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Relations between groundwater flow in an unconfined aquifer and seepage patterns in a closed-basin lake in glacial terrain

Marko Vainu, Jaanus Terasmaa and Marko Häelm

ABSTRACT

Groundwater dynamics affect lake water budgets, but its major factors and mechanisms still need clarification. This study evaluates the effects of surrounding groundwater flow on seepage direction and assesses factors that affect seepage flux in a closed-basin lake in northeastern Estonia – Lake Martiska. A piezometric map was used to determine directions of groundwater flow around the lake. Seepage meters were applied for measuring flux at 44 locations along eight transects in the lake in relation to water depth, distance from the shore, sediment type and thickness of organic sediment. Additionally nearshore ice-free areas were mapped in winter. Seepage patterns followed the estimated directions of groundwater flow in nearshore areas. Outseepage records showed the impacts of nearby groundwater-abstraction wells on groundwater flow. However, the within-lake seepage direction and flux differed from the expected at 6–15 m from the shore and water depth of 1–2 m. Seepage flux and physical factors of the lake were uncorrelated. Even with a 3.2 m thick layer of gyttja, seepage influx was 13 ml m^{-2} min^{-1}; therefore thick lacustrine sediments do not necessarily prevent inseepage. The results suggest that a local confined aquifer around and underneath the lake may cause the observed inseepage pattern.

Key words | closed-basin lake, groundwater flow, lake-bed seepage, lake-water level, seepage meter, unconfined aquifer

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INTRODUCTION

Subsurface water is a critical linkage between terrestrial and aquatic habitats (Winter *et al.* 1998). The importance of groundwater in the management of water resources has been stressed in recent studies on rivers (Delina *et al.* 2012; Ivkovic *et al.* 2014) and agricultural water supplies (Yasuda *et al.* 2013; Zhu *et al.* 2013). It is as important to understand the basic principles of the interaction of groundwater and surface water in lakes for effective management of lentic water resources and prediction of lake level changes (Hayashi & Rosenberry 2002; Sophocleous 2002; Gleeson *et al.* 2009). Although studies on the exchange of water between lakes and groundwater started in the 1970s (McBride & Pfannkuch 1975; Lee 1977), the topic has become more important in more recent hydrological studies (Winter *et al.* 1998; Rosenberry & Labaugh 2008).

There are two important aspects that should be taken into account when studying the surface water–groundwater interactions in lakes. First, general groundwater flow directions in the contributing aquifer need to be well described. Determining groundwater catchments for lakes, especially in hummocky glacial terrains, is difficult, because topographic relief does not necessarily delineate groundwater catchment and therefore they do not coincide spatially with surface-water catchments (Winter *et al.* 1998). Hence, water-level data from groundwater monitoring wells are required. That approach has been used in several case studies on lakes and lake districts in areas of highly permeable glacial terrain (e.g. Hunt *et al.* 1998; Holzbecker 2001; Kappel *et al.* 2001; Filby *et al.* 2002). Difficulties in determining groundwater catchments for lakes are not unique to

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glacial areas, though similar problems also arise in karst terrain (Winter et al. 1998; Otz et al. 2003).

Second, physical factors and variables in lakes, such as water depth, distance from the shore, sediment type and thickness of organic sediments should be carefully examined in relation to within-lake seepage patterns of groundwater. Those two aspects of regional and lake-specific groundwater flow have to be considered simultaneously, however the flow directions of groundwater estimated from piezometric maps in relation to seepage direction and flux at the lake bottoms are not often synthesized and studied together.

In theory, lake water is controlled dynamically in three 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 another part (Winter et al. 1998, 2003; Winter 2004; Rushton 2005). In glacial terrain, groundwater through-flow, with both inflow and outflow, is believed to be the most common of the three (Winter et al. 2003). However, the exact mechanisms of seepage formation and factors that influence seepage flux in lakes are still not well studied. While theoretical studies describe both in- and outseepage from lakes, field studies have often measured only seepage influx to lakes. Just a few among those studies have succeeded in measuring outseepage (Asbury 1990; Rosenberry 2000, 2005; Sebestyen & Schneider 2001; Kidmose et al. 2011; Ala-aho et al. 2013).

Most numerical modelling and some field studies describe seepage flux to be highest close to the shore and to decrease exponentially with distance from the shore (e.g. McBride & Pfannkuch 1975; Lee 1977; Winter 1978; Pfannkuch & Winter 1984; Cherkauer & Zager 1989; Shaw & Prepas 1990a; Rautio & Korkka-Niemi 2011). Conversely, many field studies have shown results which differ from the expected pattern (e.g. Woessner & Sullivan 1984; Cherkauer & Nader 1989; Shaw & Prepas 1990b; Schneider et al. 2005; Rosenberry & Winter 2009; Kidmose et al. 2011; Kidmose et al. 2013). Some studies have also demonstrated that groundwater seepage varies significantly across lake bottom, sometimes even between sites only a few meters apart, suggesting that heterogeneity of lakebed sediments influences seepage (Brock et al. 1982; Guyonnet 1991; Kishel & Gerla 2002).

The effect of lake bottom conditions, such as sediment type, texture and thickness, on seepage flux has not yet been thoroughly studied. Most of the previous studies have measured seepage flux through sand, because it is significantly easier to install seepage meters in sandy than in other types of substrates (Schneider et al. 2005); therefore, empirical data on the subject are still limited and biased. Among the few studies available, Schneider et al. (2005) demonstrated that seepage flux was unrelated to substrate texture, but Mitchell et al. (1988) showed a good correlation between seepage rate and sediment texture. In modelling studies a thick layer of organic sediments at the lake bottom is generally assumed to prevent groundwater inflow and outflow (Genereux & Bandopadhyay 2001; Cardille et al. 2004; Kidmose et al. 2011).

In some cases the discrepancy between the field results and numerical simulations has been explained by the peculiarities of regional hydrogeology instead of the parameters of the lake. Cherkauer & Nader (1989) argued based on a field study that connectivity to an underlying bedrock aquifer controlled the seepage patterns. Rosenberry & Winter (2009) reached a similar conclusion in a study on a small lake in California. Another study on a large lake in the New York State (Schneider et al. 2005) found that it was primarily the underlying geologic formations and regional precipitation patterns that controlled the observed seepage patterns, rather than lake bed sediments.

The aim of this paper is to evaluate the spatial pattern of out- and inseepage in a closed-basin groundwater-controlled lake – Lake Martiska – located in a glacial terrain in north-eastern Estonia, where groundwater flow directions derived from monitoring well data are available. We specifically address the following questions: (1) Do estimated groundwater flow directions in the surrounding aquifer coincide spatially with seepage directions in the lake bottom and therefore allow prediction of seepage patterns from piezometric maps? (2) Is seepage flux correlated to water depth, distance from the shore, sediment type and thickness of organic sediments?

STUDY AREA

Lake Martiska (hereafter L. Martiska) (59°15′45″N, 27°34′14″E) is a small closed-basin lake in the centre of the Kurtna Lake District (Figure 1), which contains almost

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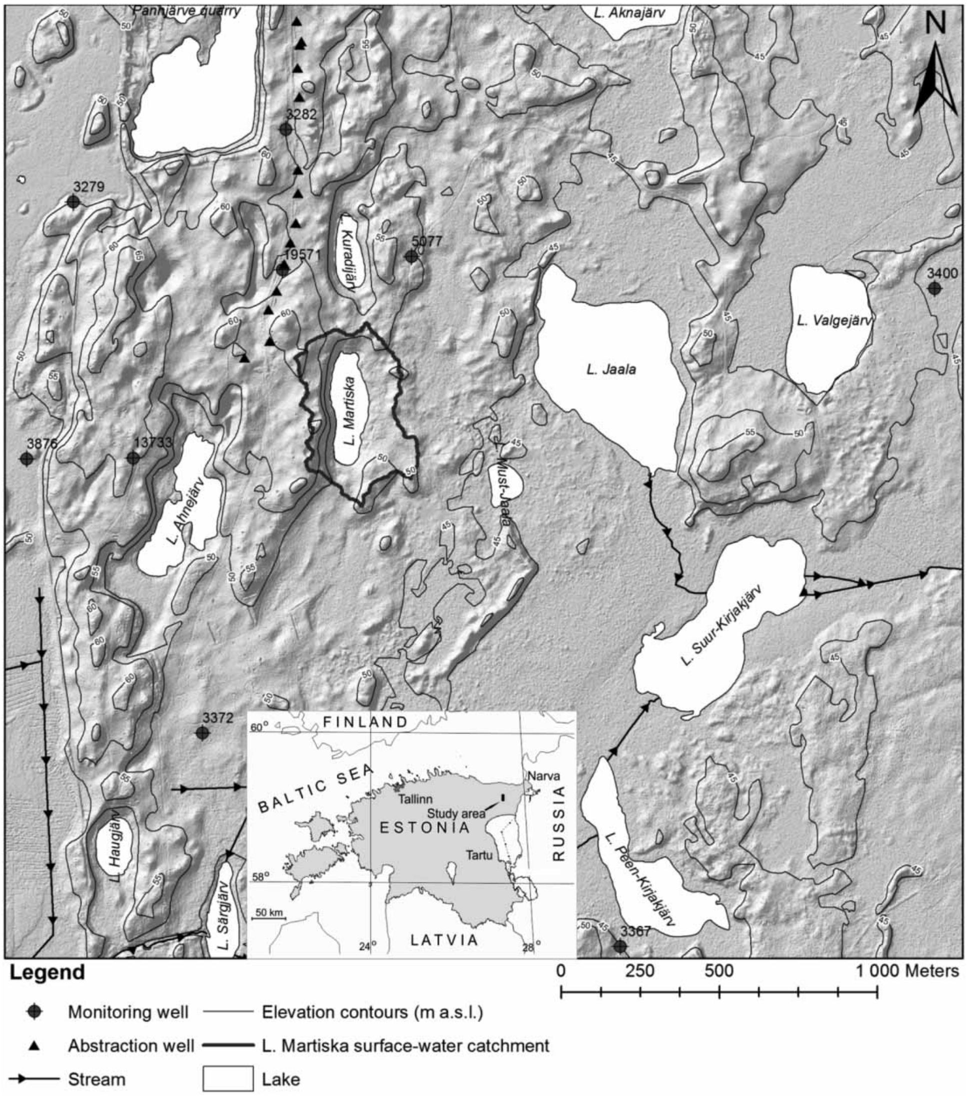

Figure 1 | Location and topography of the surface-water catchment of L. Martiska with location of wells used for groundwater abstraction and water level monitoring (the digital elevation model was created according to year 2009 LIDAR-points obtained from the Estonian Land Board).

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 44.21 m above sea level (a.s.l.), the surface area of the lake was 2.7 ha, its mean depth 2.2 m and maximum depth 7.7 m (Figure 2). The shape of the lake is elongated from north to south. The lake lies in a kettle hole that has a steep western slope and a gentle eastern slope.

The regional climate 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 characterise L. Martiska's annual water-balance. For the period 2000–2009, the average precipitation input to the lake was estimated to be 23,000 m^3 year^{-1}, average evaporation output from the lake surface 20,000 m^3 year^{-1}, combined surface water and groundwater runoff from the surface-water catchment 38,000 m^3 year^{-1}, and the residual seepage

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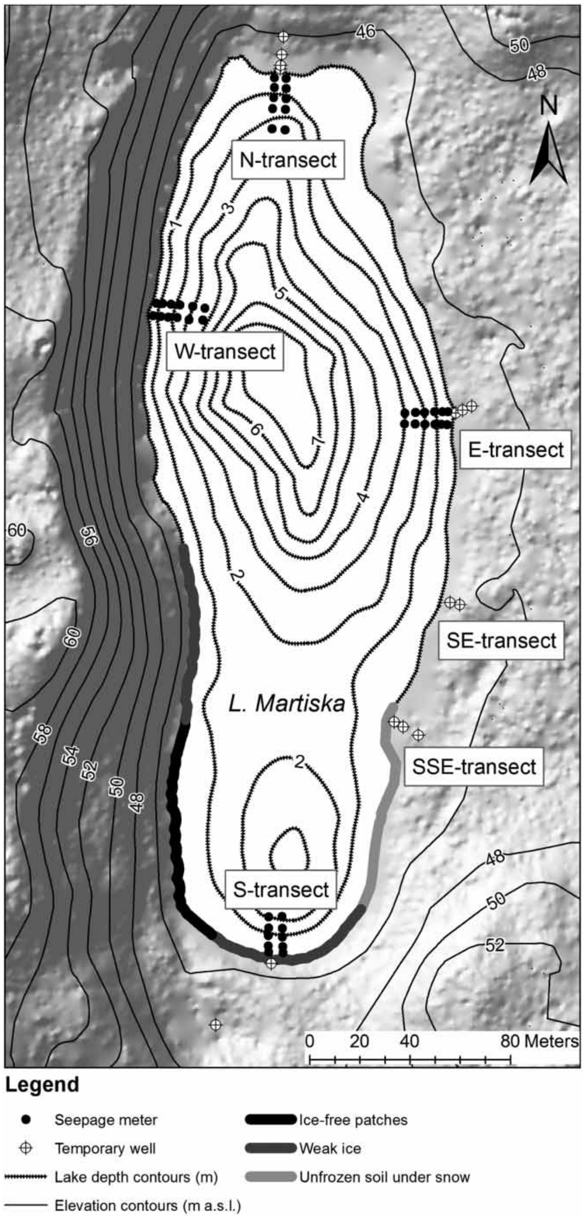

Figure 2 | Bathymetry of L. Martiska, location of seepage meter transects, temporary wells for groundwater level monitoring and unfrozen portions of the lake perimeter according to winter mapping (the digital elevation model was created according to year 2009 LIDAR-points obtained from the Estonian Land Board).

from the lake into groundwater 41,000 m^3 $year^{-1}$ (Vainu & Terasmaa 2014). However, the amounts of runoff and outseepage are likely to have been underestimated, because the actual groundwater catchment of the lake is expected to be larger than the surface-water catchment that was used for those statistics.

Most of the lake bottom is covered with a layer of organic sediment consisting of homogenous light-brown gyttja. The average water content of the topmost 30 cm of the sediment is 86.6–95.6%, and 24–74.2% of the dry matter in the sediment is organic. 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. As the lake level has fluctuated significantly in recent decades, a considerable proportion of the littoral zone is covered with the remains of dead trees and live bushes from the period of lower water level.

The surface-water catchment of the lake is 14.3 ha in area (Figure 1); though the groundwater catchment of the lake has not been delineated. The surface-water catchment is virtually fully (93%) covered with ca. 60-year-old pine forest and some small and occasional birch groves near the shore. Soil cover in the catchment is also uniform with 94% covered by sandy soils and the rest by peat soils (according to the digital soil database of Estonia, maintained by the Estonian Land Board). The kame field around the lake consists of kames ranging from 40 to 70 m a.s.l. and small depressions between them. It was formed to the location of the ancient Vasavere valley by a retreating ice sheet during the final stages of the Late Wechselian glaciation (Ilomets & Kont 1994). The glacial deposits in the area and under the lake are 50–60 m thick, consist of medium- to coarse-grained glaciolacustrine and glaciofluvial sands and contain the unconfined Quaternary Vasavere aquifer (Erg 1994).

The area of the Vasavere aquifer is 75 km^2 (EME 2008). Average saturated thickness 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, and perched water tables have been observed only in the western and easternmost edges of the aquifer. Although groundwater–lake water interactions have not been studied directly in the aquifer, the lakes in the kame field area are considered to be hydraulically connected to the groundwater table (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

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intake consisting of 14 abstraction wells, 60 m deep, was established in the vicinity of the lake less than 300 m away (Figure 1). The abstraction rate from the groundwater intake has varied from 5,000 to 10,000 $m^3 d^{-1}$ during its operation but has recently not exceeded 8,000 $m^3 d^{-1}$. Groundwater pumping has caused the formation of a depression cone located northwest of the lake on the piezometric map (Erg 1994).

The groundwater level in the aquifer is regularly monitored by the Geological Survey of Estonia in accordance with the national environmental monitoring programme administered by the Estonian Environmental Agency. The monitoring network consists of scattered distributed wells (Figure 1), some of which are equipped with automatic data loggers and some are hand measured with dippers.

Although the water level of L. Martiska has not been under long-term regular monitoring, the results of occasional water-level measurements have shown that the lake has gone through severe water-level fluctuations in recent decades. The lake level dropped ca. 2.5 m in the 1970s and rose ca. 2 m between 1990 and 2012. Vainu & Terasmaa (2014) showed that the major cause for the lake water-level drop in the 1970s was the initiation of the groundwater intake; the subsequent water-level rise was caused by the combination of reduced groundwater pumping rates and increased precipitation rates. The period of lower water level has affected the trophic state of the lake, changing the once oligotrophic lake to more eutrophic (Punning *et al.* 2006). In Kurtna, rapid eutrophication of the closed soft-water oligotrophic lakes is characteristic for the region. Varvas (1994) showed a correlation between the PO_4^{3-} concentration and openness of the lake shores to erosion. Other closed-basin lakes around L. Martiska, especially L. Kuradijärv and L. Ahnejärv, have gone through a similar change in water level and trophic state (Erg 1994; Vainu & Terasmaa 2014).

Lake Martiska was chosen for the study on lake water–groundwater interactions for the following reasons: The Vasavere aquifer is covered with a groundwater monitoring network; the lake has no surface water in- nor outflow, indicating that it is highly dependent on groundwater; the lake is small with a weakly indented shoreline, hence it is possible to derive a general seepage distribution with moderate labour costs; the lake bottom is covered with various types of sediments, which allows evaluation of their role on seepage pattern; the lake shore has plant-free areas suitable for seepage meter installation; and the groundwater intake near the lake has caused a depression cone according to the piezometric map indicating potential groundwater outseepage.

MATERIAL AND METHODS

Seepage meter measurements

Groundwater seepage directions and fluxes in the bottom of L. Martiska were recorded with seepage meters. They are the most commonly used devices for direct flux measurement between groundwater and surface water (Rosenberry *et al.* 2008).

The current study uses classic Lee-type seepage meters (Lee 1977). They consist of a plastic open chamber, a flow tube and a measuring bag. The chambers were made from the bottom part of plastic 90-litre containers that were cut to four different heights (15, 20, 30, 35 cm), and the diameters of the seepage meters were 53, 55, 58 and 60 cm, respectively. The smallest seepage meter was used in shallow nearshore water, the largest one in the areas of thick organic sediments, and the other intermediate types in intermediate conditions. The chamber had two openings, one at the top for venting excess gas and the other at the side, as close to the upper part of the chamber as possible, for attaching the flow tube. The flow tube was a 1 m long garden hose (ID 20 mm) connected to the side of the container by a quick-release fitting. The other end of the tube was connected to a collection bag through a quick-release fitting as well. The collection bags were 5 L double-layered plastic bags originally made for storing juice. A shutoff valve was attached to the bag. For protecting the collection bag from possible measurement errors caused by water movement around the bag (Rosenberry *et al.* 2008), a perforated bucket was used to shield the bag during measurements.

Seepage was measured in the beginning of June 2012 at four study sites on eight transects (Figure 2). The locations of the study sites were chosen so that each of the four sides of L. Martiska could be covered. The specific locations were

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determined by the possibility to effectively install seepage meters, because these were the reed-free areas of the lake shore. At each site the seepage meters were installed on two parallel transects perpendicular to the shore, starting from as close to the shore as possible to keep the seepage meters fully submerged. Along each transect five or six seepage meters were installed (Figure 2). The parallel transects at each site were ca. 5 m apart, and seepage meters were set at roughly every 5 m. They were named after their position – N, W, E and S, and measurement locations were numbered according to the average water depth. The water depths of the measurement locations varied from 0.3 to 3.8 m.

Divers installed the seepage meter chambers 15–16 h before first measurements. This procedure was required to allow the disturbed sediment to settle (Rosenberry *et al.* 2008). The vent on the top of the chamber was left open during this period to let possible gases emitting from the sediment to escape. Before measurements started the collection bags were prefilled with 1 L of lake water, to reduce the memory effect of the bag (Shaw & Prepas 1989), emptied of air and attached to the meter chamber. The shutoff valve of the collection bag was opened after attachment. Measuring time varied from 68 to 209 min, after which the shutoff valve was closed again. The residual amount of water in the bag was measured on the shore with a standard laboratory 2 L graduated cylinder. Measurement precision of the cylinder was 20 ml. Three consecutive measurements were made with each seepage meter at every location.

Evidently incorrect seepage measurements were excluded from the subsequent data analysis; those include such cases where (1) the shutoff valve of the measurement bag was leaking, (2) the flow tube had become clogged with air, and (3) the top vent of the seepage cylinder had been left open.

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). As measurement times and seepage meter diameters varied, the theoretical imprecision of the flux rates caused by reading values from the graduated cylinder was measurement-specific. The calculated average measurement imprecision was ± 0.36 ml m^{-2} min^{-1}.

It is common to multiply measured seepage rates with a correction coefficient ranging from 1.05 to 1.82 (Rosenberry *et al.* 2008), because studies with test tanks have shown that seepage meters tend to underestimate actual fluxes (Lee 1977; Murdoch & Kelly 2003; Rosenberry & Menheer 2006). Large diameter (>9.5 mm) flow-tubes and thin-walled collector bags have been shown to reduce the appropriate correction factor to 1.05 (Rosenberry 2005). As the constructed seepage meters took those conditions into consideration and considering the major objectives of this study, the absolute values of seepage flux were unnecessary and thus no correction factors were applied for the measurements.

During the field study, 132 seepage flux measurements at 44 locations were made. Fourteen measurements were excluded from the analysis because of evident measurement errors. In order to derive general seepage directions and fluxes for the nearshore regions of the lake, the seepage flux measured by the two seepage meters on the parallel transects were averaged, resulting in 22 measurement locations. Thus 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 at each measurement location.

Determination of lake bottom sediment type and thickness

Lake bottom sediments were mapped at each of the 44 seepage meter locations. The type of sediments (sand or gyttja) was visually determined by divers during the installation of seepage meters. Where gyttja was observed, the thickness of organic sediments was measured with a Belarusian peat probe (Jowsey 1966) after the completion of seepage measurements.

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Determination of groundwater levels and flow lines

To compare the direction of measured seepage in the bottom of L. Martiska to groundwater flow directions in the surrounding aquifer, two groundwater level maps with different spatial scales, corresponding to June 2012, were constructed and the flow lines determined with ArcGIS 10.1 through interpolation.

One of the maps represented the immediate vicinity of the lake. Both the water-level data of temporary test wells at the lake shore and of the lake itself were used for the interpolation. A total of 14 temporary test wells were manually dug in the vicinity of the lake in the beginning of June 2012. Those wells were dug with a spade until the water level was reached on the extensions of three of the four seepage meter transects and additionally to two transects on the eastern shore of the lake (Figure 2). Because of the high inclination of the lake's western shore, the water table could not be reached there. The cross-section area of the wells was 50×50 cm. The water levels in the wells were left to equilibrate for 30 minutes and then their relative height to the lake level was measured with a Leica level. The lake level in m a.s.l. was measured with a differential global positioning system (GPS) device (Leica CS09) and the groundwater levels were related to that datum. Measurement precision of the lake level was ± 2 cm.

The second map represented groundwater level and flow directions in a larger area around L. Martiska. The same data as for the creation of the first map as well as water-level data of the permanent monitoring wells in the Quaternary aquifer and lake-level data of the surrounding lakes were used for interpolation.

Nine permanent monitoring wells, situated closest to L. Martiska (Figure 1; Table 1) were chosen for interpolation; those wells were installed between 1960s and 1990s and have been regularly monitored by the Estonian Geological Survey. The length of the screen in the wells ranges from 2 to 7 m. Some of the wells are equipped with automatic data loggers and some are hand measured with dippers.

It was not possible to use abstraction well data, as both their rest and pumping water levels are unavailable. Therefore, estimated water levels of the abstraction wells were used in the interpolation to create a depression cone with a realistic extent on the map. The abstraction wells lying south of the monitoring well 19571 were given the same water level as in that monitoring well. The abstraction wells lying north of the monitoring well 3282 were given the same water level as in that monitoring well. Water levels in the abstraction wells between the two monitoring wells were linearly interpolated so that the given water level in the abstraction wells gradually rose from the location of well 19571 towards the location of well 3282.

Water-level data of 10 neighbouring lakes were used for the second interpolation (Table 2). The levels of five lakes were measured in the field with a differential GPS device (Leica CS09) in the beginning of June 2012; the level of five lakes were estimated from a LIDAR-based topographical model of the Kurtna Lake District, which had been previously created in the Institute of Ecology at Tallinn University from the data provided by the Estonian Land Board. The LIDAR data were collected in May 2009.

The groundwater level for both maps was interpolated in ArcGIS 10.1 using well data (as points) and lake data (as contours) with the 'Topo to Raster' method that allows both contour and polygon data to be used as inputs. 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 two maps of groundwater levels and flow direction arrows (coordinate reference system Lambert-Est), which were qualitatively compared with the seepage meter measurements.

Winter observations

The perimeter of L. Martiska was mapped in the beginning of March 2013 when the lake was frozen and covered with snow for verification of the locations of groundwater discharge and recharge; those locations were estimated based on the seepage measurements and the groundwater flow map at the shoreline of L. Martiska. The average lake ice thickness was 40 cm. The areas with unfrozen water, with a weak ice cover over water or with unfrozen shore under the snow cover, were registered as sites for potential

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Table 1 | Characteristics and water levels of the permanent monitoring wells used for the interpolation of groundwater levels around L. Martiska

Well no.[a]	Well elevation (m a.s.l.)[a]	Water level in June 2012 (m a.s.l.)[b]	Water level depth in June 2012 (m below ground)	Well depth (m below ground)[a]	Well stratigraphy (m below ground)[a]
3279	49.46	45.51	3.95	13.4	0.0–7.8 sand 7.8–11.0 silt 11.0–13.4 sand
3282	56.88	43.89	12.99	39.7	0.0–11.6 mixed-grained sand 11.6–14.7 silt 14.7–19.0 clayey till 19.0–39.7 mixed-grained sand
3367	42.23	41.91	0.32	7.2	0–0.6 peat 0.5–2.6 fine-grained sand 2.6–7.2 medium-grained sand
3372	47.16	44.44	2.72	11.0	0.0–2.0 fine-grained sand 2.0–11.0 medium-grained sand
3400	44.80	42.47	2.33	16.3	0.0–0.2 peat 0.2–14.9 fine-grained sand 14.9–16.3 clayey till
3876	47.23	47.29	+ 0.06	4.0	0.0–4.0 sand
5077	49.86	44.01	5.85	35.5	0.0–30.2 fine-grained sand 30.2–35.5 limestone
13733	58.80	46.34	12.46	28.5	0.0–27.5 sand 27.5–28.5 limestone
19571	54.26	43.14	11.12	48.8	0.0–4.0 mixed-grained sand 4.0–20.0 coarse-grained sand 20.0–24.0 gravel and sand 24.0–31.0 fine-grained sand 31.0–36.2 gravel and sand 36.2–41.0 coarse-grained sand 41.0–46.0 coarse-grained gravel 46.0–48.0 till 48.0–48.8 limestone

[a]Data from the Estonian Public Borehole Database (VEKA 2013).
[b]Data from the Estonian Geological Survey.

groundwater discharge (methodology after Rautio & Korkka-Niemi 2011).

Data analysis

SPSS Statistics 17.0 was used for data analysis. Correlation between seepage flux and distance from the shore, lake depth or thickness of organic sediments was calculated using data of the measurement locations with inseepage (locations on transects S, W, E and location N2.6). As out-seepage occurred only on one transect, adding these data to the analysis would have distorted the results. Because of the predicted nonlinearity in the relationships Spearman's rank correlation coefficient 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.

RESULTS

Lake bed seepage

At the northern transect, N, groundwater outflow was higher than $-12\ \mathrm{ml\ m^{-2}\ min^{-1}}$ at sand-covered locations closest to the shore (N0.3 and N0.5). The negative seepage

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Table 2 | Lake water levels used for groundwater level interpolation and the origin of the water-level data. Measurement errors of the water levels were calculated by the differential GPS device used

Lake name	Water level (m a.s.l.)	Origin of the data
L. Martiska	44.21 ± 0.02	Measured in the field
L. Kuradijärv	44.00 ± 0.04	Measured in the field
L. Ahnejärv	44.85 ± 0.03	Measured in the field
L. Jaala	42.80	Estimated from LIDAR
L. Särgjärv	46.65 ± 0.04	Measured in the field
Pannjärve quarry	44.10	Estimated from LIDAR
L. Must-Jaala	44.30	Estimated from LIDAR
L. Suurjärv	46.50	Estimated from LIDAR
L. Aknajärv	42.50	Estimated from LIDAR
L. Valgejärv	44.23 ± 0.02	Measured in the field
L. Suur-Kirjakjärv	41.52 ± 0.03	Measured in the field

flux decreased to below -3 ml m^{-2} min^{-1} at locations N1.2 and N1.8. At the furthest location (ca. 25 m) from the shore (N2.6), seepage flux was positive, indicating that groundwater discharged into the lake through a 0.25 m thick layer of gyttja at a moderate rate (6 ml m^{-2} min^{-1}) (Table 3; Figures 3 and 4).

At the southern transect, S, seepage was clearly positive at every location with the average flux being the highest (19–24 ml m^{-2} min^{-1}) at locations S0.8 and S1.7, where the thickness of gyttja was ca. 0.5 m. At locations further from the shore the seepage flux decreased to 11 ml m^{-2} min^{-1}, but remained higher than in any location at the northern or eastern transects (Table 3; Figures 3 and 4).

At the western transect, W, a weak positive seepage flux (below 4 ml m^{-2} min^{-1}) occurred at the sand-covered

Table 3 | Characteristics of the seepage measurement locations and measured seepage fluxes; S – sand, G – gyttja

Measurement location	No. of proper measurements	Seepage flux (ml m^{-2} min^{-1})	Standard error of seepage rate	Water depth (m)	Distance from the shore (m)	Bottom type	Thickness of organic sediments (m)
N0.3	3	−16.4	1.4	0.3	2.0	S	–
N0.5	6	−12.5	1.2	0.5	6.0	S	–
N1.2	5	−1.4	0.6	1.2	10.0	S	–
N1.8	6	−2.3	0.8	1.8	14.0	S	–
N2.6	6	6.4	1.0	2.6	23.0	G	0.25
S0.4	5	13.2	5.2	0.4	2.5	G	0.25
S0.8	5	24.1	11.3	0.8	5.0	G	0.40
S1.7	6	19.1	3.2	1.7	9.0	G	0.50
S1.9	6	11.1	2.2	1.9	12.0	G	2.00
S2.1	6	12.9	2.6	2.1	16.0	G	3.20
W0.4	2	0.6	3.1	0.4	2.0	S	–
W1.1	6	3.5	1.5	1.1	5.0	S	–
W1.8	6	17.8	5.4	1.8	8.0	S	–
W2.3	6	11.5	4.2	2.3	11.0	G	0.25
W3.0	6	6.4	2.9	3.0	16.0	G	1.80
W3.7	5	3.0	0.5	3.7	21.0	G	2.70
E0.3	6	2.4	1.0	0.3	2.0	S	–
E0.6	4	1.5	1.1	0.6	4.0	S	–
E1.1	5	0.7	0.6	1.1	7.0	S	–
E2.0	6	9.5	2.6	2.0	11.0	G	0.05
E2.6	6	7.9	2.1	2.6	15.0	G	1.00
E3.0	6	7.6	1.7	3.0	19.0	G	1.70

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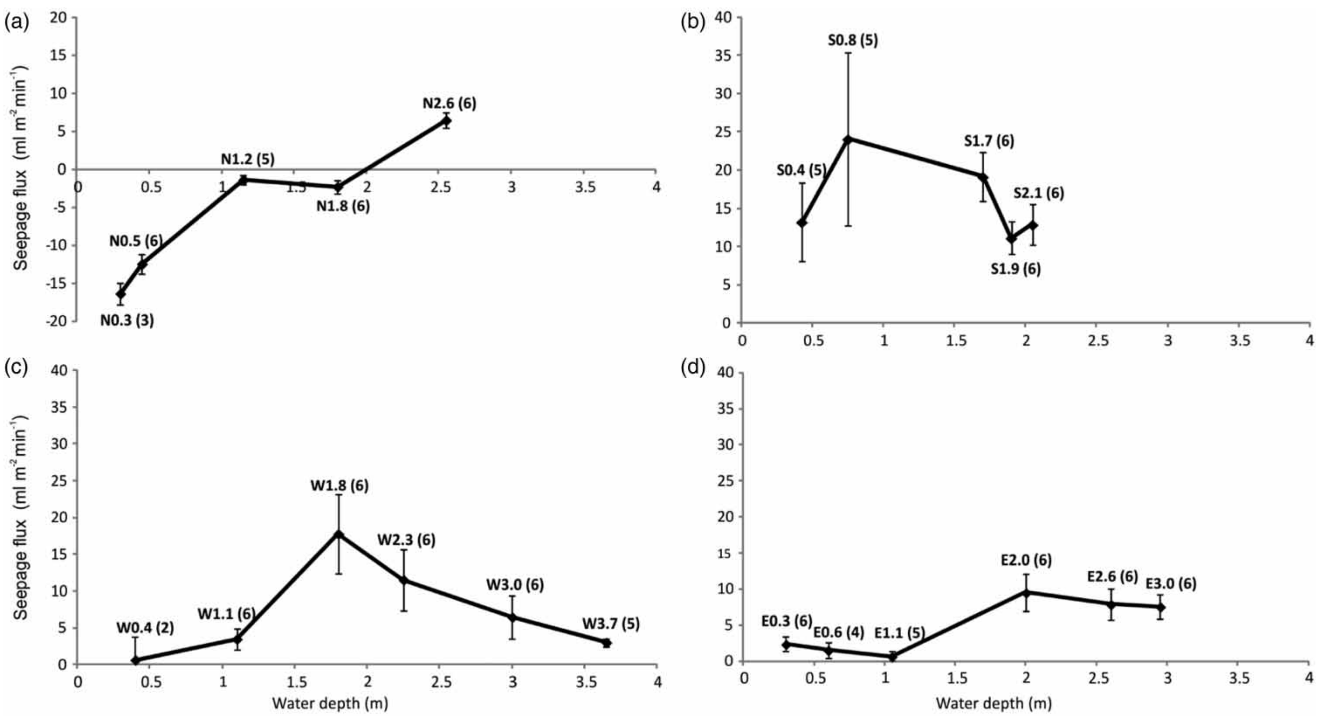

Figure 3 | Seepage fluxes at the measurement locations on the (a) northern, (b) southern, (c) western and (d) eastern transect.

locations closest to the shore (W0.4 and W1.1). The seepage rate was highest at the sand-covered location W1.8 (18 ml m^{-2} min^{-1}) where the distance from the shore was ca. 10 m and the water depth ca. 2 m. Further offshore the seepage flux decreased to below 4 ml m^{-2} min^{-1} (Table 3; Figures 3 and 4).

At the eastern transect, E, a weak positive seepage flux occurred close to the shore at the sand-covered locations E0.3 to E1.1 (below 3 ml m^{-2} min^{-1}). The seepage flux rose significantly (above 9 ml m^{-2} min^{-1}) further away from the shore at location E2.0 where the water depth was 2 m and the bottom was covered with a thin layer of gyttja. At locations E2.6 to E3.0, the seepage flux decreased, but remained above 7 ml m^{-2} min^{-1} (Table 3; Figures 3 and 4).

In Figures 3 and 4, the results were averaged over the measurements from two seepage meters on the parallel transects. Negative values indicate outseepage and error bars show standard error margins. As erroneous measurements were excluded, the number of proper measurements at each location is not equal.

Determined groundwater levels and flow lines

The groundwater level on the northern shore of the lake on the extension of transect N (Table 4) fell with increasing distance from the lake. At the distance of 2 and 7 m from the lake, the groundwater level was 8 and 10 cm, respectively, lower than the lake level. In the wells on the eastern shore of the lake on the extension of transect E, the groundwater level was only marginally higher than the lake level: 2 cm at 8 m from the shoreline. On the two transects on the SE shore, the groundwater level was equal ($\pm$1 cm) to the lake level as far as 15 m from the shore. On the southern shore, the groundwater level was 7 cm higher than the lake level in the temporary well 35 m from the shoreline.

The groundwater level interpolation (Figure 5(b)) shows a distinct northward groundwater flow around the lake. The groundwater level map interpolated according to the water-level data of permanent monitoring wells and neighbouring lakes shows a similar pattern of groundwater flow (Figure 5(a)). Groundwater enters the lake from the southern and south-western shore and leaves the lake through the

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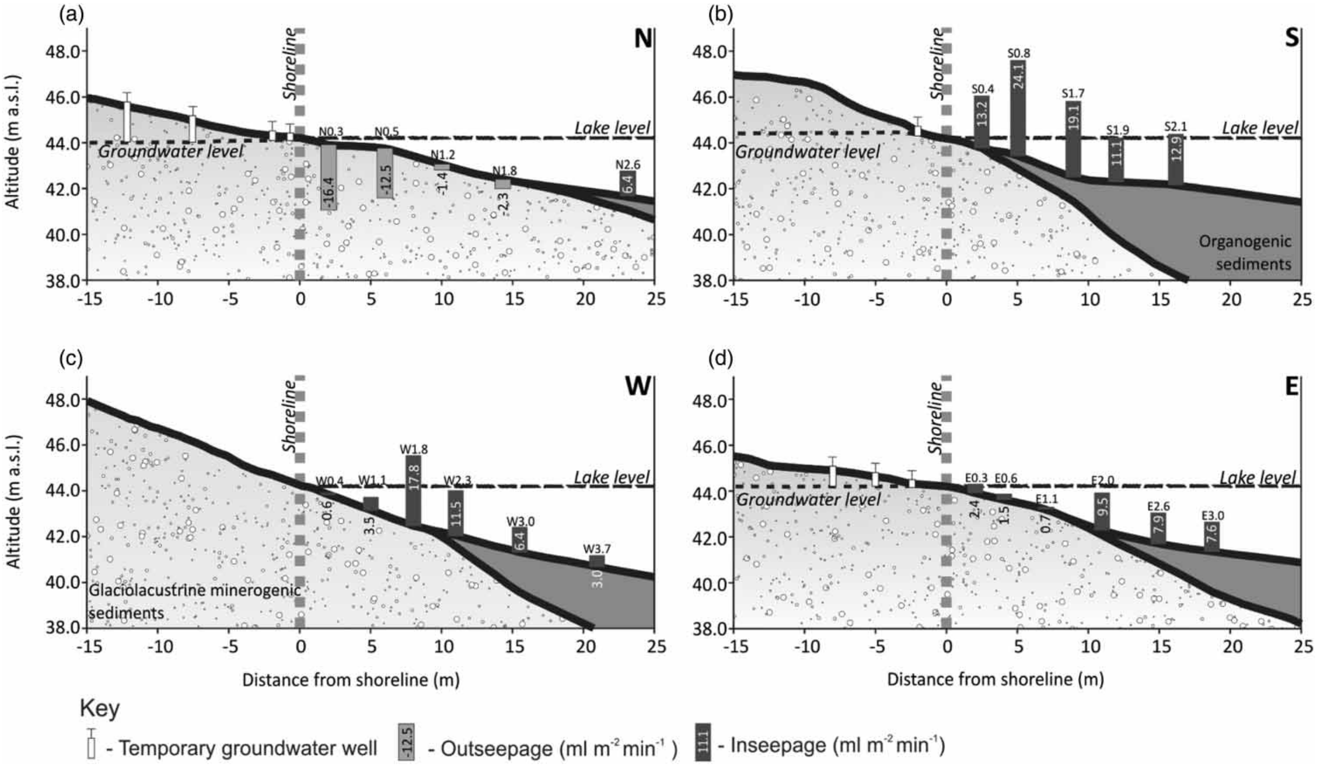

Figure 4 | Seepage direction and rates on the (a) northern (N), (b) southern (S), (c) western (W) and (d) eastern (E) transects of L. Martiska in June 2012. The heights of the columns indicate seepage rate at that location. The numbers in the measurement location codes, e.g. N0.3, indicate water depth at that location in meters. Seepage direction and rates are shown in the context of onshore groundwater level and characteristics of the measurement location – sediment type (minerogenic vs. organogenic) and organic sediment thickness.

Table 4 | Characteristics and measured water levels in the temporary wells on the shore of L. Martiska

Well location	Distance from lake shore (m)	Well water level minus lake water level (cm)	Water level depth in well (cm below ground)	Well depth (cm below ground)	Well stratigraphy (cm below ground)
N1	1	−2	4	22	0–22 sand
N2	2	−8	17	34	0–34 sand
N3	7	−10	102	123	0–123 sand
N4	14	−10	183	196	0–196 sand
E1	1	−1	5	24	0–24 sand
E2	4	0	45	67	0–67 sand
E3	8	2	96	117	0–117 sand
SE1	4	−1	21	37	0–37 sand
SE2	8	0	94	113	0–113 sand
SSE1	3	1	22	35	0–35 sand
SSE2	7	2	41	59	0–59 sand
SSE3	14	1	106	122	0–122 sand
S1	1	5	11	22	0–22 sand
S2	35	7	164	193	0–150 peat 150–193 sand

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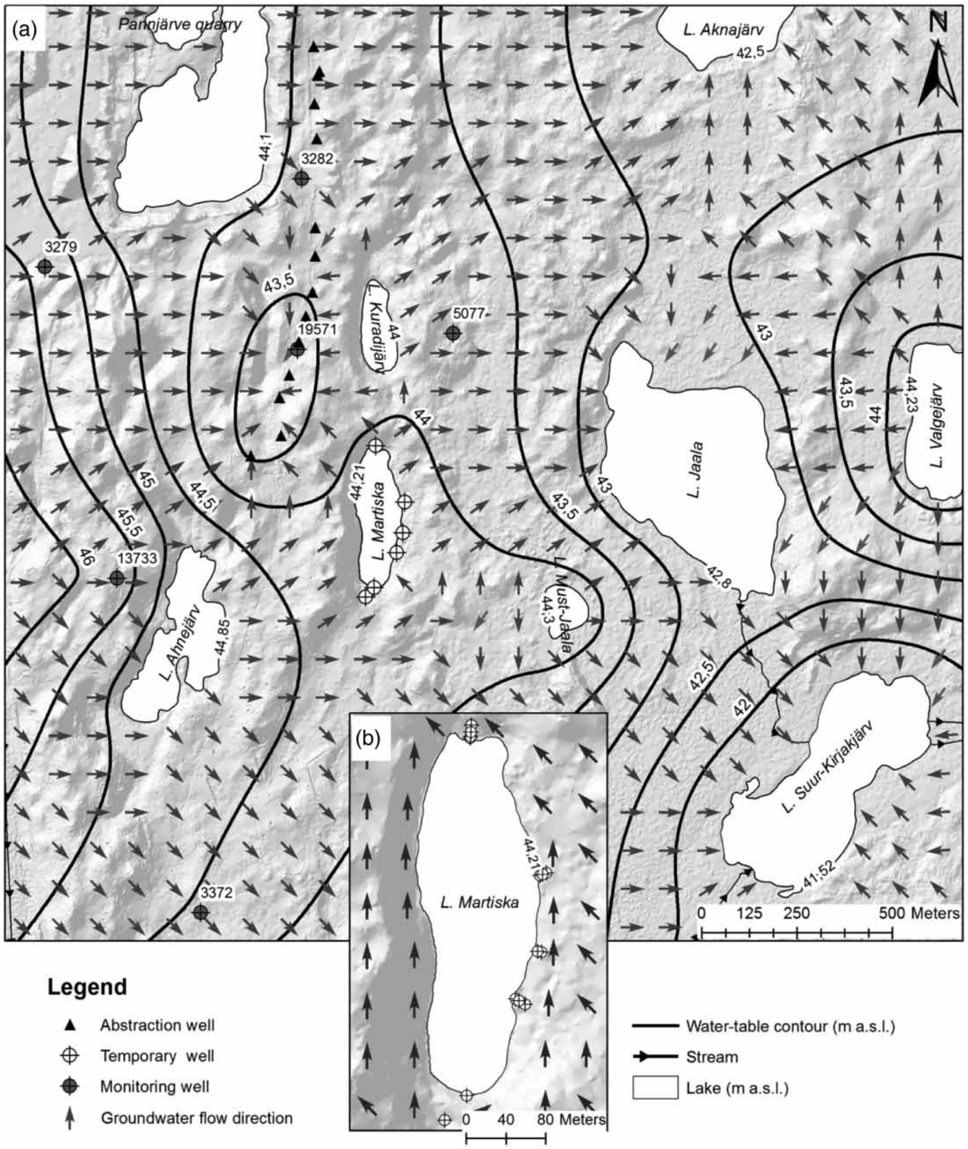

Figure 5 | (a) Piezometric map and groundwater flow directions in the central part of the Kurtna Lake District in June 2012, interpolated according to water levels from temporary and permanent wells and lake levels; (b) groundwater flow directions around L. Martiska in June 2012, interpolated according to water levels from temporary wells and the lake level (the digital elevation model was created according to year 2009 LIDAR-points obtained from the Estonian Land Board).

northern shore. The results suggest that most of the groundwater is coming to L. Martiska from the direction of L. Ahnejärv that has a higher water level. The groundwater seeps out of the lake towards the abstraction wells, where a groundwater depression has formed. The western and eastern side of the lake are in the transition zone where groundwater flow lines are clearly parallel to the lake shore on Figure 5(b) and relatively parallel on Figure 5(a).

Unfrozen and open water areas on the lake shoreline

An extensive area of open water patches and thus presumable groundwater inflow was detected on the SW shoreline, whereas an area of weak ice near the shore or unfrozen soil under the snow embraced the whole southern shore of the lake (Figure 2). Flow of water was not visible in the ice-free patches, however. No similar areas were found

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on the northern shore of the lake where thick ice extended to the ground and the soil was frozen under the snow cover.

Data analysis

Seepage flux showed no statistically significant correlation (at $\alpha = 0.05$) with sediment thickness ($\rho = 0.393$, $p = 0.107$, $N = 18$), distance from the shore ($\rho = 0.139$, $p = 0.583$, $N = 18$) and lake depth ($\rho = 0.118$, $p = 0.642$, $N = 18$). The *t*-test shows that the difference of the mean seepage flux in locations covered with sand was statistically significant ($p = 0.044$, $N = 18$) compared to locations covered with organic sediments. The mean seepage flux was lower in sandy locations ($Q = 4.4\ \text{ml m}^{-2}\ \text{min}^{-1}$, $N = 6$) than in locations with gyttja ($Q = 11.1\ \text{ml m}^{-2}\ \text{min}^{-1}$, $N = 12$).

DISCUSSION

The northern part of the lake was the only location where groundwater outseepage occurred. That was an expected result, because that part of the lake is closest to the groundwater abstraction wells and the depression cone caused by it. In agreement with the seepage measurements, the groundwater level in the temporary wells on the northern transect fell further from the lake. Also, the piezometric maps showed a northward flow in that area (Figure 5). Although there are no seepage measurements from lakes available from the time before the groundwater extraction began, studies have shown that the natural direction of the groundwater flow in the Quaternary aquifer would be from west to east without anthropogenic influences (Vallner 1987).

Our results suggest that the formation of the depression cone north of the lake has influenced seepage directions in L. Martiska, causing the lake water to seep towards the groundwater intake. Winter *et al.* (1998) has described the process of an artificial drawdown changing the magnitude and direction of seepage in surface water bodies. Only a few studies on groundwater–lake water interactions have managed to measure groundwater outflow with seepage meters (Asbury 1990; Rosenberry 2000, 2005; Sebestyen & Schneider 2001; Kidmose *et al.* 2011; Ala-aho *et al.* 2013), however, none of these studies have reported the outflow pattern to be the side-effect of groundwater pumping. The observed phenomenon at L. Martiska has the same mechanism as induced bank filtration that is used in some countries as a method for drawing purified drinking water from surface water bodies (UNESCO 2006; Sharma & Amy 2009). Although it is more actively practised on rivers, lakes have been used as well (Miettinen *et al.* 1997; Dash *et al.* 2008; Hoffman & Gunkel 2011). The situation is different at L. Martiska, because bank infiltration has occurred unintentionally and has lead to an unintentional deterioration of the lake ecosystem.

In the southern part of the lake, groundwater influx was notable throughout the transect. In the temporary water-level well south of the lake, the groundwater level was higher than the lake level. According to the water level maps, the southern shore was expected to be the area where groundwater seeps into the lake (Figure 5). This was confirmed by the winter observations on the southern shore (Figure 2). The area of unfrozen water at the SW shore of the lake was exactly at the same location where most intensive groundwater flow was expected. Unfortunately seepage measurements were not possible from the area of presumably highest inseepage at the SW shoreline, because the lake bed was covered by thick vegetation and dead trunks of trees and bushes. Nonetheless, seepage meter transect S was the only location where notable groundwater discharge into the lake occurred at the locations closest to the shore.

In the western and eastern nearshore areas of the lake virtually no seepage occurred. These areas coincide with the 'hinge-line' according to Winter *et al.* (1998) between groundwater recharge and discharge on the larger scale groundwater flow map (Figure 5(b)). The water level in the temporary wells on the eastern shore showed an almost non-existent groundwater gradient towards the lake. Hence, no or very weak seepage flux was expected. The groundwater flow directions at the eastern shore of the lake on the smaller scale interpolated piezometric map (Figure 5(a)) are not fully in agreement with the measurement data. The flow lines are not fully parallel to the shore but lead towards L. Jaala. The pattern was caused by the 1.4 m lower water level in L. Jaala than that of L. Martiska and the lack of groundwater monitoring wells between the lakes (Figure 1). The interpolation method that was able to produce flow lines parallel to the shore using water levels

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from the temporary wells close to the shore was biased by the distant data point that had a significantly lower water level. It shows that in hummocky glacial terrain the density of groundwater level data should be higher than in our study to produce reliable groundwater level and flow direction maps. Despite those limitations, the interpolated groundwater flow directions agree well with measured seepage directions in the nearshore bottom areas of L. Martiska.

Surprisingly, the conformity of seepage flux with the groundwater flow directions around the lake disappeared further offshore. This was most notable in the northern part of the lake, where negative seepage flux turned positive about 25 m from the shore, where the water depth exceeded 2 m (Figure 4). In the eastern and western parts of the lake, the seepage flux showed unexpected patterns as well: almost no flux was measured close to the shore and a significantly higher flux at 10 to 15 m from the shore at the water depth of about 2 m. Only in the southern part of the lake the seepage direction and rate did not show an abrupt change with the increase in distance from the shore and in water depth. These results suggest that general groundwater flow lines around a lake can be used to predict seepage patterns only in the nearshore areas; however, predicting seepage patterns in deeper offshore areas must be treated with caution. In our study the change seems to take place in areas where the water depth exceeds 2 m (Figures 3 and 4).

Many theoretical and modelling studies (as referred to in the Introduction) have assumed an exponential decrease in seepage flux with increasing distance from the shoreline in geologically homogenous conditions. Our study did not show this pattern, however. Although the measurements from the northern transect showed a decrease in seepage flux as the distance from the shore increased, the flux did not become zero but became positive even further from the shore (Figure 4). On other transects the exponential decrease was not visible at all.

As the simplest mechanism of seepage distribution was unobservable in the study, it was hypothesised that sediment type and thickness are the major factors that control the distribution of seepage. However, we found that the varying thickness of organic sediments does also not explain the significant changes observed in offshore inseepage. More specifically, the dominantly negative seepage at the northern transect became positive at location N2.6 even though one of the seepage meters lay on sand and the parallel seepage meter on organic sediments. At the western transect, the highest inflow was measured at a location with no organic sediments (W1.8) and the seepage rate decreased with the growing thickness of sediments (W2.3 to W3.7) (Figure 4). Conversely, at the eastern transect the seepage rate did not change substantially with the changing thickness of organic sediments (E2.0 to E3.0).

The standard errors were relatively high at some measurement locations on the southern and western transects (Figure 3). That was mainly caused by the differences in the flux at the two seepage meter locations averaged to one measurement location, and to a lower extent by the temporal variability of the seepage flux across the three consecutive measurements. High spatial variability of seepage flux has been described in several studies (Brock *et al.* 1982; Schafran & Driscoll 1990; Guyonnet 1991; Kishel & Gerla 2002). A recent study by Rosenberry *et al.* (2013) has shown that seepage rates also exhibit high daily temporal variability that would be caused by various hydro-meteorological processes. Therefore, the observed standard errors in the current study are not exceptional. The variability would make the quantification of the absolute amounts of groundwater inflow to or outflow from a lake rather difficult. However, as that was not an objective, the high variability does not influence the inferences from our study.

Our results do not allow making any implications on the influence of organic sediments to outseepage. However, when looking into the distribution pattern of inseepage rate, it was unexpectedly higher in areas covered with gyttja than in areas covered with sand. The difference was statistically significant. However, it would be unreasonable to conclude that seepage flux is amplified by organic sediments, because the significant difference resulted from the high rates at the gyttja-covered southern transect. Still, our results question the validity of the assumption that organic lacustrine sediments seal the lake from interacting with groundwater, which has been used in several modelling studies (e.g. Genereux & Bandopadhyay 2001; Cardille *et al.* 2004; Kidmose *et al.* 2011). At least for inseepage, the layer of organic sediments does not seem to pose an evident barrier. The extent of influence of gyttja probably depends

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on its water content and density throughout the sediment column – the issue clearly requires further research.

Although the correlation analysis showed no monotonic relationship between seepage influx and the analysed variables, Figures 3(b)–3(d) and 4(b)–4(d) show that the rates tended to become higher with increasing distance from the shore and water depth, peak within 5–11 m from the shore and 1–2 m of water depth and decrease in deeper water further from the shore. A similar pattern of seepage being higher in the offshore than in the nearshore has been described also in some previous studies. Many of those have hypothesized that the non-uniformity of the underlying geological structure is the major cause (Cherkauer & Nader 1989; Schneider *et al.* 2005; Rosenberry & Winter 2009). Kidmose *et al.* (2011) explained observed peaks in offshore inseepage with the presence of a low-conductivity layer of peat in the nearshore area, and in another study (Kidmose *et al.* 2013) with the presence of a thick layer of nearshore gyttja. In the study by Kidmose *et al.* (2011), the layer of peat had formed during a period of a lower water level. L. Martiska has gone through a period of lower water level in the recent past as well; however, a peat-layer does not exist at the locations where low nearshore inseepage occurred.

Ala-aho *et al.* (2013) hypothesised that an anomalous temporal trend in inseepage locations compared to outseepage locations could have been caused by a different groundwater flow system between inflow and outflow. According to the present general knowledge about the Vasavere aquifer (Erg 2012), the Quaternary sediments around and underneath L. Martiska are considered to consist of relatively uniform mixed-grained sands and discontinued water tables have not been registered around the centre of the Kurtna Kame Field. Still, the unexpected behaviour of offshore seepage could be caused by the opening of a small but not-yet-discovered local confined aquifer into the lake underneath the unconfined aquifer, as detailed geological studies in the exact location of L. Martiska have not been made. The presence of two contributing aquifers would explain the measured seepage directions observed both in the nearshore areas of the lake and in the offshore areas within the lake. The proposed hypothesis needs to be evaluated with further studies on the geology of the Quaternary sediments of the immediate surroundings of L. Martiska.

CONCLUSIONS

This paper represents the first study in the Baltics on groundwater–surface water interactions in lakes. The major finding and conclusions are as follows.

Groundwater seepage patterns followed the estimated groundwater flow directions in the surrounding aquifer only in the nearshore areas of the lake, but the conformity disappeared further offshore. Therefore, the areas of out- and inseepage in lakes cannot be determined according to simple piezometric maps and winter mapping of ice-free areas only; additional direct measurements from both near- and offshore areas are needed.

Seepage flux did not correlate with water depth, distance from the shore nor thickness of organic sediments. The most significant finding was that inseepage does not decrease with increasing thickness of organic sediments as was expected from previous studies. In contrast, higher inseepage was recorded in lake bed areas covered with organic sediments. Therefore the assumption, often used in modelling studies, that a layer of lacustrine sediments obstructs groundwater–lake water exchange, is not universal and should be used with caution, at least in the case of inseepage.

Outseepage, which has been rarely measured in previous seepage meter studies, occurred in the northern part of the lake close to groundwater abstraction wells. It demonstrates that seepage patterns in the potentially affected lakes should be clarified while planning the establishment of groundwater intakes to prevent unwanted bank filtration from occurring. Uncontrolled bank filtration can cause significant changes in the water balance of lakes nearby and result in lowered water level and associated changes in lake ecosystems.

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