Lakes, reservoirs and ponds, vol. 9(1): 29-42, 2015

CHANGES IN SEDIMENTATION AND AQUATIC VEGETATION CAUSED BY DRASTIC LAKE-LEVEL FLUCTUATION

Tiit VAASMA, Jaanus TERASMAA, Egert VANDEL
Institute of Ecology, Tallinn University
Uus-Sadama 5, Tallinn, Estonia; Tel: +3726199828, Email: vaasma@tlu.ee

Abstract

This study identifies the water-level fluctuation signals from the lake sediment. The water level of small Lake Martiska (Estonia) decreased 3.4 m from 1946 to 1987 and only 29% of lake area and 21% of total volume remained. Since the 1990s the water level started to rise. The comparison between the LOI, grain-size distribution and documented water-level changes suggests that sign of water-level fluctuation in clearly reflected in sediment cores from the transportation and accumulation area. Regression causes the coarse-grained sediment transportation to the deepest area of the lake, but the transgression leaves a different pattern – when the lake level recovers, the connection with the previously available near-shore sand is still missing and only the previously reworked material can be transported to deeper area. During the water-level fluctuation period the accumulated sediments originate from two main sources: previously accumulated lacustrine sediments and the glaciolacustrine nearshore sands. The water-level fluctuation has also affected the ecology of the lake. Previously oligotrophic lake is now mesotrophic and the rare characteristic species for oligotrophic lakes such as *Isoëtes lacustris* L. and *Lobelia dortmanna* L. have disappeared.

Keywords: grain size, water-level fluctuation, lake sediment, lake ecology, macrophytes, human impact, palaeolimnology

1. INTRODUCTION

One possibility to study past lake-level changes is to use grain-size analysis. The amount of mineral matter and grain-size composition of sediment are the indicators of sedimentation processes in the lake basin (Digerfeldt, 1986; Dearing, 1997; Boyle, 2001; Punning et al., 2006; 2007;

Sun et al., 2002; Terasmaa, 2005; Terasmaa et al., 2013; Vaasma, 2010) and changes in water level, which enable reconstruction of the hydrological balance of the lake. Due to fractionation of sediment (Hilton et al., 1986; Gilbert, 2003) the mean grain size of mineral deposits decreases with increasing distance from the shore at which the sediment originate (Allen, 1970).

Human impact and water-level fluctuations may affect the lake ecosystem and sedimentation (Vandel & Koff, 2011), as well as lake morphometry and characteristics of the sedimentation zones (erosion, transportation, accumulation; Håkanson, 1977) of the lake bed. Water-level fluctuations can also affect the balance between clear water and turbid states through abundance of submerged macrophytes (Blindow, 1992). Once the equilibrium is unbalanced, the new state can be long-termed without natural scenario to preliminary state as the decreasing submerged vegetation can lead to wind driven sediment resuspension (Liu et al., 2013) and thereupon to release of nutrients, phytoplankton blooms and reduced photic conditions, all having again a negative impact on submerged vegetation (Schallenberg&Burns, 2004). 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 abruptly lowered water levels are quite rare. Study from Swedish small oligotrophic lakes (Lillieroth, 1950) showed that water-level lowering (up to 2 m) tended to affect the lakes macrophytic and planktonic communities towards slightly more eutrophic direction.

Lakes of the Kurtna Kame Field (Kurtna Lake District) in Estonia have been previously actively studied (Mäemets, 1977; Pallo, 1977; Varvas&Punning, 1993; Punning, 1994; Ott et al., 1995; Koff &Vandel, 2008; Marzecova et al., 2011; Vainu&Terasmaa, 2014; Vainu et al., 2015). From 1985 to 1989 a complex research was carried out on the Kurtna Kame Field including hydrology and hydrobiology of the area, regional ecosystem development, geochemical analyses, mining impact on hydrological conditions, etc. These studies have been published in two comprehensive collections of articles (Ilomets, 1987; 1989).

In the Kurtna Lake District large scale water-level changes have occurred during the last decades. Therefore it offers a valuable case study where human induced lake-level lowerings are long-termed and vast – only less than quarter of the lake volumes remained. The previous conducted studies of the area make the site suitable for calibrating the palaeolimnological methods. It also presents an opportunity to observe if and to which extent the vegetation and ecological status of once oligotrophic lake have recovered after partial water-level restoration. Historical datasets combined with our studies provides possibility to assess the effect of water-level changes to the lithological composition of the sediment - whether and how this signal is preserved in the lake sediment and how much the position of the sampling point from the shoreline and slope inclination affects the information signal.

The main aim of this research was to identify the effect of water-level fluctuations to sedimentation patterns and lake ecology (macrophytes) of small Lake Martiska, based on documented historical changes in human impact, macrophyte monitoring and comparison of eight short-core (up to 36 cm) sediment records. In order to comprehend and interpret the palaeoecological signal it is highly essential to understand the processes and how the changes are stored in sediments.

2. STUDY AREA

Lake Martiska (L. Martiska) is located in northeastern Estonia (57°38´07´´ N, 27°05´06´´ E) (Figure 1) in the area of the Kurtna Kame Field, where about 40 lakes with different shape, size, drainage area, hydrological regime and trophic status form the Kurtna Lake District. The Kurtna Lake District, located between heavily industrialised oil shale mining and processing region (Figure 1), is an area with the highest lake density in Estonia. Most of the lake district belongs to the Kurtna Landscape Conservation Area with large forests and mires. It is very popular recreation area for tourists and local people. The Natura 2000 Network habitat lake L. Martiska is strongly affected by groundwater abstraction since 1972 from Vasavere wells (Vainu&Terasmaa, 2014). Hydrology of the Kurtna region is also affected by oil shale mining and processing (Punning, 1994).

L. Martiska formed during the Preboreal (ca 10,000-9,500 years ago) and lies in a deep kettle hole. The lake is small (area 3.0 ha, maximum depth 7.8 m), closed, fed by groundwater and atmospheric precipitation, north-south elongated with a weakly indented shoreline. Its dynamic ratio is 0.08, which means that sedimentation is very weakly influenced by wind/wave activities (Håkanson&Jansson, 1983). The lake is dimictic and strongly stratified in summertime. The anoxia occurs in hypolimnion throughout the year, except during the spring and autumn overturn periods. L. Martiska has been described as an oligotrophic lake but its trophic state has increased in the last decades due to the direct and indirect human impacts (Punning, 1994). During 1946–1987 lake level dropped from 46.0 m a.s.l. to 42.6 m a.s.l. (Erg&Ilomets, 1989). In May 2012 lake level was measured to be 44.2 m a.s.l.

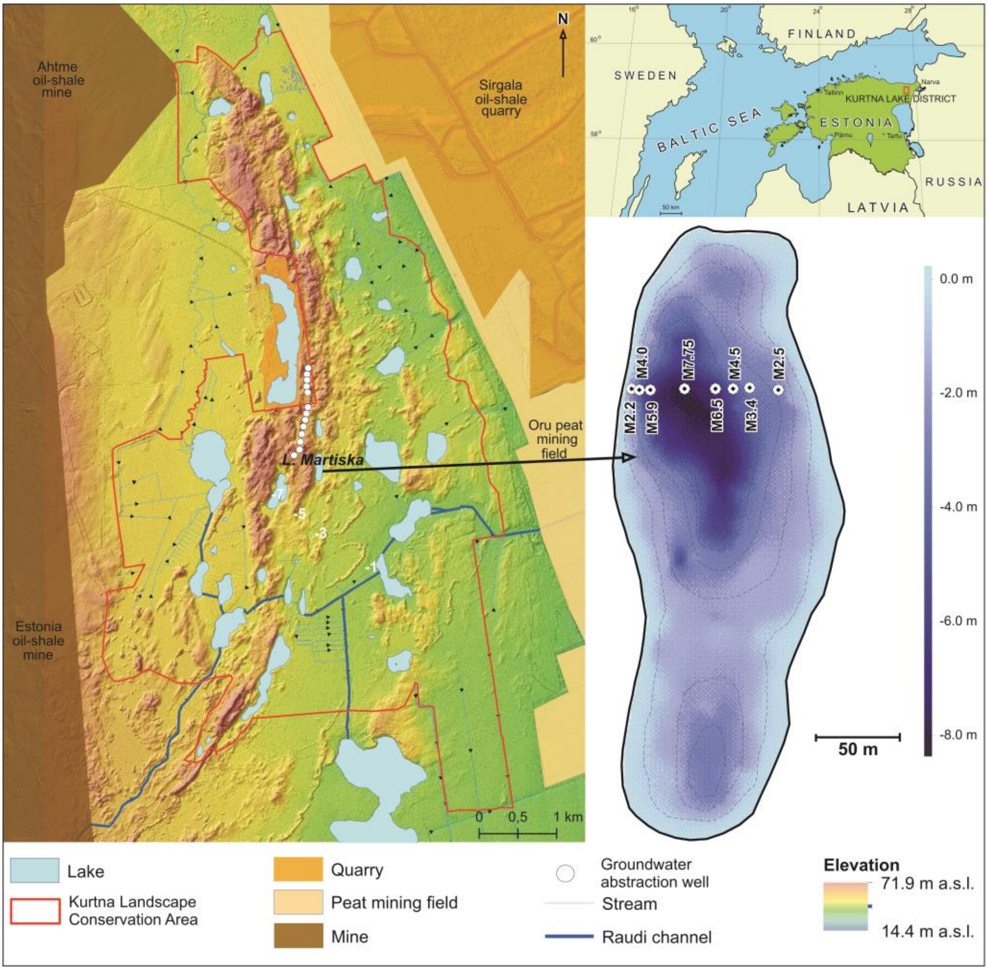

Figure 1. Location of Kurtna Lake District in northeastern Estonia and L. Martiska with the sampling points. The index of the sampling point marks also the water depth at this point on sampling day.

L. Martiska feeds from precipitation directly and through the surface and groundwater. The lake loses the water by evaporation from the lake surface and by seepage to groundwater. The main input of L. Martiska water is from catchment runoff and the main output of water is seepage into groundwater. (Vainu&Terasmaa, 2014)

L. Martiska used to be *Lobelia-Isoëtes* lake. Before the industrial impact and water-level lowering 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* Michx. was found. *Nymphaea candida* C. Presl and *Nuphar lutea* (L.) formed the majority of floating-leaved species, but the lake was rich with oligotrophic species such as *Lobelia dortmanna* L. and *Isoëtes lacustris* L.

On the L. Martiska catchment area pine forests dominate; soils are poor and well-sorted mostly fine-grain sands (Vares, 1987; Kont&Arold, 1987).The western part of the lake catchment area is steep sandy kame which is up to 20 m in relative height. The kame to the east of the lake is gentler and up to 6 m in relative height. The northern sandy shore is a popular swimming area. The southern part of the lake is rich in vegetation and there are old stumps and trunks of trees in the lake.

3. METHODS

Eight short sediment cores (18-36 cm) were collected during winter on ice using a modified Livingstone-Vallentyne piston corer. The sediment cores were visually recorded and described in the field. The cores were taken from different depths (2.2, 4.0, 5.9, 7.75, 6.5, 4.5, 3.4, 2.5 m) on transect from west to east through the deepest part of the lake (Figure 1 and 2).

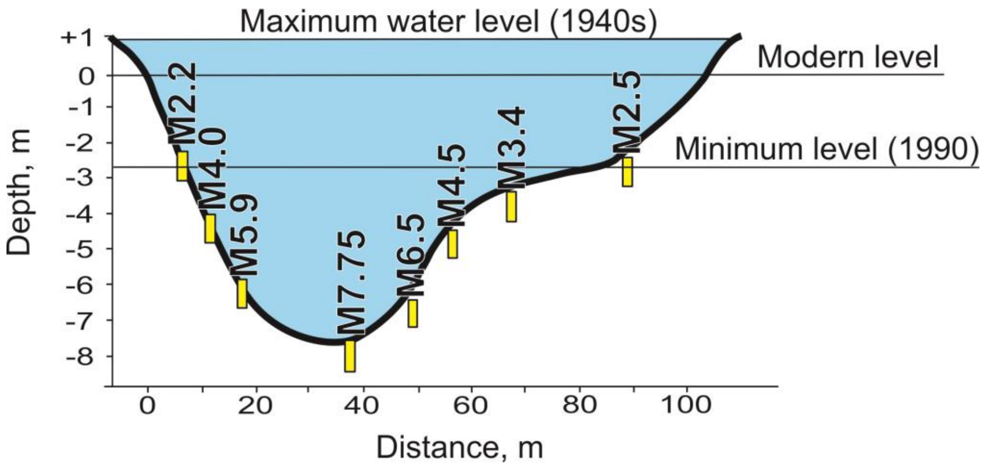

Figure 2. The locations of the sampling points on the profile view with water levels during last 70 years. The index of the sampling point marks also the water depth at this point on sampling day.

The sediment cores were sliced with intervals of 1 cm and stored in the plastic boxes and analysed in the laboratory immediately. The concentration of dry matter in the sediment was measured after drying the samples at 105°C to constant weight. Organic matter was determined from the dried sample by loss on ignition (LOI) method after heating at 550°C for 3.5 h (Heiri et al., 2001). The residual amount was considered as mineral matter. Before grain-size measurements the sediment was pre-treated with hydrogen peroxide for removing the organic matter (Vaasma, 2008). Then the grain size was determined using Fritsch Laser Particle Sizer "Analysette 22".

For the age-depth model one core was radiometrically dated (^{210}Pb method and CRS ^{210}Pb model was used) at the Centre for Environmental Monitoring and Technology, Ukrainian Hydrometeorological Research Institute in Kiev.

Cluster analysis was performed using the results of grain-size analysis and other lithological characteristics (mineral, organic, dry matter).

In order to describe the modern aquatic vegetation the whole littoral zone was traversed by boat and the species composition and depth limits of different plant groups were recorded. For submerged aquatic plants, which were not visible, five throws with a grapple were made around the boat at random depths and points every now and then.

4. RESULTS AND DISCUSSION

In L. Martiska the water level started to decline already since the end of the 1940s caused by the growth of a pine forest (before the 1950s the vicinty of the lake was treeless) on the lake catchments, due to this evapotranspiration and subsequently runoff from the catchment decreased. Also meteorological changes (drier climate) played an important role (Vainu&Terasmaa, 2014). The main reason for the water-level drop between the 1970s and 1987 was the beginning of groundwater abstraction from the Vasavere wells in 1972. The result of the water-level drop was a decrease in the lake area from 4.5 to 1.3 ha and volume from 124,000 to 26,000 m^3. The water-level rise since the beginning of the 1990s has been caused by the change of meteorological conditions and the rise of groundwater level – the abstraction of groundwater from Vasavere wells decreased.

According to the data, three phases could be distinguished in the water level and sedimentation process in L. Martiska:

(1) water-level declining since the end of the 1940s;
(2) minimum lake-level phase in 1988-1992;
(3) water-level rising since 1992.

The water-level fluctuation causes erosion and redeposition of sediments. Such changes affect the mineral content and the grain-size distribution of the sediment (Shteinman&Parparov, 1997). In L. Martiska the eroded material originates from limnoglacial sands that surround the lake and from previously accumulated lacustrine sediments. The mineral matter concentration values of eight studied short cores show that the variations are marginal in the lowermost part (deeper than 14 cm) of the cores (Figure 3). This means that the sedimentation conditions were stable. Above ca 14 cm the concentration of mineral matter increases steadily except in the core M2.5. During the water-level decline the mineral matter content in the deeper area of the lake increases because these areas were closer to the shoreline and sand was eroded to deeper down compared to the higher water period. During the regression period, the mineral matter content reached the maximum values (Figure 3), which reflects the addition of eroded material.

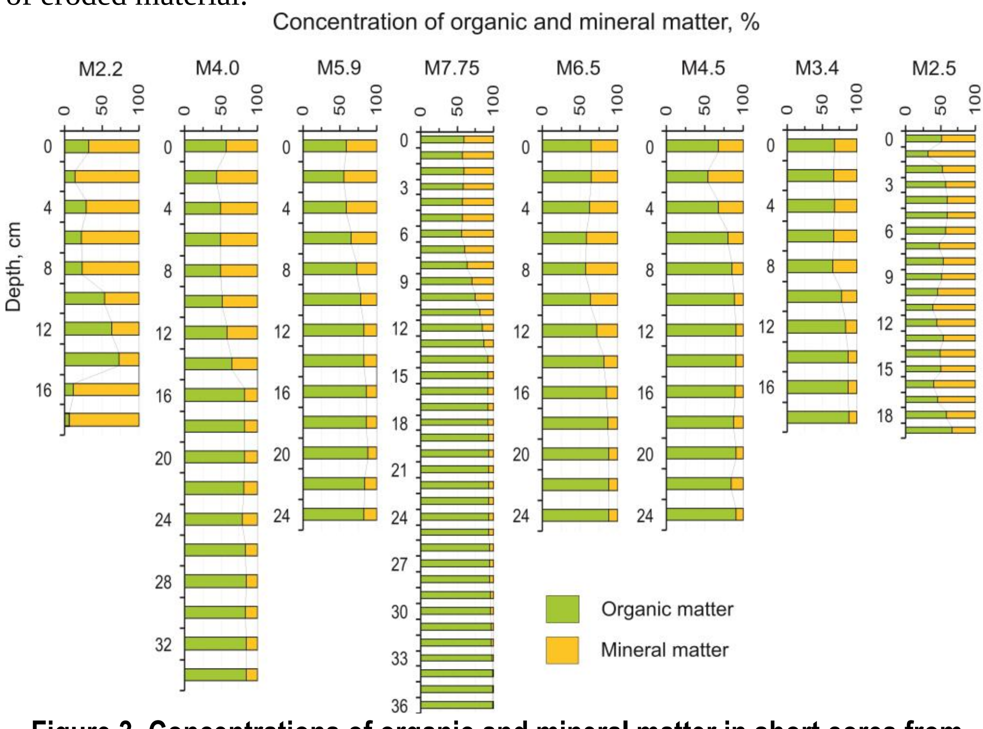

Figure 3. Concentrations of organic and mineral matter in short cores from L. Martiska (locations of the sampling points on Figure 1 and 2; dates on Figure 4).

The high mineral matter content of the sites M2.2 and M2.5 (Figure 3) is caused by the location of the sampling points: in shallow water and close to the shore. In these cores the grain size of sediment is close to sands around the lake. On the steeper slope (36.3%) and closer to the shore (6 m) the core M2.2 has a little higher mineral matter content in the sediment than the site M2.5 (with slope inclination 11.3% and 20 m from shore). Håkanson&Jansson (1983) demonstrated that the mineral matter content is considerably higher in shallow areas of the lake with steep slopes compared to the deeper areas that are further away from the shore.

In L. Martiska the signal of the water-level fluctuation is stronger in the deeper area of the lake (in sites M5.9, M6.5 and M7.75; Figure 3 and 4). In the deeper part of the core M7.75 the median values of grain size vary from 7.0 to 9.9 µm, corresponding to fine and medium silt. The data suggest (Figure 4) that during the regression phase (sediment layers from depths of 14-15 cm up to 6-7 cm) mainly medium and coarse silt accumulated. Above 14 cm in the core M7.75 the content of the coarser fraction increases, reaching a sharp maximum at 7 cm (median value 16.1 µm; coarse silt). This layer is probably accumulated in the beginning of the 1990s when the water level was the lowest. It describes the situation when main source of the mineral matter was well-sorted sediments that accumulated in the lake before the water-level drop. The mineral matter is carried into the lake from the catchment area by erosion. It starts to focus and fraction in a way that leaves the coarse-grained material in the shallower areas and finer-grained material in the deeper areas of the lake (Dearing, 1997; Terasmaa, 2005). The increase in the grain-size median value that took place at the site M5.9 between 12 and 4 cm was caused by the increasing domination of coarse-grained silt. When the water level gradually declined, coarse-grained material could move towards the deeper areas (Blazevic et al., 2009).

In the transgression period the sedimentation regime stabilised and sediments became better sorted and more fine-grained. During the transgression (sediment layers above 6-7 cm) the proportion of fine-grain silt increases, but the median grain size (in the core M7.75 from 10.8 to 12.8 µm) remains higher than in the deeper layers. The earlier regression reworked the top layer of the sediment (certain fraction intervals were carried away), and as water level rose the material that had already been processed once was processed again. The lake water table had no direct contact with the shore areas from where new sand could be eroded.

Regression and transgression periods are distinguishable also by cluster analysis (Figure 4) with some shorter periods but we can clearly recognise stable sedimentation before regression (up to17-14 cm), regression (up to 7 cm), and transgression according to the core M7.75. Thus statistical processing confirmed the influence of water-level fluctuation on grain-size distribution.

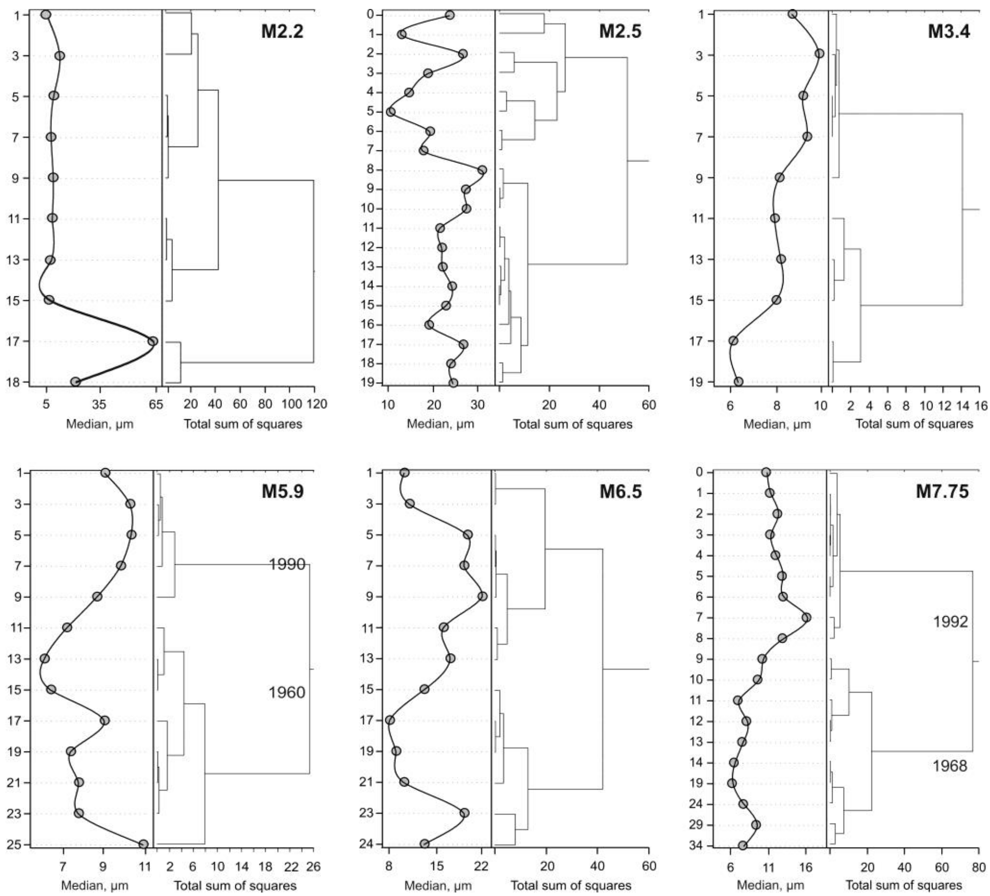

Figure 4. Median values of grain-size distribution and results of cluster analysis (grain size, mineral, organic and dry matter). Locations of the sampling points are on Figure 1 and 2.

Water-level changes have also impacted the lake ecology. In 1935-1936 L. Martiska was inhabited by *Lobelia dortmanna* and *Isoëtes lacustris* (Riikoja, 1940). In 1968 (Ott, 2001) *Lobelia dortmanna* and *Isoëtes lacustris* were still found in moderate amount even though the water level had already begun to drop. They were also noted in 1980-1981 but in 1985, just two years before the water level had dropped to its minimum level (3.4 meters below maximum) *Lobelia dortmanna* and *Isoëtes lacustris* had disappeared (Ott, 2001). Instead the helophyte zone was abundant and *Potamogeton* species thrived. In 2001 the lake level had already started to increase but vegetation showed (Ott, 2001) and still does not show (summer 2013) any signs of recovery. Based on the gradual disappearance of *Lobelia dortmanna* and *Isoëtes lacustris* in L. Martiska we can hypothesize that if the lake-level drop would have been more gradual and expanded on longer time period, these oligotrophic species could have adapted to new conditions and habitat. There is also possibility that even though *Lobelia dortmanna* and *Isoëtes lacustris* almost coped with the abrupt water-level lowering they did not stand the water-level rise. Similarly to mineral matter the seeds of plants are transported during water-level lowering to areas suitable for seed germination, but during water-level rise the produced seeds will be settled in the area not suitable (too high water level) for germination. The experiment of reintroduction of *Lobelia dortmanna* is being considered in L. Martiska but the ecological conditions of the sediment and water needs prior studies.

5. CONCLUSION

The water-level fluctuations in L. Martiska since the end of the 1940s have had significant impacts on the concentration of mineral matter and its grain-size composition in sediment. During regression the concentration of mineral matter was rising and the sediment became coarser in the deeper area of the lake and vice versa in transgression period. The lake-level fluctuation was responsible for essential changes in the composition and structure of sediments and consequently in the trophic status and biodiversity. Rapid water-level drop caused by the groundwater abstraction had also severe impact on the vegetation of the L. Martiska: oligotrophic species like *Lobelia dortmanna* and *Isoëtes lacustris* have disappeared. Even though the water level has partially recovered after the beginning of 1990s, the vegetation shows no sign of recovery.

Acknowledgements

The authors thank the Environmental Conservation and Environmental Technology R&D Programme Project “EDULOOD”, Estonian Research Council grants ETF6857, ETF8189 and SF0280016s07 and colleagues from the Institute of Ecology at Tallinn University.

REFERENCES

Allen, J.R.L. 1970, Physical processes of sedimentation: an introduction, In: Sutton, J. (ed.) *Earth Science Series, vol. 1*, Edit. George Allen and Unwin, 248p.

Blazevic, M.A., Kirby, M.E., Woods, A.D., Browne, B.L. & Bowman, D.D. 2009, A sedimentary facies model for glacial-age sediments in Baldwin Lake, Southern California, *Sedimentary Geology*, **219**, 151-168.

Blindow, I. 1992, Long- and short-term dynamics of submerged macrophytes in two shallow eutrophic lakes, *Freshwater Biology*, 28:1, 15-27.

Boyle, J.F. 2001, Inorganic geochemical methods in palaeolimnology, In: Last, M.L. & Smol, J.B. (eds.) *Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Geochemical Methods*, Edit. Kluwer Academic Publishers, Dordrecht/Boston/London, 83-141.

Dearing, J.A. 1997, Sedimentary indicators of lake-level changes in the humid temperate zone: a critical review, *Journal of Paleolimnology*, **18**, 1-4.

Digerfeldt, G. 1986, Studies on past lake-level fluctuations, In: Berglund, B.E. (ed.) *Handbook of Holocene Palaeoecology and Palaeohydrology*, Edit. John Wiley and Sons, Chichester – New York, pp. 127-143.

Erg, K. & Ilomets, M. 1989, Mäetööde mõju Kurtna järvede veetasemele seisund ja prognoos (The effect of mining on the water level of Kurtna lakes current state and prognoosis), In: Ilomets, M. (ed.) *Kurtna järvestiku looduslik seisund ja selle areng II (Natural Status and Development of Kurtna Lake District II),* Valgus, Tallinn, pp. 47-54 [in Estonian].

Gilbert, R. 2003, Spatially irregular sedimentation in a small, morphologically complex lake: implication for paleoenvironmental studies, *Journal of Paleolimnology*, 29, 209-220.

Havens, K.E., Sharfstein, S., Brady, M.A., East, T.L., Harwell, M.C., Maki, R.P. & Rodusky A.J. 2004, Recovery of submerged plants from high water stress in a large subtropical lake in Florida, USA, *Aquatic Botany*, **78**:*1*, 67-82.

Heiri, O., Lotter, A.F. & Lemcke, M.-J. 2001, Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results, *Journal of Paleolimnology*, **25**, 101-110.

Hilton, J., lishman, J.P. & Allen, P.V. 1986, The dominant processes of sediment distribution and focusing in a small, eutrophic, monomictic lake, *Limnology and Oceanography*, **31**, 125-133.

Håkanson, L. 1977, The influence of wind, fetch and water depth on the distribution of sediments in Lake Vänern, Sweden, *Canadian Journal of Earth Sciences*, **14**, 397-412.

Håkanson, L. & Jansson, M. 1983, *Principles of Lake Sedimentology,* Edit. Springer-Verlag, Berlin, 316p.

Ilomets, M. (ed.) 1987, *Kurtna järvestiku looduslik seisund ja selle areng. 3-8. november 1986. a. toimunud ametkondadevahelise nõupidamise ettekannete kogumik (Natural Status and Development of the Kurtna Lake District I)*, Edit. Valgus, Tallinn, 234p [in Estonian].

Ilomets, M. (ed.) 1989, *Kurtna järvestiku looduslik seisund ja selle areng. 7. ja 8. aprillil 1988. a. toimunud II ametkondadevahelise nõupidamise ettekannete kogumik (Natural Status and Development of the Kurtna Lake District II)*, Edit. Valgus, Tallinn, 169p [in Estonian].

Koff, T. & Vandel, E. 2008, Spatial distribution of macrofossil assemblages in surface sediments of two small lakes in Estonia, *Estonian Journal of Ecology*, 57:1, 5-20.

Kont, A. & Arold, I. 1987, Kurtna mõhnastiku reljeefi põhijooni (Topography of Kurtna Kame Field), In: Ilomets, M. (ed.) *Kurtna järvestiku looduslik seisund ja selle areng II (Natural Status and Development of Kurtna Lake District I),* Valgus, Tallinn, pp. 25-31 [in Estonian].

Lillieroth, S. 1950, Über Folgen kulturbedingter Wasserstandsenkungen für Makrophyten- und Planktongemeinschaften in seichten Seen des südschwedischen Oligotrophiegebietes; eine Studie mit besonderer Berücksichtigung der angewandten Limnologie: eine Studie mit besonderer Berücksichtigung der angewandten Limnologie. Edit: Thunmark, S. *Acta Limnologica*, 3, 288p [in German, summary in English].

Liu, X., Zhang, Y., Yin, Y., Wang, M. & Qin, B. 2013, Wind and submerged aquatic vegetation influence bio-optical properties in large shallow Lake Taihu, China, *Journal Of Geophysical Research: Biogeosciences*, **118**, 1-15.

Marzecova, A., Mikomägi, A., Koff, A. & Martma, T. 2011, Sedimentary geochemical response to human impact on Lake Nõmmejärv, Estonia, *Estonian Journal of Ecology,* **60**:*1*, 54-69.

Miljan, A. 1958, *Toitainetevaeste järvede vegetatsioonist Eesti NSV-s [Vegetation of oligotrophic lakes in Estonian SSR]*. In: Vaga, A. (ed) Botaanika-alased tööd [Studies in Botany], Tartu Riikliku Ülikooli Toimetised, Tartu, pp. 119-137 [in Estonian].

Mäemets, A. (ed.) 1977, *Eesti NSV järved ja nende kaitse (Lakes of Estonian SSR and the protection)*, Edit. Valgus, Tallinn, 263p [in Estonian].

Ott, I. 2001, *Eesti väikejärvede monitooring 2001 (Monitoring report of Estonian small lakes 2001)*. EPMÜ Zooloogia ja Botaanika Instituut , 67p [monitoring report in Estonian].

Ott, I., Laugaste, R., Mäemets, A., Mäemets, A., Kaup, E., Künnis, K., Heinsalu, A., Toom, A., Lokk, S. & Põder, T. 1995, *Kurtna järvestiku limnoloogiline ekspertiis (Limnological assessment of Kurtna Lake District)* [manuscript in Estonian].

Pallo, S. 1977, *Kurtna järvestik (Kurtna Lake District)*, diploma, Tartu Riiklik Ülikool, Füüsilise geograafia kateeder [manuscript in Estonian].

Punning, J.-M. (ed.) 1994, *The influence of natural and anthropogenic factors on the development of landscapes. The results of a comprehensive study in NE Estonia*, Edit. Institute of Ecology, Estonian Academy of Science, Publication 2, 227p.

Punning, J.-M., Terasmaa, J. & Vaasma, T. 2006, The impact of lake-level fluctuations on the sediment composition, *Water, Air, and Soil Pollution: Focus*, **6**:*5-6*, 515-521.

Punning, J.-M., Boyle, J.F., Terasmaa, J., Vaasma, T. & Mikomägi, A. 2007, Changes in lake sediment structure and composition caused by human impact: repeated studies of Lake Martiska, Estonia, *The Holocene*, **17**:*1*, 145-151.

Riikoja, H. 1940, Zur Kenntnis einiger Seen Ost-Eestis, insbesondere ihrer Wasserchemie, In: *Eesti Teaduste Akadeemia juures oleva Loodusuurijate seltsi aruanded, XLVI*, Tartu, 1-167.

Schallenberg, M. & Burns, C.W. 2004, Effects of sediment resuspension on phytoplankton production: teasing apart the influences of light, nutrients and algal entrainment, *Freshwater Biology*, **49**, 143-159.

Shteinman, B.S. & Parparov, A.S. 1997, An approach to particulate matter transfer studies in littoral zones of lakes with changing morphometry, *Water Science and Technology*, **36**, 199-205.

Sun, D., Bloemendal. J., Rea, D.K., Vandenberghe, J., Jiang, F., An, Z. & Su, R. 2002, Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components, *Sedimentary Geology*, **152**:*3*, 263-277.

Terasmaa, J. 2005, Bottom topography and sediment lithology in two small lakes in Estonia, *Proceedings of the Estonian Academy of Sciences. Biology, Ecology*, **54**:*3*, 171-189.

Terasmaa, J., Puusepp, L., Marzecová, A., Vandel, E., Vaasma, T. & Koff, T. 2013, Natural and human-induced environmental changes in Eastern

Europe during the Holocene: a multi-proxy palaeolimnological study of a small Latvian lake in a humid temperate zone, *Journal of Paleolimnology*, **49**:*4*, 663-678.
Vaasma, T. 2008, Grain-size analysis of lacustrine sediments: a comparison of pre-treatment methods, *Estonian Journal of Ecology*, **57**:*4*, 231-243.
Vaasma, T. 2010, *Grain-size Analysis of Lake Sediments: Research Methods and Applications*, PhD theses, Edit. Tallinna University, 130p.
Vainu, M. & Terasmaa, J. 2014, Changes in climate, catchment vegetation and hydrogeology as the causes of dramatic lake-level fluctuations in the Kurtna Lake District, NE Estonia, *Estonian Journal of Earth Sciences*, **63**:*1*, 45-61.
Vainu, M., Terasmaa, J. & Häelm, M. 2015, Relations between groundwater flow in an unconfined aquifer and seepage patterns in a closed-basin lake in glacial terrain. *Hydrology Research* (in press).
Vandel, E. & Koff, T. 2011, Anthropogenically induced changes in the sedimentation processes in the littoral zone of Lake Verevi, South Estonia, *Estonian Journal of Ecology*, **60**:*3*, 167-182.
Vares, K. 1987, Kurtna mõhnastiku pinnasetete geoloogiast (Geology of the sediment of Kurtna Kame Field), In: Ilomets, M. (ed.) *Kurtna järvestiku looduslik seisund ja selle areng II (Natural Status and Development of Kurtna Lake District I)*, Valgus, Tallinn, pp. 32-36 [in Estonian].
Varvas, M. & Punning, J.-M. 1993, Use of the ^{210}Pb method in studies of the development and human impact history of some Estonian lakes, *The Holocene*, **3**, 34-44.
Wallsten, M. & Forsgren, P.-O. 1989, The effects of increased water level on aquatic macrophytes, *Journal of Aquatic Plant Management*, **27**, 32-37.