanna* and *Isoëtes lacustris* were found. Helophyte zone composed only of *Carex* spp. and five species of floating-leaved plants were reported: *Nymphaea candida*, *Nuphar lutea*, *Potamogeton natans*, *P. alpinus* and *Sparganium angustifolium* (Riikoja, 1940; Miljan, 1958).

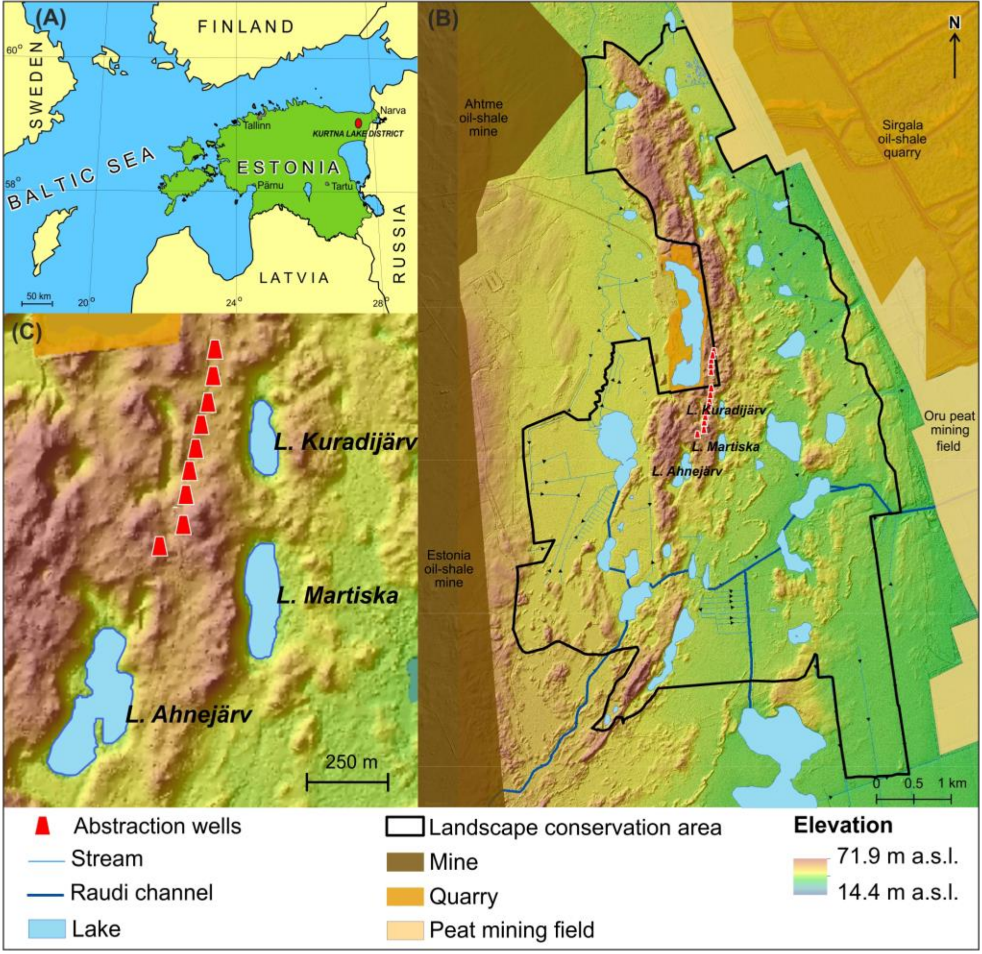

Figure 1. Location of Estonia (A), Kurtna Lake District (B) and three studied lakes (C).

2.3 Lake Kuradijärv

L. Kuradijärv (Figure 1) is a small dimictic lake (1.5 ha) with a mean water depth of 2.8 m and maximum water depth of 7.2 m. L. Kuradijärv has been described as oligotrophic, but the lake has gone through severe changes during last decades and can be described as mesotrophic. L. Kuradijärv is a closed-basin lake surrounded by sandy hills covered with pine forest. Shoreline is paludified and with peat deposits. During 1946–1987 lake level dropped from 46.0 m a.s.l. to 42.2 m a.s.l. (Erg&Ilomets, 1989). Lake level was measured to be 44.7 m a.s.l. in 2009. Before the industrial impact and water-level lowering in 1936 there was no vegetation in submerged or helophyte zone and only *Sphagnum* mats infiltrated the waterline in some parts (Riikoja, 1940).

3 METHODS

In order to compare nowadays vegetation to the past vegetation and relate the possible changes to human induced water-level lowering, historical records of vegetation, water-quality and groundwater abstraction were used. As the past vegetation records are mainly descriptive, therefore the comparison and analysis is more of qualitative than quantitative nature.

Data for the lake-level changes is quite sporadic for the last century and is derived from literature where it is often not given in absolute values. Data for recent years are on the other hand direct measurements from the water-level gauges installed into the lakes in 2012. Also water surface area and water-body volume is calculated for each lake based on the water-level records and lakes morphology data

For modern vegetation monitoring in 2011 standard methods were used. The whole littoral zone was traversed by boat and the species composition and depth limits of different plant groups were recorded. Five throws with a grapple were made around the boat to record submerged aquatic plants, which were not readily visible. We divided the macrophytes into three main groups: helophytes, floating-leaved and submerged plants. Reason for this is that the distinction between an aquatic and a terrestrial plant is often blurred as many aquatic species can have both submersed and emerged forms, and many terrestrial plants are able to tolerate periodic submersion.

4 RESULTS AND DISCUSSION

We have reasonably good though not very consistent lake-level records from the second half of the last century. Most reliable records are from 1946, 1987, 2009, 2012, 2013 and 2015 for which we have also calculated lake area and volume (Figure 2). Since 2012 when water-level gauges were installed we have continues and reliable records for all three studied lakes. As the intense groundwater abstraction started already in the 1970s and the vegetation mapping records hold also essential data and show changes from that period, it is important to use all the data we could collect concerning the changes in water levels of three studied lakes (Figure 3). Even though the available historical records are sometimes controversial they still give some insight about the temporal and spatial scale of the changes.

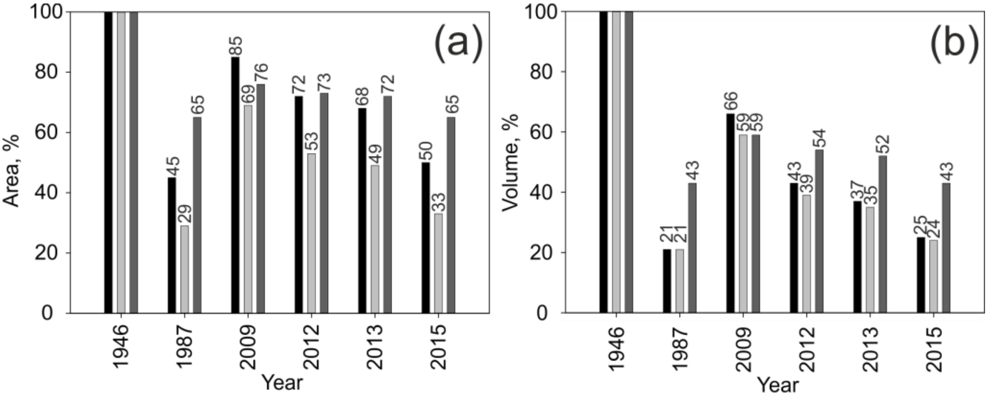

Figure 2. Changes in surface area (a) and volume (b) of three studied lakes (precentages show residue from initial values in 1946). Black column – L. Kuradijärv, light gray column – L. Martiska and dark gray column – L. Ahnejärv.

When looking at the available records (Figure 3) we can see that the lake-levels started to decline already at least decade before the establishment of groundwater intake in 1972. One explanation for this are the changes in vegetation on the catchment in the middle of the last century (Vainu&Terasmaa, 2014). During the World War II there was a fire in the central part of the Kurtna Kame Field and the pine forest covering the area was burnt. Hence at the end of the 1940s the area was covered with post-fire moor-like vegetation. As the evapotranspiration rate for full-grown pine trees are significantly higher than for sparse and shallow-rooted moor vegetation (Allen et al., 1998), more water reached the lakes from the catchment after the fire (Vainu&Terasmaa, 2014), possibly resulting in misleadingly high initial lake-level values recorded in 1946. The pine stand was fully recovered by 1960. Along with the restoration of the tree-line evapotranspiration rates increased leading to the pre-groundwater abstraction lake-level drops. Previously it has also been stated that the oil-shale mines may have affected the lakes before the groundwater abstraction as the changes in vegetation couldn't explain the whole 1 m lake-level drop as in case of L. Ahnejärv (Punning et al., 2007). Lake levels were monitored already one year after the establishment of the Vasavere groundwater wells and there had been a considerable decrease since 1960s. But when comparing data from the 1970s and the 1990s we can see that the lake-level drop which followed the initial decrease is much more extensive (Figure 3). The decline had been continuous reaching the minimum levels in the end of 1980s. After the independence of Estonia local economy was reorganized leading to a decline in groundwater abstraction. This in turn led to a restoration of lake-levels in the three studied lakes. First reliable records afterwards are from 2009 when lake-levels had risen up to 1.5 meters.

During the period of 1946-1987 the lake level dropped 2.9 m in L. Ahnejärv, 3.8 m in L. Kuradijärv and 3.4 m in L. Martiska (Figure 3), affecting also the water surface areas and lake volumes. Due to differences in the shapes of lake basins the changes in water body volumes and surface areas varied. Most drastic decline was in lake volume of L. Martiska and L. Kuradijärv where only 21% of the initial volume remained (Figure 2).

For all three lakes the number of vegetation monitoring records as well as the monitoring years slightly differ. Also the initial vegetation and overall trends in vegetation changes are quite different for all three lakes (Table 1). When looking at the vegetation monitoring data it is important to take into account that data from different years and sites have varying monitoring quality as in some years the vegetation was only observed from the lake shore. Therefore it is important to look at overall trends rather than focusing on minor details.

The most extreme change took place in L. Kuradijärv where a lake once without vegetation became moderately rich in macrophytes (Table 1). Records of vegetation monitoring show that in 1958 still no macrophytes were to be found. In 1976 there are first records of macrophytes. A patchy helophyte zone consisting mainly of *Carex* spp., *Phragmites australis* and *Typha* spp. was present. Also floating-leaved vegetation zone was formed by *Potamogeton natans*. *Elodea canadensis* was recorded among submerged vegetation. Unfortunately this leaves almost a 20 year wide gap in the monitoring data (Table 1) into which also falls the start of groundwater abstraction and extreme water-level drop. Although the water-level had already slightly dropped by 1960s in nearby situated L. Martiska and L. Ahnejärv, the data for water levels is unfortunately missing for L. Kuradijärv (Figure 3). Therefore it is hard to say if the changes started already before or after the beginning of groundwater abstraction. Considering the fact that in overall the water levels of all three lakes have quite similar trends in change during last 60 years we can assume that the water level in L. Kuradijärv had also started to decrease at least in some extent before 1972. There is no proper vegetation data until 2011 (records from 2006 is quite superficial) in L. Kuradijärv so the period with the lowest lake level is not covered. In 2011, when the water level was presumably slightly higher than in 1990s, the vegetation is mostly formed by helophyte zone where the number of species has increased. The floating-leaved plant cover has also increased as of *Potamogeton natans* forms almost a constant zone along the shoreline. Only the submerged vegetation was not to be found.

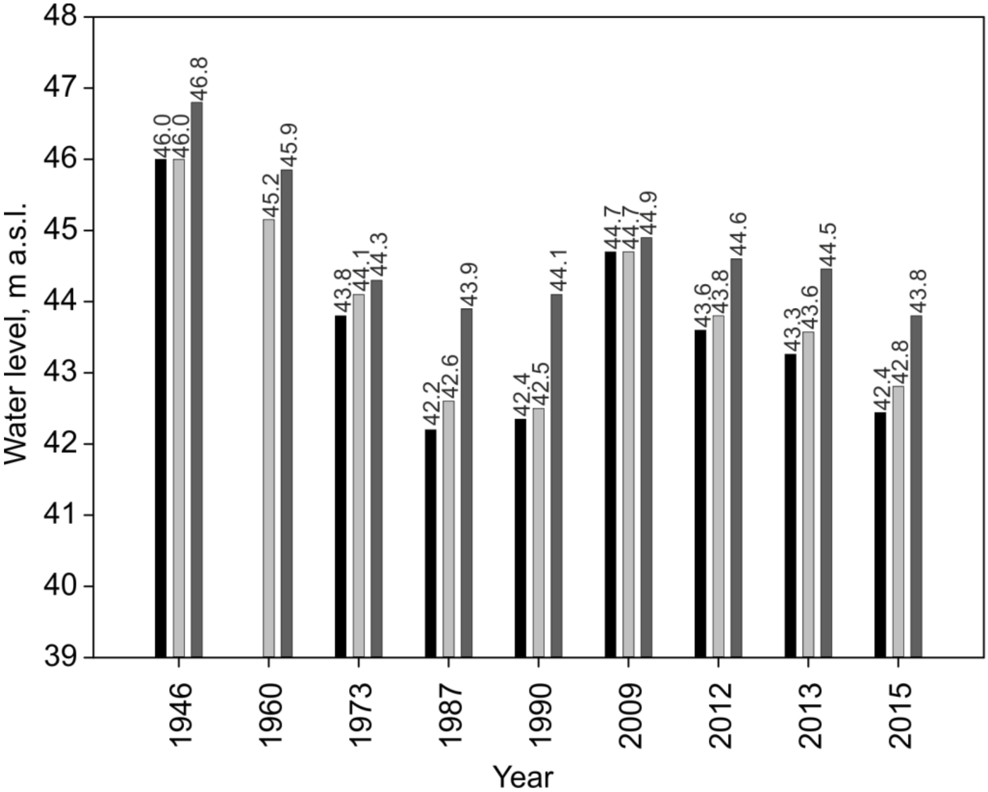

Figure 3. Water level records from three studied lakes. Black column – L. Kuradijärv, light gray column – L. Martiska and dark gray column – L. Ahnejärv. Past water levels are taken from: ELB, 1973; Erg&Ilomets, 1989; Põder et al., 1996.

In L. Ahnejärv the changes in vegetation have been different as the lake was initially in 1935 inhabited by oligotrophic species such as *Lobelia dortmanna* and *Isoëtes lacustris* (Table 1). Also *Sparganium angustifolium* was found and *Potamogeton* species, *Nymphaea candida* and *Nuphar lutea* formed the floating leaved zone. Some changes in vegetation could be found already in 1971. Helophyte zone had greater number of species and also some shifts in the composition of floating-leaved plant species had occurred (Table 1). Most important is the disappearance of *Isoëtes lacustris*, even though its presence was just noted in 1968 (Mäemets, 1977). Therefore some shifts in vegetation took place already before ground water abstraction began. It is hard to estimate the possible water-level drop by then, since previous data was from 1960 and upcoming from 1973 but we could assume it was closer to the latter. In 1976 when next vegetation monitoring took place the water level had dropped even more (Figure 3) being at least 2.5 meters lower than in 1946. These hydrological changes are also reflected in the vegetation composition as the helophyte zone has increased in mass as well as in species. Helophytes such as *Phragmites australis, Schoenoplectus lacustris* and *Typha* spp. had colonized the shoreline. *Potamogeton natans* dominated among floating-leaved plants. Most importantly *Lobelia dortmanna* and *Sparganium angustifolium* which were found just 5 years ago had disappeared. In case of L. Ahnejärv it is quite clear that the establishment of the groundwater intake in 1972 and the rapid water-level drop had direct negative impact on the vegetation just in four years. The abruptness of these changes indicates the vulnerability of the vegetation to lake-level changes. Nowadays when the lake level and volume have slightly recovered, the vegetation has not (Figures 2, 3; Table 1). Rare oligotrophic species are absent, *Phragmites australis* dominates the helophyte zone and floating-leaved plants cover most of the near shore areas. Only *Myriophyllum* sp., species not found during prior monitorings, represents the submerged macrophytes.

Table 1. Results of vegetation monitoring in three studied lakes. Data from years with italic font style are based on overall description from less thorough studies. Data from years with bold font style are from thorough studies with species list. Past macrophyte data taken from: Riikoja, 1940; Miljan, 1958; Mäemets, 1977; Pallo, 1977; Ott, 2001; 2006

	L. Kuradijärv					L.Ahnejärv				L. Martiska					
Species	*1935-1936*	**1958**	**1976**	*2006*	**2011**	*1935-1936*	**1971**	**1976**	**2011**	*1935-1936*	**1968**	**1976**	**1980-1981**	**1985**	**2001**
Alisma plantago-aquatica L.							x		x						
Bidens sp.												x			
Calamagrostis sp.															x
Carex spp.			x		x	x	x	x		x	x	x	x	x	x
Ceratophyllum sp.								x				x			
Chara spp.													x		x
Elodea canadensis Michx.			x					x			x	x	x	x	
Equisetum fluviatile L. em Ehrh.					x			x	x				x	x	x
Glyceria maxima (Hartm.) Holmb.								x							
Glyceria maxima (Hartm.) Holmb.															x
Isoëtes lacustris L.						x				x	x	x	x		
Juncus spp.			x		x		x	x				x			x
Lobelia dortmanna L.						x	x			x	x	x	x		
Lycopus europaeus L.					x							x			
Lysimachia thyrsiflora L.							x								
Molinia caerulea (L.) Moench					x				x						
Myriophyllum sp.									x						
Nitella spp.							x								
Nuphar lutea (L.)						x		x		x	x				x
Nuphar pumila							x								

Nymphaea alba L.					x		x	x	x					x	
Nymphaea candida C. Presl						x				x	x				
Peucedanum palustre (L.) Moench									x						
Phragmites australis (Cav.) Trin. ex Steud.			x	x	x			x	x			x	x	x	x
Polygonum amphibium L.				x											x
Potamogeton alpinus Balb.						x	x						x	x	
Potamogeton berchtoldii Fieber													x	x	
Potamogeton natans L.			x	x	x	x	x	x	x			x	x	x	x
Potamogeton praelongus Wulfen													x		x
Potentilla palustris (L.) Scop.								x	x						
Rorippa sp.												x			
Schoenoplectus lacustris (L.) Palla								x	x				x		
Sparganium angustifolium Michx.						x	x			x	x	x			
Sparganium sp.			x								x	x	x	x	
Spirodela polyrrhiza (L.) Schleid.															x
Typha angustifolia L.			x					x				x			
Typha latifolia L.			x		x		x	x	x			x	x	x	

L. Martiska was also initially inhabited by *Lobelia dortmanna* and *Isoëtes lacustris* (Table 1). Fortunately there are vegetation records between the initial slight water-level drop in 1950s and extreme water-level changes after 1972 (Figure 3). In 1968 the vegetation was similar to that in 1936. *Lobelia dortmanna* and *Isoëtes lacustris* were found in moderate amount and also *Sparganium angustifolium* was still present. It seems that the vegetation in L. Martiska was more resistant to slight water-level drop compared to L. Ahnejärv. Overall species composition and amount had not changed much (Table 1). Some changes in vegetation had taken place by 1976 when the water level had dropped at least 2 meters (Figure 3). Number of helophyte species had increased (including *Phragmites australis* and *Typha spp.*) but still *Carex* spp. dominated. *Nymphaea alba* and *Nuphar lutea* had been replaced by *Potamogeton natans* which now colonized the floating-leaved plant zone. Regardless to these changes *Lobelia dortmanna*, *Isoëtes lacustris* and *Sparganium angustifolium* were still found. *Lobelia dortmanna* and *Isoëtes lacustris* were also found in 1980-1981 but *Sparganium angustifolium* had disappeared. It is reasonable to assume that the water level had dropped even more by the time as the peak in the drop was recorded only a few years later. Also the helophyte and the floating-leaved plant zones had become more abundant. In 1985, just two years before the water level had dropped up to 3.4 meters and only 21% of the original lake volume remained (Figures 2, 3), *Lobelia dortmanna* and *Isoëtes lacustris* had disappeared. The helophyte zone was abundant with *Potamogeton* species. Even though *Lobelia dortmanna* and *Isoëtes lacustris* endured initial water level drop and did not disappear as quick as in L. Ahnejärv, the abundance still gradually decreased leading to eventual disappearance only 13 years after the ground water abstraction began. Vegetation showed no signs of recovery in 2001 even though the lake level had already started to increase again.

Also alternative factors besides water-level lowering must be considered as the possible reason for changes in vegetation, especially concerning the disappearance of rare oligotrophic species. Water chemistry is one possibility as it can affect the macrophytes in lakes, especially vulnerable oligtrophic species. Fortunately we have water chemistry data from times before the lake-level lowering and from the period of absolute minimum lake levels. The water-level drop slightly affected the lake water chemistry in all three lakes but not uniformly (Table 2). Mäemets (1977) suggested that the disappearance of *Lobelia dortmanna* is likely due to high mineral levels in lake water. Data on the other hand shows that mineral levels have rather dropped, only the content of $SO4^{2-}$ has slightly risen in all three lakes. Pulido et al. (2012) state that high amounts of $SO4^{2-}$ can have a negative impact on *Lobelia dortmanna* population as the increase in $SO4^{2-}$ can stimulate sediment mineralization leading to anoxia. But even though the amounts of $SO4^{2-}$ in all three lakes have increased in many folds they are still relatively low and it is questionable if that may be the cause to disappearance of *Lobelia dortmanna*. Still, the difference in $SO4^{2-}$ concentrations in L. Martiska and L. Ahnejärv could explain the faster dissapearance of *Lobelia dortmanna* in L. Ahnejärv where more sulfates were found (Table 2). But as we have water chemistry data only from two periods it would be hasty to draw any further conclusions.

Table 2. Water chemistry in 1937 (Riikoja, 1940) and 1986-1987 (Sagris, 1989)

Lake	HCO^{3-} (mg/l)		Ca^{2+} (mg/l)		Mg^{2+} (mg/l)		$SO4^{2-}$ (mg/l)	
	1937	1986-1987	1937	1986-1987	1937	1986-1987	1937	1986-1987
L. Ahnejärv	154	36.7	32.2	9.4	10.8	4.7	5.8	16.4
L. Kuradijärv	7.5	27.9	1.4	5.5	1	2.1	2.9	11.4
L. Martiska	27.2	25.4	7.5	5.1	0.7	1.7	1.9	10.7

The disappearance of oligotrophic and increase in more eutrophic species is more likely linked to the changes in lake level and therefore to the changes in possible habitats. With the water-level lowering old litoral zones became dry shoreline, sediments were washed in to deeper parts of the lake and new possible habitat areas had probably different lithological composition. As *Lobelia dortmanna* prefers sandy sediments with low oxygen consumption, it may have difficulties inhabiting new areas with higher organic content and oxygen demand resulting in limited oxygen availability not suitable for the species (Møller&Sand-Jensen, 2011). But as *Lobelia dortmanna* was still found at least in some extent even after several meters of water-level drop (Figure 3, Table 1), it must have been able to inhabit some new areas.

Based on the gradual disappearance of *Lobelia dortmanna* and *Isoëtes lacustris* in L. Martiska we can hypothesize that if the lake-level changes would have been more subtle and expanded on longer time period, it is possible that these oligotrophic species could have adapted to new conditions and habitat areas. The experiment of reintroduction of *Lobelia dortmanna* to L. Martiska was being considered, but the idea was discarded after the new water-level drops in 2012. Until the water levels are being restored and stabilized the efforts would be futile and the potential replanting experiment must wait for its time.

5 CONCLUSIONS

Aquatic vegetation of three once oligotrophic lakes was severely impacted by rapid water-level drops caused by the groundwater abstraction. Regardless of different morphological parameters the water level dropped 3–4 meters in all three lakes with a volume loss of 57–79%. The water-level drop was most extreme in L. Kuradijärv and as a result once vegetation free lake became colonized by extensive zones of helophytes and floating-leaved plants. In L. Ahnejärv the oligotrophic species *Isoëtes lacustris* disappeared already after a slight water-level drop and *Lobelia dortmanna* and *Sparganium angustifolium* were missing four years after the extreme lowering of water level. In L. Martiska the oligotrophic species *Lobelia dortmanna* and *Isoëtes lacustris* withstood water-level lowering for 13 years with gradual decrease in abundance leading to eventual disappearance. Disappearance of rare oligotrophic isoetids can also be partly due to increase of $SO4^{2-}$ in lake water but there is no conclusive evidence for that. Rather it is the combination of different factors: lake-level lowering exposing less suitable habitats for the species and changes in water chemistry making the overall environment less tolerable. The vegetation in all three lakes did not show any sign of recovery during 20 year period since the decrease of groundwater abstraction in 1990s leading to gradual increase in lake levels. Since 2012 the water levels have started to decrease again and are now reaching or even exceeding the once recorded minimum levels.

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