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GROUNDWATER SEEPAGE PATTERNS IN A CLOSED-BASIN LAKE BEFORE AND AFTER AN INCREASE IN GROUNDWATER PUMPING RATES FROM AN UNCONFINED AQUIFER IN THE KURTNA KAME FIELD, ESTONIA

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Abstract
The Kurtna Kame Field in northeastern Estonia contains around 40 small lakes in a 30 km^2 area. In 1972 a groundwater intake was established in the central part of the Kame Field into an unconfined Quaternary aquifer, which consists mostly of glacial sands. That caused a more than 3 m water-level drop in the closed-basin lakes near the intake, including in Lake Martiska. L. Martiska is a 2.7 ha lake which belongs to the Natura 2000 network of the EU Special Areas of Protection. In the 1990s the abstraction rate decreased and brought about a partial water-level recovery. In 2012 the abstraction wells were renovated and the pumping rate increased again. The subsequent effect on the water level of Lake Martiska was a ca. 0.5 m water-level drop. A two-year study on L. Martiska was carried out in June 2012 and June 2013. The first aim was to elucidate the general seepage patterns in the bottom of the lake and their concurrence with the determined groundwater flow directions. The second aim was to evaluate if and how the increased groundwater pumping affected the seepage patterns and groundwater flow directions. Seepage patterns in the bottom of the lake were measured with seepage meters in June 2012 and in June 2013. The groundwater level and estimated groundwater flow directions in the surrounding Quaternary aquifer were determined with *ArcGIS 10.1* software. For that water level data from monitoring wells, specifically established wells and adjacent lakes were used. The determined seepage patterns in 2012 followed the estimated direction of groundwater flow only in the nearshore areas of the lake. Further than 6 to 15 m offshore in the water depth of 1 to 2 m the seepage patterns ceased to coincide with the expected. Surprisingly the measured flux velocities did not correlate monotonically neither with lake depth, distance from shore nor thickness of organic sediments. Notable seepage influx was registered even through a 3.2 m thick layer of gyttja. Seepage outflux was registered towards the abstraction wells in both years. In 2013 the seepage patterns had slightly changed in the nearshore areas but not significantly offshore. The unexpected offshore patterns of inseepage are hypothesised to be caused by a small local confined aquifer around and underneath the lake.

Keywords: Closed-basin lake, Groundwater abstraction, Groundwater flow, Lake water level, Lake-bed seepage, Seepage meter, Unconfined aquifer

1 INTRODUCTION

Research on the interactions between groundwater and lake water is gaining importance in hydrological science. It has been understood that in order to manage and protect lentic water resources effectively, it is inevitable to take into consideration also the amounts of water that seep into a lake or out from a lake (Winter et al. 1998). Studies on the exchange of water between lakes and groundwater started already in the 1970s in the USA (McBride & Pfannkuch, 1975; Lee, 1977). Research on the topic in Europe has largely started only during the last decade (Kidmose et al., 2011; Rautio & Korkka-Niemi, 2011; Ala-aho et al., 2013; Kidmose et al., 2013; Vainu et al., accepted).

For a sound characterisation of lake-groundwater interaction it is necessary at first to describe the general groundwater flow patterns around the studied lake. Winter et al. (1998) have shown that in most cases it cannot be done according to topographic relief, because groundwater flow patterns tend to be independent from smaller-scale landforms, which are used to delineate surface-water catchments. Groundwater level data measured from wells are needed to determine groundwater catchments and groundwater flow paths for lakes. As groundwater levels can fluctuate because of meteorological reasons or because of groundwater abstraction, the directions of groundwater flow are also open to change (Winter et al., 1998). Changing groundwater flow paths likely bring about changes in the water-budget of the affected lakes, which in turn can cause the deterioration of their ecosystems.

Groundwater-lake water interactions have been described to occur in three general ways: 1) receiving groundwater through their bed, (2) recharging groundwater through their bed, and (3) receiving groundwater through part of their bed and recharging groundwater through the other part (Winter, 2004; Rushton, 2005). In glacial terrain mechanism no. 3 is believed to be the most common (Winter et al., 2003)

In order to determine which seepage pattern is actually occurring in the studied lake, direct measurements of seepage are needed. Several studies have shown that seepage in lake bottom is highly variable and may depend on the structure of the lake sediments and the hydrogeology of the whole lake basin (Kishel & Gerla, 2002; Schneider et al., 2005; Rosenberry & Winter, 2009; Kidmose et al., 2011; Ala-aho et al., 2013; Kidmose et al., 2013). Therefore the groundwater flow directions estimated only according to water-level data from the topmost aquifer surrounding the lake may not give a full picture of the mechanisms of groundwater exchange in the studied lake.

In the current study the patterns of groundwater exchange in a closed-basin lake in glacial terrain affected from groundwater pumping – Lake Martiska – were investigated on two years. In the first year the pumping rate was lower than in the second year. The first aim of the study was 1) to reveal the general seepage patterns in the bottom of the lake and their concurrence with the determined groundwater flow directions; the second aim was 2) to evaluate if and how the increased groundwater pumping affected the seepage patterns in the lake and groundwater flow directions in the surrounding aquifer.

2 STUDY AREA

Lake Martiska (hereafter L. Martiska) (59º15´45´´N, 27º34´14´´E) is a small closed-basin lake in the centre of the Kurtna Lake District in northeastern Estonia (Fig. 1). The lake district contains almost 40 small lakes in a 30 km^2 area in and around the Kurtna Kame Field. The lake belongs to the Natura 2000 network of the EU Special Areas of Protection. In June 2012 the water level of the lake was at 44.2 m a.s.l, the surface area of the lake was 2.7 ha, its mean depth 2.2 m and maximum depth 7.8 m. In June 2013 the lake level had dropped to 43.7 m a.s.l. The lake lies in a kettle hole, which formed during the final stages of the Late Wechselian glaciation (Ilomets & Kont, 1994).

The climate of the region is continental. Annual average air temperature is 4.7°C, monthly average air temperature stays below 0°C from November to March and average annual precipitation is 684 mm (data averaged by the authors for the period 1959-2012 according to unpublished data from the Estonian Environmental Agency). Groundwater inflow and outflow have a significant share of L. Martiska's annual water-balance (Vainu & Terasmaa, 2014).

Most of the lake bottom is covered with a layer of organic sediment consisting of homogenous light-brown gyttja. The mineral part of lake sediments consists dominantly of medium-grained silt (Punning et al., 2006). The nearshore areas up to 2-3 m of water depth are covered with fine-grained sand.

The surface-water catchment of the lake is 14.3 ha in area, the groundwater catchment of the lake has not been delineated. The glacial deposits in the area are 50-60 m thick, consist of medium- to coarse-grained glaciolacustrine and glaciofluvial sands and contain the unconfined Quaternary Vasavere aquifer (Erg, 1994). Average saturated thickness of the aquifer is 15 to 20 m, maximum saturated thickness is 77 m (Erg, 2012). The aquifer is underlain by a 2 to 6 m thick layer of till (Raukas et al., 2007). The glaciolacustrine and glaciofluvial sands form a single continuous aquifer, perched water tables have been observed only in the western and easternmost edges of the aquifer (Erg, 2012).

Without any anthropogenic disturbances the direction of groundwater flow would be from west to east in the area of L. Martiska (Vallner, 1987). In 1972 a groundwater intake consisting of 14 abstraction wells, 60 m deep, was established in the vicinity of the lake less than 300 m away (Fig.1). Groundwater pumping has caused the formation of a depression cone located northwest of the lake on the piezometric map (Erg, 1994). The average abstraction rate from the groundwater intake was from July 2011 to May 2012 4190 $m^3 d^{-1}$ and it was increased 57% to 6570 $m^3 d^{-1}$ for the period June 2012 to May 2013.

3 METHODS

Groundwater seepage directions and fluxes in the bottom of L. Martiska were recorded with self-constructed modified Lee-type seepage meters (Lee, 1977). A detailed description of the seepage meter design has been given in (Vainu et al., accepted). Seepage measurements were made in June 2012 and 2013 at four study sites on eight transects, so that each of the four sides of L. Martiska would be covered. In each of the sites the seepage meters were installed on two parallel transects perpendicular to the shore, starting from as close to the shore as possible so that the seepage meters would stay fully submerged. Each transect consisted of five or six seepage meters. The transects were ca. 5 m apart and seepage meters on each transect had 3 to 6 m between them. They were named after their position – N, W, E and S. Seepage meter measurements were carried through following the recommendations of Rosenberry et al. (2008). Three consecutive measurements were made with each seepage meter at every location.

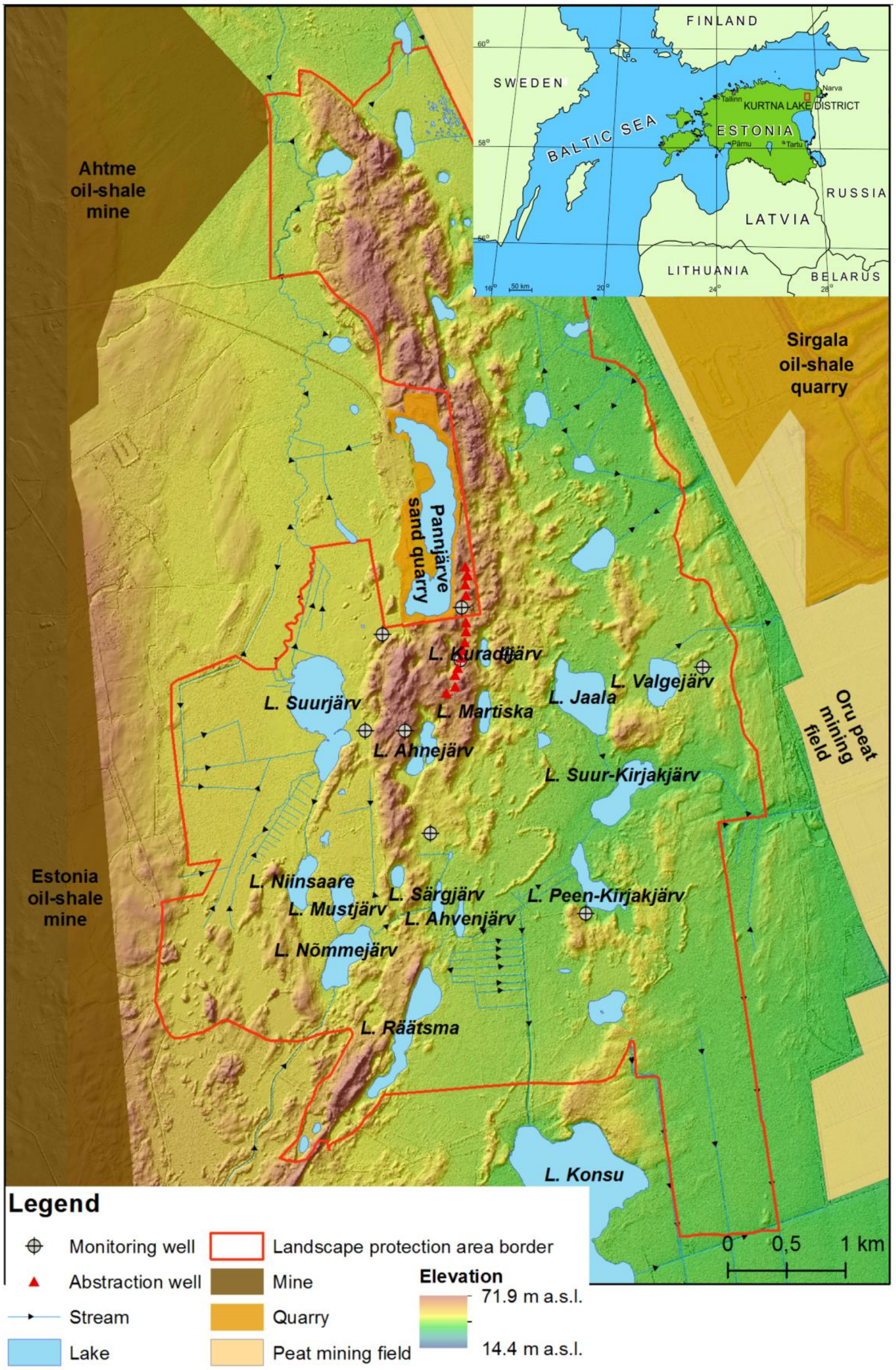

Figure 1. Location and topography of the Kurtna Lake District and the mining areas affecting it. Also the locations of groundwater abstraction wells and permanent monitoring wells used for groundwater level interpolation are shown.

The flux of groundwater seepage was calculated with the following equation:

$$Q = \frac{(V_f - V_i)}{S} / t, \quad (1)$$

where Q is the seepage flux (ml m^{-2} min^{-1}), V_f is the final volume of water in the collection bag (ml), V_i is the initial volume of water in the collection bag (ml), S is the area of lake bed covered by the seepage meter (m^2)

and t is measurement time (min); if $Q<0$ then outseepage occurs under the seepage meter, if $Q>0$ then inseepage occurs under the seepage meter (Rautio & Korkka-Niemi, 2011).

In 2012 a total of 132 seepage flux measurements (126 in 2013) at 44 locations (42 in 2013) were made. The seepage fluxes measured by the two seepage meters on the parallel transects were averaged, which resulted in 22 measurement locations (21 in 2013). Therefore a maximum of six measurements were used to calculate the average seepage flux at every measurement location. Finally a standard error value was calculated for the average flux in each measurement location

At each of the seepage meter locations the lake bottom sediments were mapped. The type of sediments (sand or gyttja) was visually determined by the divers during the installation of the seepage meters. In locations where the presence of gyttja was revealed, the thickness in meters of the layer of organic sediments was determined with a Belarusian peatprobe after the completion of seepage measurements.

In order to compare the direction of measured seepage in the bottom of L. Martiska to groundwater flow directions in the surrounding aquifer in 2012 and 2013, interpolated groundwater level maps were created and the flow lines determined with *ArcGIS 10.1* software. For the interpolation water-level data from temporary test wells at the lake shore, permanent monitoring wells in the vicinity of the lake, water level of the lake itself and of 11 surrounding lakes were used. A total of 14 temporary test wells were manually dug around the lake in the beginning of June 2012 (20 in 2013). The wells were dug with a spade until water level was reached. The water levels in the wells were measured with a *Leica* level. Nine permanent monitoring wells in the Quaternary Vasavere aquifer, situated closest to L. Martiska (Fig. 1), were chosen for the interpolation. Some of the wells are equipped with automatic data loggers and some are hand measured with dippers. The groundwater level for the map was interpolated in *ArcGIS 10.1.* using well data (as points) and lake data (as contours) with the *Topo to Raster* method. The obtained 10 m resolution raster layers of groundwater level were then processed with the *Darcy Velocity* tool in the *Spatial Analyst* extension. The output flow direction raster was converted to a point feature layer and classified into eight groups according to the angle of flow direction. Each group was given a distinct arrow symbol. The result was a map of groundwater levels and flow direction arrows, which were compared qualitatively with the seepage meter measurements.

Data analysis was carried through on the June 2012 data with *SPSS Statistics 17.0* software to find if correlations existed between seepage flux and distance from the shore, lake depth or thickness of organic sediments. Only the measurement locations with inseepage were included in the analysis. Because of the predicted nonlinearity in the relationships, correlation coefficient Spearman's rho was used. T-test was used to evaluate if the seepage flux differed between sediment types (organic and sand). All the results were evaluated at significance level 0.05.

4 RESULTS AND DISCUSSION

Groundwater level interpolation showed that in 2012 groundwater flowed to L. Martiska from the direction of L. Ahnejärv and leaved the lake towards the nearby groundwater abstraction wells (Fig. 2). Therefore the highest inseepage was expected to occur in the southern part of the lake and the highest outseepage in the northern part of the lake. The eastern and western sides of the lake were expected to be in the so-called „hinge-line" (Winter et al., 1998) region, where groundwater flow is parallel to the lake shores and no significant seepage is occurring at the bottom of the lake. The arrows representing the direction of flow in 2012 in Fig. 2 are not completely parallel at the eastern side of the lake, though. That interpolation result was caused by the lack of groundwater-table data east of the lake.

Seepage measurements in the bottom of the lake showed that groundwater was seeping out of the lake in the nearshore areas in the northern part of the lake as expected (Fig. 3). The outseepage rate was the highest (-16.4 ml min^{-1} m^{-2}) in the measurement location closest to the shore and decreased further from the shore. But at the furthest measurement location on the northern transect about 20 m from the shore at the water depth of 2.6 m groundwater was seeping into the lake at a moderate rate (6.4 ml min^{-1} m^{-2}). On the southern transect inseepage was measured throughout the transect, also as expected. The seepage rate was the highest 5 to 10 m from the shore, where the water depth was 1 to 2 m. Further from the shore the seepage rate decreased, but even at the furthest measurement location where a 3.2 m thick layer of gyttja was present seepage influx of 12.9 ml min^{-1} m^{-2} was measured. On the eastern and western transects the seepage rate was low in the measurement locations closest to the shore, but increased to about 10 m from the shore and decreased in the further measurement locations.

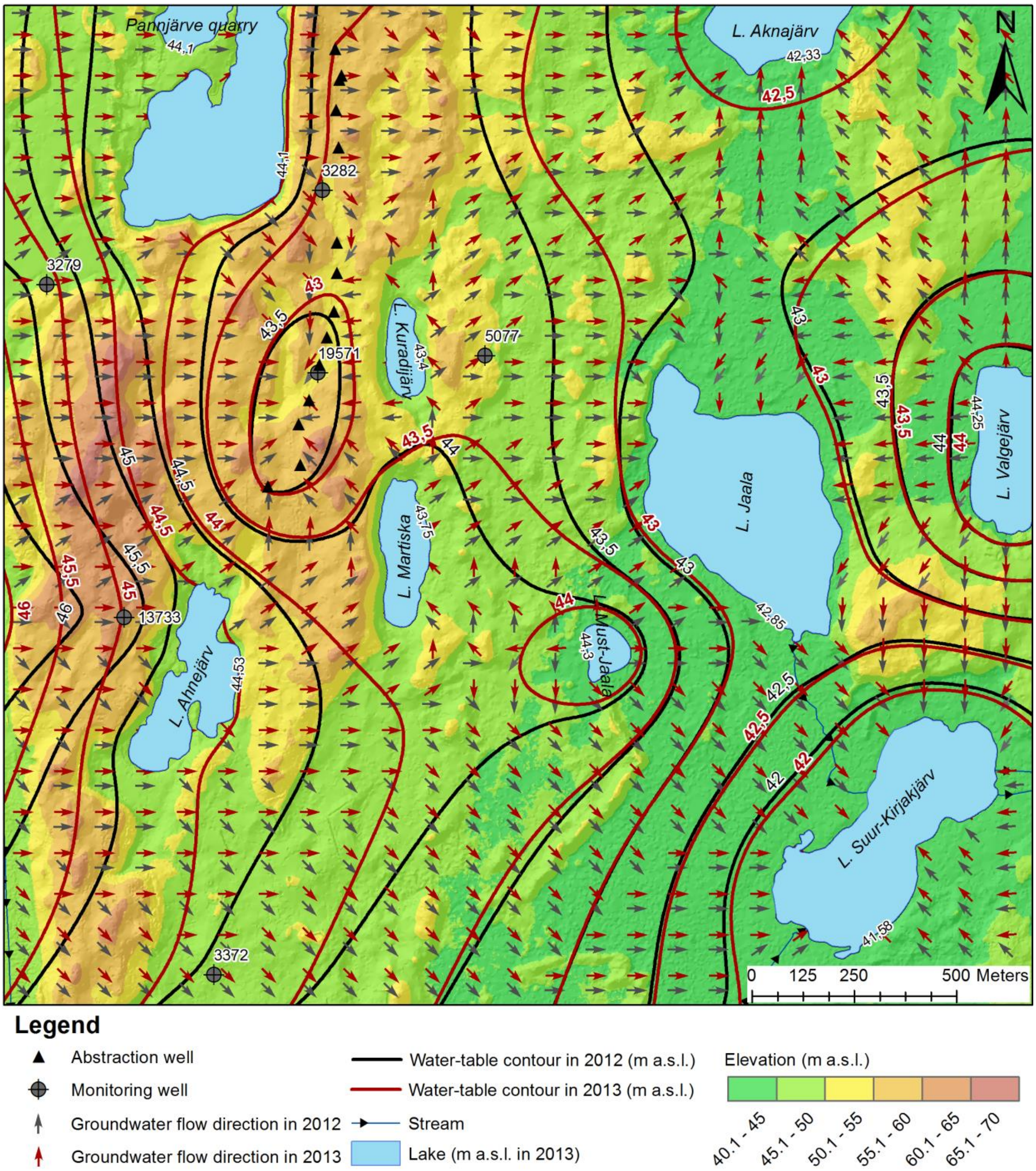

Figure 2. Groundwater level map and groundwater flow directions in the central part of the Kurtna Lake District in June 2012 and June 2013, interpolated according to water levels from temporary and permanent wells and lake levels in June 2012 and June 2013

Therefore the seepage patterns coincided with the expected groundwater flow directions on the interpolated groundwater map only in the nearshore areas. Further than 6 to 15 m offshore in the water depth of 1 to 2 m the seepage patterns ceased to coincide with the expected. Data analysis showed that no statistically significant monotonic relationship existed between seepage rate and distance from the shore ($\rho=0.139$, $p=0.583$, $N=18$), lake depth ($\rho=0.118$, $p=0.642$, $N=18$) or organic sediment thickness ($\rho=0.393$, $p=0.107$, $N=18$). T-test showed that the difference of seepage influx in measurement locations covered with sand compared to locations covered with organic sediments were significantly different ($p=0.044$, $N=18$). Surprisingly the mean seepage influx was higher in the locations covered with gyttja ($Q=11.1$ ml m^{-2} min^{-1}, $N=12$) than in locations covered with sand ($Q=4.4$ ml m^{-2} min^{-1}, $N=6$). The results allowed concluding that a layer of gyttja does not necessarily prevent inseepage from occurring (Vainu et al., accepted). However, in several lake-budget modelling studies (e.g., Genereux & Bandopadhyay, 2001; Cardille et al., 2004; Kidmose et al., 2011) a layer of gyttja has been assumed to completely seal the lake from interacting with groundwater. Probably the restrictive nature of gyttja depends on its water content and density throughout the sediment column. The phenomenon should be further researched to be able to make stronger conclusions.

Other studies where inseepage has been measured to be higher offshore than inshore have explained it with geological peculiarities (Rosenberry & Winter, 2009), a thick low-conductivity layer of peat (Kidmose et al., 2011) or gyttja (Kidmose et al., 2013) near the shore, or with different contributing groundwater flow-systems (Ala-aho et al., 2013). In the case of L. Martiska the seepage pattern which did not follow the expected pattern further from the shore was hypothesised to be caused by a small confined subaquifer, which is opening into the lake underneath the unconfined aquifer (Vainu et al., accepted).

In 2013 the interpolation results showed that the groundwater level was ca. 0.5 m lower around the wells if compared to the 2012 level, but similar to the 2012 level further away, especially in the east around L. Valgejärv. Therefore the results show that the increased abstraction rates had caused a groundwater level drop in the central part of the Vasavere aquifer. Groundwater flow directions, as such, had not changed significantly around L. Martiska. Only in the northwestern side of the lake the flow directions had turned away from the lake towards the abstraction wells. As the level of L. Martiska also showed a 0.5 m drop between June 2012 and June 2013, then the interpolation results are in agreement with the lake-level measurements. Therefore the increased pumping rates likely caused the water-level drop in the lake. A recent study on White Bear Lake in the USA (Jones et al., 2013) also showed that increased groundwater pumping can cause a decrease in the water levels of the lakes that are connected to the pumped aquifer(s).

The strongest subsequent effect of the changed groundwater-level on the seepage patterns in the bottom of the lake was expected to be an increased outseepage area in the northern part of the lake. Seepage measurements from June 2013 showed that in the northern part of the lake, where outseepage was measured also in 2012, the area of higher outseepage had moved further into the lake (Fig. 3). On the western transect, weak seepage outflux was measured in the locations closest to the shore. In 2012 the same locations had exhibited seepage influx. Therefore the area of outseepage had indeed increased in the northern part of the lake, as expected from the groundwater flow direction map (Fig. 2). In the eastern and southern part of the lake the seepage directions were the same as in 2012. Weak seepage influx was measured in the locations closest to the shore on the eastern transect and high seepage influx was measured throughout the southern transect.

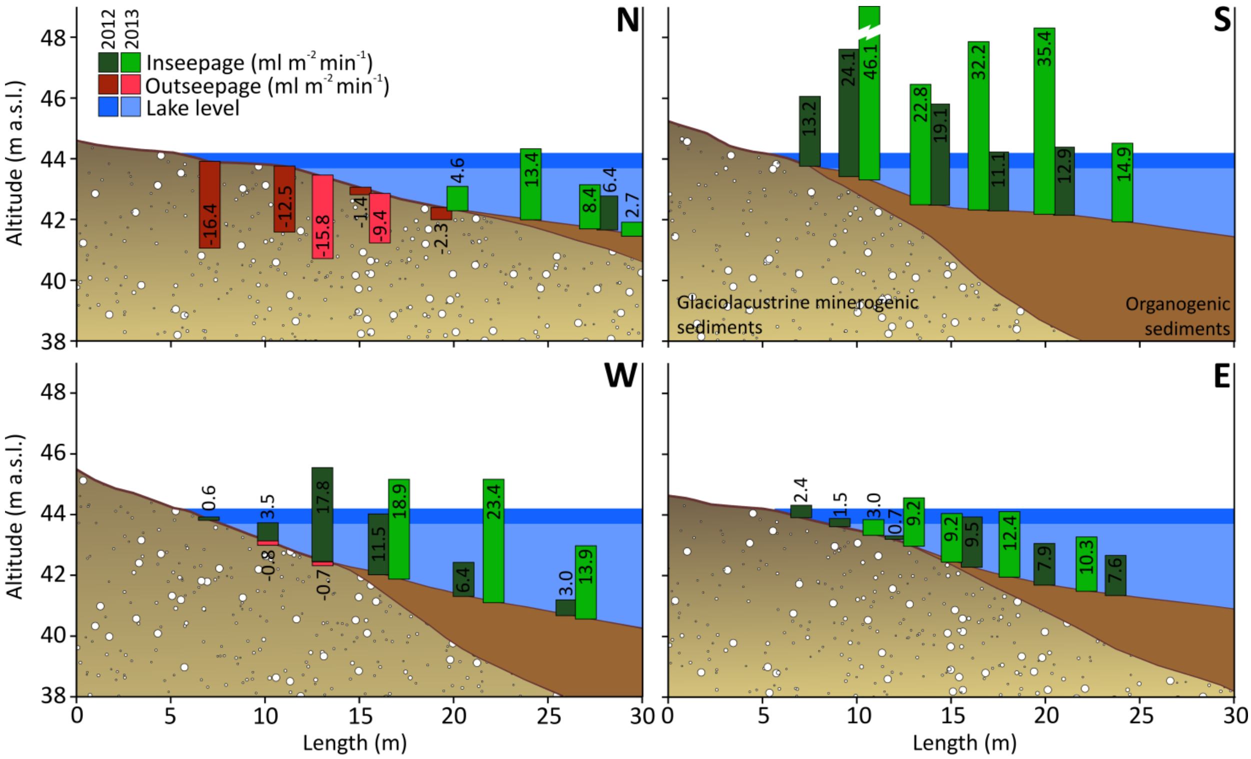

Figure 3. Seepage direction and rates on the northern (N), southern (S), western (W) and eastern (E) transects of L. Martiska in June 2012 and June 2013. The heights of the columns indicate seepage rate at that location.

A bit unexpectedly the measured inseepage rates had increased at almost all of the measurement locations. The possible reasons for that are still unknown, but some of the increase could be explained by the shorter average measurement times in 2013 compared to 2012. In 2012 the average time for a single seepage measurement was 2 h and 3 min, in 2013 1 h and 16 min. As seepage meter collection bags have shown to be starting to fill more slowly when the amount of water in the bag increases, the shorter measurement times could result in higher seepage fluxes. Therefore the comparison of absolute amounts of seepage through the two years should be done with caution, but the patterns of seepage can be compared nevertheless. In 2013 the inseepage rates generally increased moving away from the shore and at a certain distance started to decrease, as in 2012. Also, as in 2012, a few meters of gyttja did not seem to distract inseepage in 2013.

Therefore the results allow to conclude that fallen groundwater levels affected seepage patterns in the nearshore areas of L. Martiska, which were hypothesised previously to be connected with the main Vasavere aquifer, where the pumped groundwater originates from. In the deeper parts of the lake the groundwater level drop did not seem to affect the seepage patterns, which is also in agreement with the theory that these areas of the lake are fed by a small local confined aquifer which opens into the lake.

The results of the study indicate that groundwater abstraction can have a direct effect on the water budget of the lakes situated in the pumped aquifer. Changes in lake water budget can alter the ecosystem of the affected lake, as has been the case for L. Martiska (Vallner, 1987). Thus, the seepage patterns in the affected lakes and their potential changes should be studied before the initiation of pumping to avoid unwanted side effects.

5 CONCLUSIONS

A two-year study was conducted on the interactions between groundwater and surface water at L. Martiska – a closed-basin lake affected by groundwater abstraction, situated in northeastern Estonia. During the two years groundwater abstraction rate was increased 57%. The results showed that:

1) Groundwater seepage patterns in the bottom of the lake were unrelated to water depth, distance from the shore and thickness of organic sediments. Inseepage did not decrease with the increasing thickness of organic sediments, as was expected before.

2) The seepage patterns followed the estimated groundwater flow directions in the surrounding aquifer only in the nearshore areas of the lake, but not further offshore. The cause for that phenomenon is hypothesised to be a small local confined aquifer around and underneath the lake.

3) Increased water abstraction rates caused a 0.5 m drop in the groundwater levels around the lake and a consequent 0.5 m drop in the lake-level. Groundwater flow direction changed in the northwestern part of the lake, where it became oriented towards the abstraction wells.

4) Seepage measurements showed that the area of outseepage increased in the nearshore measurement locations in the northern and western part of the lake in 2013 compared to 2012. In locations further offshore no notable change in groundwater seepage patterns was detected. Therefore the change in seepage directions was in accordance to the estimated groundwater directions.

5) Seepage patterns in lakes potentially affected by a groundwater intake should be clarified while planning the establishment of the intake to prevent unwanted water-level changes. Otherwise, significant changes in the water budget of nearby lakes could occur and result in a deterioration of the lake's ecosystem.

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