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Interaction of esker groundwater with headwater lakes and streams

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SUMMARY

Groundwater–surface water interactions were studied in a Finnish esker aquifer system where some lakes suffer from periodic water level decline and others from eutrophication. Natural tracers (Ca^{2+}, SiO_2 and PO_4^{3-}) were used on the aquifer scale and seepage meter measurements and water level recordings on the single lake scale to better understand the complex interactions between groundwater, lakes and streams in the area. The natural tracers showed that lakes located in lower landscape positions and connected with streams were richer in tracer concentrations and that their water chemistry resembled that of the groundwater. On the other hand, closed basin lakes located at higher altitudes were nutrient-poor seepage lakes with some groundwater through flow. The data suggests that the subsurface acts as a phosphate source for the surface water bodies and the nutrient rich groundwater inseepage dictates the trophic status of the lakes in the area. The seepage meter measurements verified a strong interaction between groundwater and surface water and revealed spatial distribution of lake seepage and a temporal co-variation in lake seepage rates. A statistical analysis of seepage meter and water level observation time series were useful to show groundwater flow regimes controlling lake seepage. Using the natural tracer analysis and seepage meter measurements, we developed a novel conceptual model for the study site where the differences in lake trophic state and water table behavior were explained by assigning lakes to local and regional groundwater flow regimes. The obtained results provide new knowledge on using natural tracers in complex glacial aquifer systems and can be used in integrated groundwater–surface water management.

1. Introduction

Eskers are abundant in the Fenno-Scandinavian shield and are common in other regions covered by the last glaciation. Esker aquifers are often connected to rivers, lakes and wetlands and such groundwater-dependent systems are of high ecological value (Kløve et al., 2011). Eskers consist geologically of permeable sandy soils and gravels, so surface runoff is usually minor. Instead, water ponds in landscape depressions as a result of subsurface flow, forming closed basin lakes and wetlands. As such lakes are usually embedded in the aquifer and their water level and water chemistry are highly dependent on the groundwater system (Winter et al., 1998). In addition to the physical characteristics of the lakes, groundwater exchange affects ecosystems by providing nutrients, inorganic ions and a stable water temperature (Hayashi and Rosenberry, 2002).

In glacial terrain, such as eskers, lakes interacting with groundwater can be roughly categorized into three types with a typical position in the landscape and in the groundwater flow system (Winter et al., 1998): (1) Drainage lakes that receive groundwater inflow throughout their bed and are usually located in topographically low-lying areas, in the regional groundwater discharge area. (2) Recharge lakes that recharge groundwater throughout their bed and often occur topographically high in the groundwater recharge area. (3) Seepage lakes located between the extreme cases above and that can receive groundwater inflow in some lake sections and lose water to groundwater in others. The concept of local and regional groundwater systems, first introduced by Toth (1963), has provided theoretical background for several aspects of lake-groundwater interaction. Following Winter (1976), many studies suggest that lake position with respect to local and regional flow systems may determine a number of factors in their hydrology and chemistry.

Despite growing interest in groundwater–surface water interactions, few field studies have sought to explain the hydrological conditions or water quality of lakes by their position with respect to local or regional groundwater flow systems. Most field methods for studying groundwater–surface water interactions aim to quantify the water flux at the interface, disregarding the fact that groundwater inseepage to lakes may differ in solute concentrations and inflow stability depending on the groundwater flow system. However, Winter and Carr (1980) used numerical groundwater

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modeling to relate lakes with high concentrations of total dissolved solids to regional or deep intermediate groundwater flow systems and lakes with lower concentrations to local or small intermediate flow systems. Aquifer scale flow systems were also studied by Webster et al. (1996) who concluded that the landscape position of a lake can control its ionic composition and may influence its chemical response to droughts or other climatic changes. A study by Kratz et al. (1997), conducted in the same lake system, also attributed the biological composition of lakes to their position in the landscape.

In comparison with studies examining lake systems on the aquifer scale, studies distinguishing between local and regional origins of groundwater inflow to lakes are more abundant on the scale of a single lake. Researchers report cases where changes in regional groundwater systems affect water and nutrient fluxes in individual lakes (see e.g. Brock et al., 1982; Anderson and Cheng, 1993; Winter, 1999; Hagerthey and Kerfoot, 2005). In addition, many studies have recognized groundwater as an important source of nutrients and inorganic ions in lakes (Shaw et al., 1990; Krabbenhoft and Webster, 1995; Devito et al., 2000; Hayashi and Rosenberry, 2002; Sebestyen and Schneider, 2004; Hagerthey and Kerfoot, 2005).

Kenoyer and Bowser (1992) provided a theoretical background to the chemical evolution of groundwater along different groundwater flow systems and showed that longer subsurface flow paths lead to increased alkalinity and increased concentrations of some major cations. The starting hypothesis for our investigations at aquifer scale was that the chemical constitution of lake water in terms of natural tracers (silica, calcium and phosphate) can be explained by the position of the lake with respect to groundwater flow systems as the contact time with water and soil in the regional groundwater system can be assumed to be longer than in small local flow systems (Kenoyer and Bowser, 1992). In addition, at the scale of a single lake, we used natural tracer analyzes to look for similarities between the quality of lake water and that of groundwater adjacent to the lake.

Of the selected analytics, phosphate is not a suitable natural tracer as such because of its active biological uptake and tendency to be adsorbed on soil minerals and organic matter. Nevertheless below the organic rich and biologically active soil zone the amount of phosphorus in groundwater is mainly controlled by solubility of slightly soluble phosphate-bearing minerals (Freeze and Cherry, 1979). In this respect groundwater inflow can provide a phosphate source to lakes. Even though both surface waters and groundwater are naturally low in phosphates (Freeze and Cherry, 1979), concentrations in groundwater usually tend to be higher than those in surface water (Holman et al., 2010). Finnish bedrock, and the sediments eroded from the bedrock, can locally be rich in phosphorus. Phosphate flux from groundwater to lakes might be ecologically relevant, because in most Finnish inland lakes phosphate is the limiting nutrient for primary production and lakes rich in phosphate are usually eutrophic. Excess phosphate in natural systems in Finland is most commonly derived from anthropogenic sources such as sewage treatment plants and fertilizer use for agriculture and forestry (Soveri et al., 2001) and transported to lakes by either surface or subsurface pathways. Still, as some lakes in the Rokua area are distinctly more eutrophic than others without any obvious reason, we sought to determine whether phosphate originated by mineral dissolution, weathering or desorption in the subsurface and transported to lakes by groundwater flow could explain the different trophic status of lakes in the area.

The overall aim of this study was to identify suitable methods to distinguish groundwater flow systems on regional (aquifer) and local (single lake) scale in order to explain spatial variation in lake trophic status and temporal variability in lake water level. We used a statistical approach to outline the complex groundwater flow systems surrounding lakes with data from well-established field measurements. Firstly, we used natural tracers to pinpoint lakes and streams to different flow systems according to their tracer concentration, water body type and landscape location. Secondly, we demonstrate methods for separating groundwater flow systems surrounding a single lake by statistical analysis, using data from seepage meters and standard hydrogeological observations. With the methods presented, we developed a conceptual model for the groundwater flow system that could explain anomalous behavior of lakes co-occurring in similar geological and land-use settings: a periodically declining water level in some lakes and a eutrophic state in others.

2. Materials and methods

2.1. Study site

The Rokua esker aquifer is part of a long esker ridge stretching inland from the North Ostrobothnian coast (Aartolahti, 1973) and was formed during the last deglaciation some 9000–12,000 years ago (Tikkanen, 2002). Eskers are long, narrow formations of sand and gravel associated with the retreat of the ice cover (Svendsen et al., 2004). Hydrologically, the Rokua esker aquifer is a very complex, unconfined aquifer system with interdependent groundwater, lakes and streams in the aquifer recharge area and groundwater-fed springs and streams in the groundwater discharge area (Fig. 1). According to groundwater head observations, the aquifer water table has two regional groundwater mounds. Groundwater flows from the areas of high water table in recharge zone in a radial fashion towards the low-laying discharge zones (Fig. 1).

In geological terms, the aquifer material is fine and medium sand derived from sedimentary rock of the Muhos formation (Pajunen, 1995) and consists mainly of quartz. Thickness of the sand deposits varies from 30 m to more than 100 m above the bedrock. In addition, some loam lenses and gravel deposits, typical of glacial esker formations, have been located in geological surveys. The Rokua recharge area has rolling terrain because of kettle holes, wave action and aeolian dunes (Aartolahti, 1973). The aquifer has a recharge area of 90 km^2 and it discharges groundwater to peatlands surrounding the esker. The permeability of the peat soil is low and peat layers partially confine the aquifer in the discharge zone (Rossi et al., 2012).

Long, narrow depressions in the landscape, geological landscape forms referred to as ‘‘kettle holes’’, are abundant, in the Rokua esker aquifer (Fig. 1). Kettle holes were formed during deglaciation as large blocks of ice were encased within the sand deposits. When the ice later melted, a depression was left in the landscape. The size of these kettle holes varies widely, with their depth ranging from 1–2 m to 40 m and their diameter from some 10 m to 1.5 km long by 0.4 km wide (Aartolahti, 1973). The majority of the kettle holes are dry, but approximately 90 lakes or ponds with surface area ranging from 0.02 to 165 ha are located in the area.

The geological and ecological uniqueness of the Rokua esker area is widely acknowledged. Rokua was recently granted membership of the UNESCO GeoPark Network and it is also part of the Finnish nature reserve network. Some ecosystems in the area are protected by Natura 2000 (Metsähallitus, 2008). Most of the kettle hole lakes and ponds in the area are of high ecological and recreational value because of their crystal clear waters (Anttila and Heikkinen, 2007). Some of the lakes habitats are included in the Natura 2000 program as ‘‘oligotrophic water containing very few minerals of sandy plains’’ (Metsähallitus, 2008). The lakes are widely used for recreational activities such as fishing, swimming and scuba diving, and most of the lake shores are populated with holiday homes and hotels.

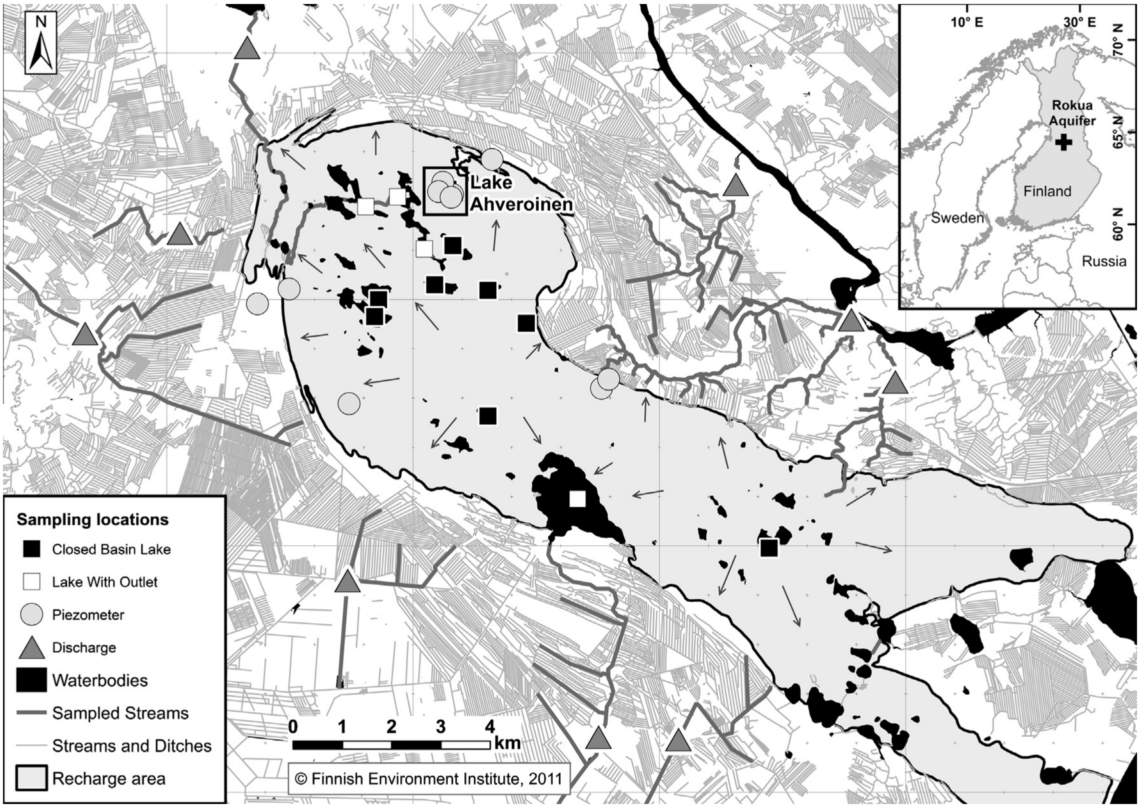

Fig. 1. The Rokua esker aquifer, with several groundwater-dependent lakes in the recharge area and streams and ditches in the discharge area. Water sampling locations in the aquifer are presented with different symbols for closed basin lakes, lakes with outlets, piezometers and streams. Small arrows indicate the general ground water flow directions.

Kettle hole lakes imbedded in the Rokua esker aquifer are affected by two problems: (1) periodically declining water level in closed basin lakes; and (2) eutrophication of lakes with a surface water outlet. Water levels in the closed basin lakes in the area have been unusually low for several periods of 1 or 2 years during recent decades, causing concern among environmental agencies and local residents (Anttila and Heikkinen, 2007). The water levels have partially recovered after years of water level minima, but the cumulative decline in lake levels has reached approximately one meter below the historical normal level as interpreted from past shoreline and vegetation, revealing several meters of lake bed in parts of the shoreline. Previous lake stage monitoring by local environmental officials (during 1980–1982 and 2004–2008 with variable, approximately monthly time resolution) shows that level declines in different lakes in the area have been variable both in magnitude and in timing (Anttila and Heikkinen, 2007). Historical climate data and sparse lake stage monitoring data indicate that periods of low water levels are to some extent related to consecutive years of below-average precipitation. However, despite a rising trend in precipitation during recent decades, lake water levels have not been restored to their original positions and a declining trend has been observed in some piezometers in the area (Anttila and Heikkinen, 2007). Water quality in the closed basin lakes is optimal for recreational use, but a permanent lake water level decline would be disadvantageous for both the ecological and recreational values of the Rokua area.

The lakes that are suffering from eutrophic conditions manifested in poor water quality (high phosphorus concentrations and occasional oxygen depletion) and algae blooms (Väisänen et al., 2007) are different from those in which water levels are periodically declining, though one overlapping lake exists. Nutrient loading from anthropogenic sources can be considered to be a minor nutrient source for both oligotrophic and eutrophic lakes. Of possible anthropogenic sources, agriculture in the aquifer recharge area is non-existent. Forestry activities, which have been shown to be a potential source of e.g. phosphate to groundwater (Devito et al., 2000), are practiced in the area. Yet fertilization in forestry has been minimal and the nutrient leaching from forestry is estimated to be at the level of natural background loading (Väisänen et al. (2007).

In addition, most of the lake shores are inhabited by holiday homes (apart from two lakes located in the natural park) which may unintentionally release small volumes of sewage to groundwater. However, density of holiday homes around lake shores is low (on average one residence per 250 m of shoreline) and is similar in lakes located both high and low in the landscape. Residential development beyond immediate vicinity of lake shores is almost non-existent. Even though holiday homes may leach some nutrients to the aquifer, Väisänen et al. (2007) estimated the above mentioned to be too small to explain the different trophic status of lakes and concluded that both the eutrophic and oligotrophic lake types are in a natural state. The only obvious difference between the two lake types are surface water outlets, which exist only in the eutrophic chain of lakes. However, previous studies have not explained why some lakes in the Rokua area are distinctly more eutrophic than others, despite being located in similar hydrogeological settings.

Lake Ahveroinen located in the northern part of the esker aquifer (Fig. 1) was selected as a pilot lake to gather detailed information on the lake–aquifer interaction in the area. Lake is of special importance for the area's recreational use due to a wellness-center located next to the lake. Therefore the periodical water level decline in the lake Ahveroinen has been of major concern. We were particularly interested in the strength and variability of the water exchange between groundwater and the lake, not only for the sake of lake Ahveroinen, but also to gain a representative example of the conditions likely present in other similar lakes in the area. In addition, the lake was a suitable pilot site because of its easy access and manageable size for the field methods used in the study.

2.2. Water sampling for flow path determination

Natural tracers calcium (Ca^{2+}) and silica (SiO_2) and ecologically significant nutrient phosphate (PO_4^{3-}) were used in this study at the scale of the aquifer and a single lake to identify different groundwater flow systems providing subsurface inflow to the lakes. The selected tracers are almost completely absent in meteoric water falling as precipitation and emerge in groundwater as a result of soil mineral dissolution processes when groundwater is in contact with mineral surfaces (Freeze and Cherry, 1979). Thus the naturally emerging increase of major cation and silicate concentration can be utilized as a tracer of the groundwater age in sandy silicate aquifers typically found in Finland (Kenoyer and Bowser, 1992; Soveri et al., 2001).

Water samples were taken in all relevant hydrological compartments of the study site (10 piezometers, 13 lakes, 9 streams and one precipitation as snow) at a total of 33 locations (Fig. 1). The piezometers were water table wells with unsaturated depth varying between 2 and 30 m. The wells were pumped from one meter below the water table for at least 10 min or until the color of the water was clear (max 30 min).

These samples were analyzed for calcium (Ca^{2+} [$mg\,l^{-1}$]), silica (SiO_2 [$mg\,l^{-1}$]), and phosphate (PO_4^{3-} [$\mu g\,l^{-1}$]) by the Finnish Environmental Institute (SYKE) laboratory with methods based on international (ISO) and national (SFS) standards (modified ISO 11885:2007 ICP-OES-technique, ISO16264:2002, SFS 3025:1986, respectively (FINAS, 2012)). Precipitation samples were taken from the snow pack and melted for analysis. Sampling was carried out in years 2010, 2011 and 2012 during minimum flow conditions at the end of March. Prior to sampling in March, snow cover had prevented most water exchange between atmospheric water and the sampling locations (piezometers, lakes and streams) from three to four months. During this time lake evaporation, which often plays a role in concentrating solutes in lakes, has been inactive. As a result, the conditions prevailing at the time of water sampling were more similar than at any other time of the hydrological year, making the samples between years comparable.

2.3. Seepage meter measurements

Seepage meter measurements were conducted in the study lake Ahveroinen (Fig. 2) in order to: (1) verify the interaction between the lake and the aquifer; (2) determine the spatial distribution of lake seepage rates; (3) study temporal variations in seepage rates within specific locations; and (4) compare the temporal variations in lake seepage and changes in lake and groundwater levels in order to outline different groundwater flow systems affecting seepage rates in the lake.

The seepage meter, also referred to as a seepage chamber, is a simple, inexpensive and most commonly used method for directly measuring seepage flux between groundwater and surface water bodies (Brodie et al., 2007; Rosenberry et al., 2008). In its simplest design the device consists of a chamber enclosing a part of the lake or stream bed and a collection system to measure the volume of water flowing in or out of the bed section enclosed by the chamber. In the present study, groundwater–surface water interactions in the lake Ahveroinen were studied with seepage meters resembling the design introduced by Lee (1977). Equipment consisted of a 208 l steel drum barrel (diameter 57 cm) with a cut-off end, a plastic bag and a smooth 20 cm connection hose between the bag and the chamber. In total six seepage meters, all identical in design and components, were used in the study.

Most common sources of errors occurring inseepage meter studies described by Rosenberry et al. (2008) were acknowledged in both seepage meter design and in carrying out the measurements. Resistance of flow in the meter was minimized by selecting large diameter components for the hose connection between the seepage meter chamber and the measurement bag. Even with careful construction and design, the seepage measurements have been shown to underestimate the true seepage rate. In many studies this error has been corrected with a coefficient ranging from 1.05 to 1.82 (Rosenberry et al., 2008). However, in this study the interest was in comparing the changes in the seepage rates at different measurement times and locations within the same lake, not in determining the true value for the seepage flux, so correction coefficient was considered non-pertinent. In this respect the measurements are only strictly relative to each other, but still provide a reasonable estimate for the actual seepage velocity.

All components and connections associated with the meter were tested for waterproofness and durability. The bag was carefully attached to and detached from as far away from the chamber as possible to avoid displacement of water from lake bed sediments to the chamber. Head loss due to water flow velocity or wave action around the bag was considered to be very small and the seepage chambers were not equipped with current shields. Water movement near the lake shoreline was minimal because the lake was sheltered from wind due to its small size (Fig. 2), location in a landscape depression, and a tall pine tree canopy surrounding the lake. Potential sources of error noted during measurements were occasional gas accumulation in the seepage chamber and the bag, suspected holes in the measurement bags causing leakage, and difficulties in installing the chambers in soft lake bed sediments in the north–west part of the lake.

The first set of seepage meter measurements focused on determining the spatial distribution of seepage direction and rate in the lake. A set of 13 measurements were made between 14–18 August 2009 and seven additional measurements on 17–18 September 2009. The latter measurements were performed to verify the results of measurements in the north–east corner of the lake. Measurements were done in the vicinity of the shoreline. The measurement depth (mean = 0.87 m, standard deviation = 0.43 m) and distance from shoreline (mean = 4.0 m, standard deviation = 2.9 m) was kept as similar as possible for all of the measurement points but some variability was introduced because of different lake bed slopes and installation suitability of the lake bed in a given measurement location. A trial measurement was performed directly after the chamber installation to obtain a rough estimate of the seepage rate in order to estimate a suitable volume of prefilling water for each measurement location. After the trial measurement the chambers were left undisturbed for overnight so that the seepage chamber and the lake bed sediment would reach equilibrium flow conditions after the disturbance caused by chamber installation. The final spatial distribution of seepage rates around the lake in 2009 was determined at 16 locations (Fig. 2).

A second set of seepage meter measurements focused on determining temporal variations in seepage rates in Lake Ahveroinen. Eight seepage meter measurements were made at six locations (Fig. 2) with similar measurement depths (mean = 0.67 m, standard deviation = 0.13 m) and distances from shoreline (mean = 4.0 m, standard deviation = 1.3 m) during the period 1 June-4 November 2010 (in total 64 measurements). The measurement locations were selected to represent different seepage rates and directions, using knowledge of the spatial distribution of seepage gained in the 2009 measurements. The measurement interval was approximately 3 weeks, and the seepage meter chambers were not detached from

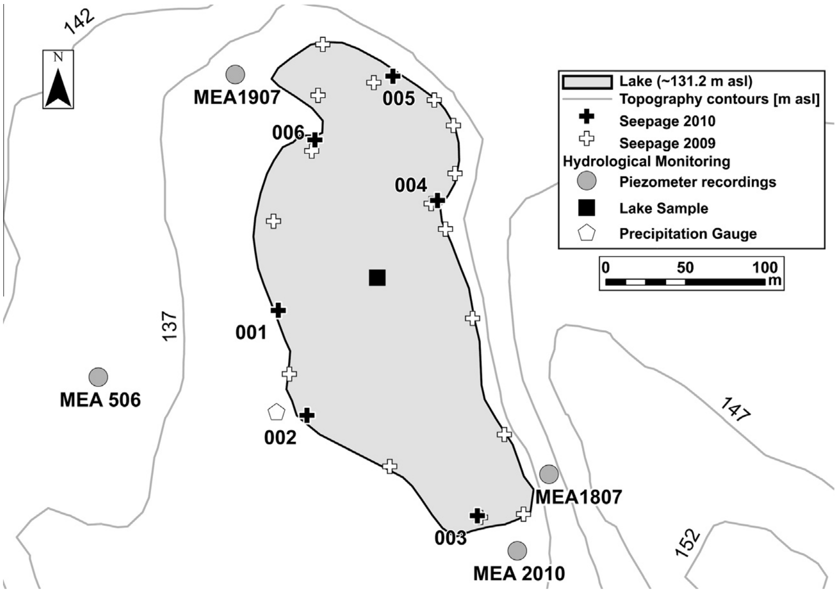

Fig. 2. Hydrological monitoring locations in the study lake Ahveroinen. Spatial distribution of seepage meter measurements for the 2 years is represented as crosses of different color and the locations to study temporal seepage variability during 2010 are named (001–006).

the lake bed between measurements, but left in place to maintain as similar conditions as possible for measurements at each site during the 5-month observation period.

2.4. Hydrologic observations

Groundwater level and lake stage were recorded continuously to monitor the hydrogeological conditions surrounding the study lake (Fig. 2). Precipitation at the lake was recorded with a tipping bucket rain gauge (TruTrack) from 28 April to 3 November 2010. The quality of precipitation data was verified by correlation analysis against data obtained from the Finnish Meteorological Institute recorded 10 km south of the study site.

Water levels were recorded with pressure-based data loggers (Solinst Levelogger Gold) at 1-h intervals. Groundwater level was determined using three groundwater wells installed near the lake (Fig. 2). Piezometer MEA2010 was installed after the seepage meter measurements and was used only for water sampling during years 2011 and 2012. Data from wells with an unsaturated zone over 7 m and 9 m (MEA1907 and MEA506, respectively) showed rapid fluctuations (noise), most likely caused by discrepancies in barometric pressure changes in the unsaturated zone and in the borehole (Rasmussen and Crawford, 1997). To eliminate this noise, groundwater level readings were smoothed with 150-h moving averages. Time step for moving average was found with trial and error so that essential dynamics of the water table (e.g. responses to precipitation events) remained in the time series. The residual (time series of the moving average subtracted from the original data) had a zero mean and a normal distribution around the mean indicating that only random noise was removed from the data. Lake stage was recorded with similar water level datalogger as groundwater level, placed on the lake bed and protected with a plastic shelter and a filter.

2.5. Statistical data analysis

In aquifer scale, tracer concentrations were statistically compared to altitude of the sampling location using the rank-based Kendall correlation analysis. The underlying assumption was that water sampled at lower altitudes had travelled along a longer flow path in the subsurface and therefore would be richer in tracers indicating mineral weathering and dissolution. Altitude of the sampling location was used as a proxy for flow path length; the lower the altitude, the longer the assumed travel distance in the subsurface. In addition, phosphate concentrations were compared with the calcium and silica to determine if the phosphate concentrations in different parts of the study site were related natural tracers known to reflect the length of the subsurface flow path. For descriptive statistics, the median was selected as the measurement of central location and inter quantile range as the measurement of spread because of observed non-normal distribution especially in phosphate samples.

For the pilot lake Ahveroinen, we used a novel approach to statistically compare time series of seepage meter measurements and hydrogeological conditions at the time of seepage measurements to find indications of different groundwater flow systems controlling the lake seepage. First, we tested if lake seepage velocities measured on the same date but at different locations were cross-correlated. Rank-based Kendall's tau correlation coefficient (see e.g. Helsel and Hirsch, 2002) was used in cross-correlation analysis between seepage measurement locations. Kendall's tau analysis was chosen because it describes the monotonic relationship between two examined variables and we were more interested in the direction than the magnitude of seepage change. The time series for each seepage measurement location was treated as an independent variable and a correlation coefficient matrix was calculated to express correlation between all measurement locations.

In the next step we analyzed the correlation between seepage velocities and lake and groundwater levels on the date of seepage measurements. The purpose of this analysis was to detect whether changes in seepage rates co-varied with changes in the surrounding hydrogeology. Because we wanted to acknowledge the linear relationship between hydraulic gradient and groundwater flow velocity (in this case seepage velocity), Pearson correlation coefficient expressing linear correlation was used in the analysis and correlations with p-values below 0.05 were considered to demonstrate a strong correlation. It should be noted that reported p-values for correlations between seepage measurements and hydrological observations are prone to type I errors, because the seepage measurements themselves are correlated (Table 3) thus the variables are not independent. However, we want to examine if the seepage rates are responding to different parts of the hydrogeological system.

Table 1
Means and standard deviations of sampling location altitudes and medians and inter quantile ranges of analyzed tracer samples divided to different hydrological compartments for all three sampling years.

	Altitude (m asl)		SiO_2 (mg l^{-1})		Ca^{2+} (mg l^{-1})		PO^{3}_{4-} (μg l^{-1})	
	Mean	Std	Median	IQR	Median	IQR	Median	IQR
Closed basin lakes ($n = 27$)	134.7	3.9	0.3	0.4	1.2	1.2	1	1
Lakes with outlets ($n = 12$)	127.5	1.9	14.5	4.1	3.2	0.9	30.5	28.0
Groundwater ($n = 30$)	127.7	3.7	9.3	2.1	2.1	1.1	32.0	93.0
Streams ($n = 27$)	104.3	9.2	16.0	1.8	6.5	5.9	68.5	64.8

For our aim the *p*-value provides a convenient cut-off point to classify locations to correlated and non-correlated, even though the statistical validity of significance is compromised.

Finally, we looked for correlations between seepage rates and prevailing climatic conditions. Groundwater recharge resulting from precipitation increases groundwater storage and raises groundwater levels. As a result, precipitation data can be considered to give an estimate of changes in water input and the status of the hydrogeological system. We looked for correlations between temporal variations in seepage rates and cumulative precipitation preceding the day of seepage measurement, with different lag periods for the latter. Value for sum of precipitation variable (P_{sum}) for a given seepage measurement day and time lag was calculated according with following equation:

$$P_{\mathrm{sum}}(P_n, j) = \sum_{i=1}^{j} P_{n-i} \tag{1}$$

where n is the indexed day number of precipitation data for the day of a seepage meter measurement ($n = 34, 56, 83, 104, 128, 148, 166, 190$) for total of total 190 days of precipitation data, j is the summation time lag (5, 10, 15, 20, 25 and 30 days).

After the calculations for precipitation sum variables were carried out using Eq. (1), the resulting 8 by 6 matrix for precipitation sum values was used in the Pearson correlation analysis with the seepage meter measurements.

3. Results

3.1. Natural tracers at regional (aquifer) and local (lake) scale

The chemical signature of water in terms of silica, calcium and phosphate depended on its sampling altitude in the aquifer and type of the sampled water body (Fig. 3). A significant Kendall correlation was observed between concentration and altitude ($p < 0.001$) for all three tracers. Samples from the closed basin lakes were distinctly different in tracer concentrations and may therefore have a strong impact on the results of the correlation analysis by creating a bimodal concentration distribution.

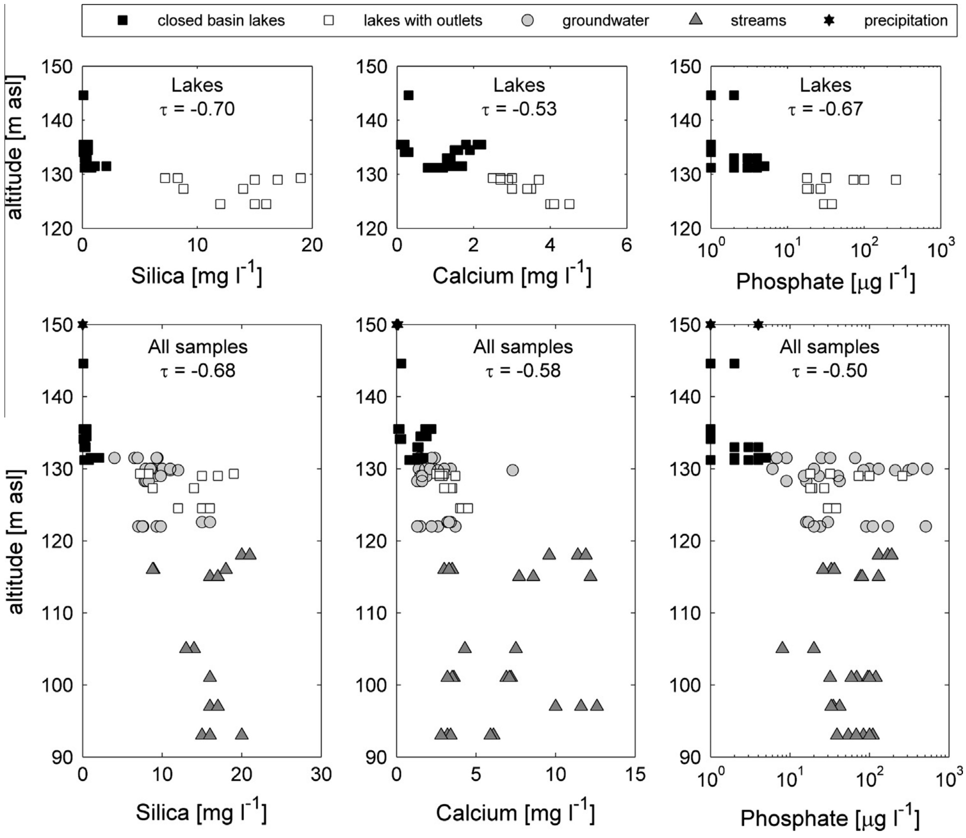

Fig. 3. Natural tracer concentrations as a function of landscape altitude (m above sea level, asl) at the sampling locations for all three sampling years. Upmost plots show only the lake concentrations ($n = 39$) and lower plots include all the sampling locations ($n = 95$).

Table 2
Natural tracer concentrations in the study lake Ahveroinen and adjacent piezometers for years 2010–2012.

	SiO_2 (mg l^{-1})			Ca^{2+} (mg l^{-1})			PO^{4}_{3-} (μg l^{-1})		
	2010	2011	2012	2010	2011	2012	2010	2011	2012
Lake	2.1	1.1	1.0	1.7	1.5	1.3	5	2	4
MEA506	9.4	10.0	11.0	1.8	3.4	3.0	6	550	350
MEA1807	6.5	6.9	4.0	1.5	1.4	1.4	9	25	7
MEA1907	7.9	8.7	8.5	1.4	2.3	2.1	99	130	20
MEA2010		9.4	9.3		2.4	2.2		66	32

Table 3
Kendall correlation coefficient matrix for seepage measurement locations 001–006.

	001	002	003	004	005	006
001		0.40	−0.33	**0.68***	0.00	**0.91***
002	0.40		−0.43	**0.71***	0.05	0.50
003	−0.33	−0.43		−0.24	0.24	−0.21
004	**0.68***	**0.71***	−0.24		0.33	**0.81***
005	0.00	0.05	0.24	0.33		0.14
006	**0.91***	0.50	−0.21	**0.81***	0.14	

* $p < 0.05$.

Lakes and rivers located in lower landscape positions had a higher tracer concentration than closed basin lakes in higher altitudes (Table 1). The water bodies were subdivided into four categories to emphasize the differences in hydrological compartments, namely closed basin lakes, lakes with outlets, ground waters, and streams. Closed basin lakes stood out as a separate group, with high landscape position and low concentrations of each compound (Fig. 3 and Table 1). Groundwater samples and lakes with outlets were similar in terms of both tracer concentrations and landscape location. Streams were a distinctly separate group because of both their low landscape position and high tracer average concentration and variability. The median concentration of all tracers was highest in streams (Table 1 and Fig. 3), but the difference was most pronounced in calcium concentrations. The concentrations of phosphate in streams were close to those in groundwater and lakes with outlets, but the calcium and silica values tended to be higher in streams than in other locations. Data on natural tracer concentrations in the vicinity of Lake Ahveroinen showed generally higher concentrations of natural tracers at all groundwater sampling locations compared with the lake (Table 2). Silica appeared to provide the strongest and most consistent signal separating lake water from groundwater.

Phosphate concentration at a given sampling location showed a statistically significant ($p < 0.001$) monotonic Kendall's correlation with both silica and calcium concentrations (Fig. 4). The phosphate increases in a log-linear fashion with increasing silica concentrations whereas the trend in correlation between calcium is less obvious but still monotonically increasing. Again the bimodal distribution created by closed based lakes is apparent in the data.

3.2. Seepage meter measurements and correlations with lake seepage

Strong spatial variations in seepage rates were observed in 2009 and the spatial distribution of seepage differed between 2009 and 2010, especially in the north–west part of the lake (Fig. 5). The areas of highest inflow were in the south and south–east parts of the lake, and the highest outflow was observed in the northern part of the lake. This direction coincides with the direction of the esker and the expected pattern of regional groundwater flow. In 2009, considerable outflow was only noted in the north–east corner of the lake. In 2010, temporal changes inseepage rates were observed at every observation point, but the temporal variation in seepage rates was low (Fig. 6).

The seepage rates and patterns co-varied between measurement points, forming clusters with similar variation. Kendall correlation analysis of seepage rate changes revealed a statistically

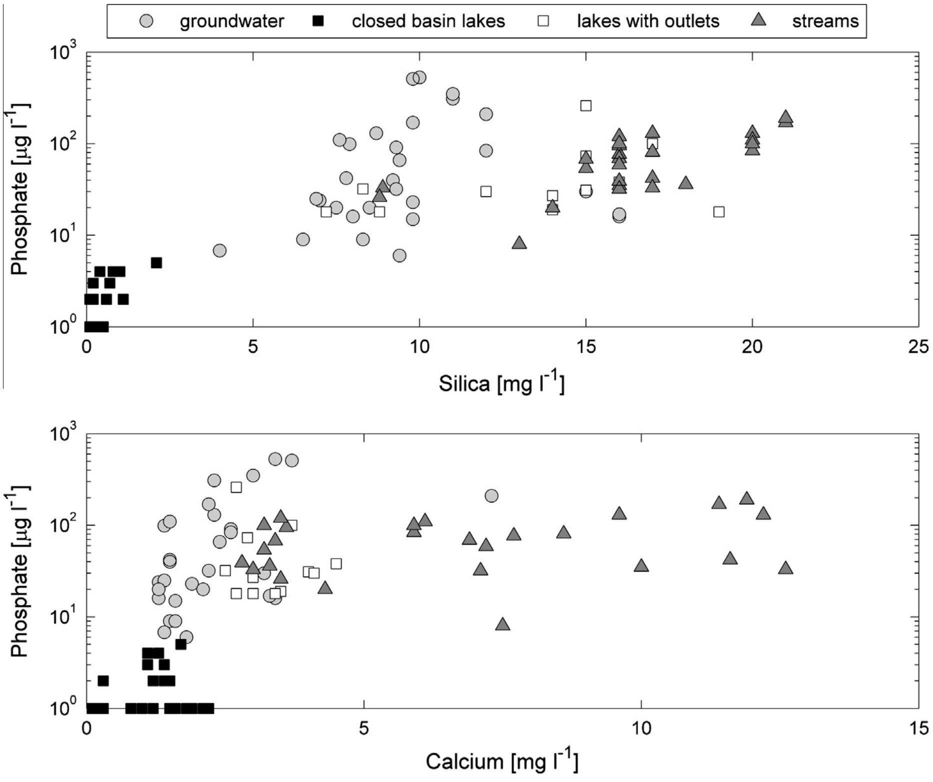

Fig. 4. Crossplots of phosphate concentrations with silica (tau = 0.60, pval < 0.001) and calcium (tau = 0.50, pval < 0.001).

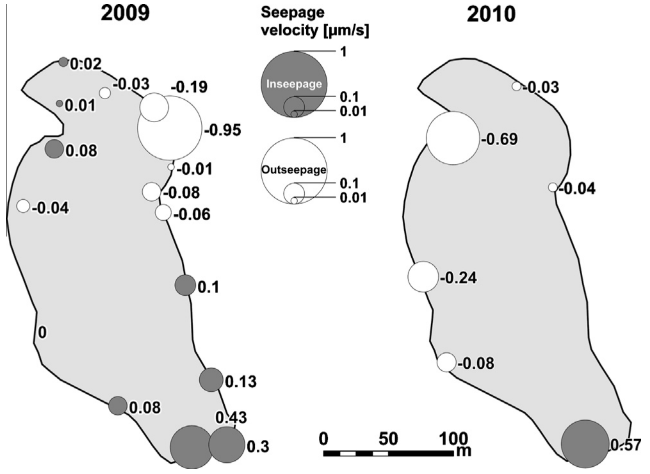

Fig. 5. Spatial variations in seepage (μm s^{-1}) for two consecutive years. Seepage rates are presented as circles, with relative size and color showing the rate and direction of seepage, respectively. For the year 2010 the average value from the eight performed measurements is shown.

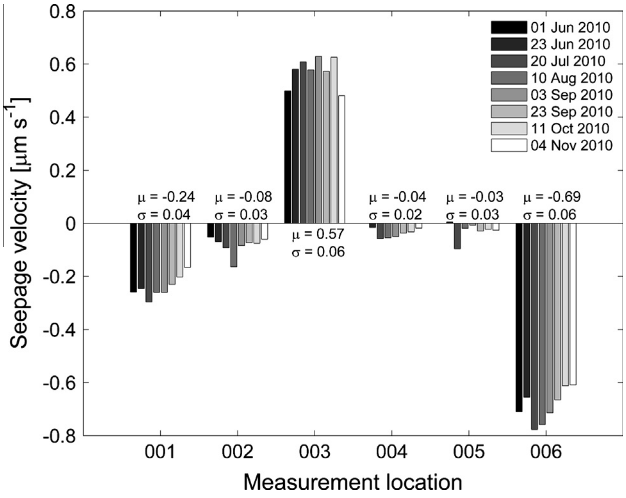

Fig. 6. Temporal variations in seepage (μm s^{-1}) during 2010 for each seepage measurement location in the study lake Ahveroinen. Positive values correspond to inseepage, μ denotes the mean and σ the standard deviation of the measurements.

significant correlation between some of the locations 001, 002, 004 and 006 (Table 3). Location 004 was correlated with three other locations, despite having one of the lowest measured average seepage rates. Locations 003 and 005 did not exhibit statistically significant correlations with other measurement locations, but a persistent negative correlation was found at location 003.

3.3. Correlation analysis of seepage measurements and hydrogeological settings

The lake stage and the groundwater level in piezometer MEA1807 co-varied and responded to precipitation and dry periods with similar dynamics showing rapid short-term variations (Fig. 7). In contrast, piezometers MEA506 and MEA1907 exhibited a steadier rising trend and a more modest response to precipitation. Differences in the dynamics of the three piezometers were expected because MEA1807 was located approximately 20 m from the shoreline and the depth from soil surface to groundwater was on average only 3.5 m. Piezometers MEA506 and MEA1907 were positioned further from the lake and the depth of the unsaturated zone was on average 9 m and 7.5 m, respectively. After August, all level measurements followed the same rising trend.

Seepage measurement locations were correlated with different parts of the hydrogeological system (Table 4). Locations 001 and 006, where the highest outseepage rates were measured, correlated with piezometers MEA1907 and MEA506. Location 004 with low seepage rate was correlated with lake stage and the piezometer MEA1807 where the water table closely followed the lake level. The location of inseepage, 003, differed from other locations and was the only one with negative, yet not statistically significant, correlation with hydrological observations.

At locations of consistent outseepage (001, 002, 004, and 006), general negative correlation was observed with cumulative precipitation for preceding days with different lag periods of summation (Fig. 8). The correlation coefficient value peaked between cumulative precipitation lags from 15 to 25 days. The location of inseepage (003) showed a positive correlation with cumulative precipitation, but only as the time lag of summation increased.

4. Discussion

4.1. Groundwater flow systems reflected in natural tracers

Analysis of natural tracers suggested a link between the landscape position of a sampling location and water quality at the location on aquifer scale; as the location moved progressively to lower locations in the landscape, the water was generally richer in silica, calcium and phosphate (Fig. 3 and Table 1). Silica and calcium in particular can be considered tracers indicating groundwater influence on surface water bodies. In previous studies, the landscape position of lakes has been defined with elaborate water balance calculations or numerical modeling (Winter and Carr, 1980; Webster et al., 1996). Statistically significant correlation between sampling location altitude and tracer concentration suggest that lake altitude by itself can give some indication of lake position with respect to groundwater flow systems, at least in a geologically homogeneous aquifer.

According to the natural tracer data, lakes in the area can be divided into two groups: closed basin lakes poor in solutes and solute rich lakes with surface flow outlets (Fig. 3 and Table 1). Closed basin lakes, located at higher altitude, were poorer in all tracers compared with lakes with outlets lying at lower altitudes. Concentrations in lakes with outlets were within the same range as those in groundwater samples whereas the water chemistry in closed basin lakes resembled that of precipitation. The difference between the two groups of lakes was especially distinct in terms of silica concentrations, for which there was no overlap between the lake groups. In terms of calcium and phosphate, the concentrations in lakes moved gradually from precipitation quality towards groundwater quality with decreasing altitude. This finding, along with seepage meter measurements in Lake Ahveroinen (Fig. 5), suggests that the oligotrophic lakes in the Rokua aquifer are to some extent seepage lakes receiving nutrients and cations from groundwater inflow.

The observation that the closed basin lakes have a clearly different water chemistry makes the tracer concentration distributions binary, especially for silicate and phosphate. When the closed basin lakes are excluded from the correlation analysis, the correlation coefficient remains statistically significant for landscape position and silica and calcium (tau = −0.45 and −0.44, respectively, $p < 0.001$ for both) but the statistical significance breaks down for phosphate. Statistically significant correlations remain also between silica and phosphate and calcium and phosphate (tau = 0.27 and 0.23 respectively, p-value for both <0.01) even if closed basin lakes are not considered in the analysis (Fig 5). The re-

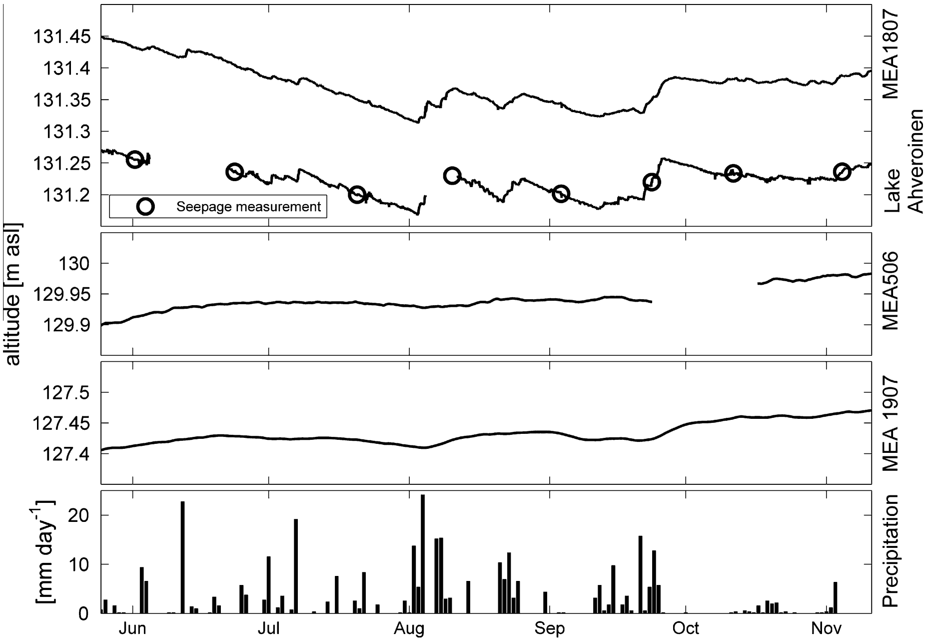

Fig. 7. Recorded groundwater and lake levels (m asl) and daily precipitation during the year 2010 seepage measurement period (note the discontinuity in the *y*-axis).

Table 4
Pearson correlation coefficients for the relationship between seepage measurements at sampling locations 001–006 and lake and groundwater levels in adjacent piezometers.

	001	002	003	004	005	006
Lake stage	0.42	0.27	−0.68	**0.76**[*]	0.55	0.44
MEA1807	0.20	0.46	−0.62	**0.84**[*]	0.43	0.31
MEA1907	**0.86**[*]	0.25	−0.11	0.59	0.18	**0.76**[*]
MEA506	**0.79**[*]	0.15	−0.08	0.55	0.05	0.65

[*] $p < 0.05$.

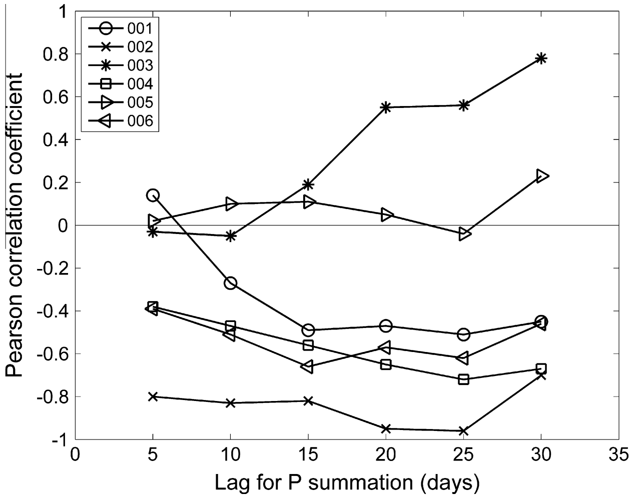

Fig. 8. Pearson correlation coefficient for cumulative precipitation with different time lags (*x*-axis) and seepage rate measurements at locations 001–006. The data shows similar negative correlation for outseepage locations and precipitation but positive for inseepage location 003 and precipitation.

sult that the correlations hold even without the chemically deviating closed basin lakes, gives more confidence to the conclusion that the used traces give indication of groundwater flow path length. Phosphate, on the other hand, does not correlate as strongly with landscape position but nevertheless increases alongside with silica and calcium. The accumulation of phosphate might be a combination of recharge related leaching in the vadose zone and dissolution along saturated groundwater flow.

Concentrations of silica and calcium in the groundwater were on average lower than in lakes with outlets (Table. 1) and in similar sand and gravel aquifers in Finland (median for Ca = 3.2 $\mathrm{mg\,l^{-1}}$ and SiO_2 = 12.0 $\mathrm{mg\,l^{-1}}$ (Soveri et al., 2001)). Because the groundwater was sampled from water table wells with variable unsaturated zone depth with presumably different residence times in the saturated zone, some variability in the tracer concentration is inherent due to the sampling strategy. Phosphate concentrations, in particular, varied both spatially and interannually (see e.g. Table 2) and were distinctly higher than in Finnish aquifers in general (median = 6 $\mu\mathrm{g\,l^{-1}}$, 90th percentile 28 $\mu\mathrm{g\,l^{-1}}$ (Soveri et al., 2001)). Interannual variability suggests that leaching from the uppermost soil layers is highly variable between hydrological years especially for the samples with shallow unsaturated zone. Some of the measured phosphate concentrations were unusually high, close to the maximum value observed in the Finnish aquifers (610 $\mu\mathrm{g\,l^{-1}}$, (Soveri et al., 2001)). Nevertheless, as the median value of phosphate in groundwater seems to be evidently higher than in Finnish aquifers without any major anthropogenic inputs and phosphate appears to accumulate along groundwater flow paths (Fig. 4), subsurface origin for phosphate appears possible.

The concentrations of the silica and calcium were in general higher in stream samples than in other parts of the hydrological system. All the sampled streams originated in the groundwater discharge area (Fig. 1) covered by peat soils. Because during late winter, when the sampling was performed, streams receive very little water from precipitation or surface runoff and most of their discharge can be assumed to consist of base flow provided by the aquifer. However, the stream samples showed more variability in terms of both concentration and altitude than samples from other sampling locations. The streams run on peat soils where the interaction of stream water and peat soil provide a different environment compared to subsurface flow, creating more sources and sinks for the tracers in the streams than in other sampling locations. In addition, high variability during winter conditions may be affected by legacy of land use practices affecting stream water chemistry during the snow free periods. Nevertheless it is reasonable to expect that groundwater entering the streams as base flow has travelled along longer subsurface flow paths than the water sampled from lakes and piezometers in the recharge area. As a result, groundwater seepage to the streams is likely richer in weathering compounds which is in turn seen as elevated tracer concentrations in the stream samples.

In terms of the two lake types described above, study Lake Ahveroinen fell into the category of solute poor closed basin lakes. Tracer concentrations in the lake were distinctly lower than those in the groundwater surrounding the lake (Table 2). It should be noted that cation concentrations in inland piezometers may overestimate the concentrations in water actually discharging to the lake (Brock et al., 1982; Krabbenhoft and Webster, 1995). Water quality in piezometer MEA1807 was closer to that of lake water than the other piezometers. This may be the result of exchange of water between the piezometer and the lake, or a shorter subsurface groundwater flow path to the piezometer than in other locations.

Because the tracer concentrations in the lake do not resemble the concentrations in the surrounding aquifer, the solute rich groundwater input to lake water balance seems to be of minor importance in comparison to solute poor inputs from precipitation. This conclusion is to some extent supported by the seepage meter measurements, where the only consistent location of groundwater inflow was observed in the south east part of the lake. However, the tracer concentrations in Lake Ahveroinen (Table 2) are slightly higher than in other lakes in the area (Table 1), which suggest there is more groundwater influence in Lake Ahveroinen than the average closed basin lake in the area. Furthermore, the non-conservative properties of the used tracers, especially phosphate, in biologically active environments do not allow for rigorous water balance estimation based on water origin and concentration, but rather provide qualitative information on the presence of groundwater influence in the lake.

4.2. Spatial and temporal variations in lake seepage

Seepage meter measurements for two consecutive years revealed permanent areas of inseepage and outseepage in the study lake. The largest difference between the two years, which was found for the north–west corner of the lake (Fig. 5), was probably due to measurement error in 2009 caused by installation difficulties in the soft organic lake bed sediments, which is also reported to be a problem in other studies applying seepage meters (Rosenberry et al., 2008).

No reversals in seepage direction were observed during 2010 measurements, but a small variation in seepage rate was found at each measurement location (Fig. 6). This variation, despite being small, cannot be attributed to measurement error or random natural variability because of the high observed co-variation between seepage rates at four out of six measurement points. This result demonstrates the capability and accuracy of the seepage meter measurement method to distinguish small changes in the groundwater flow environment as long as the meter chambers are not removed between measurements.

Statistically significant correlations were found between locations with measured outseepage (001, 002, 004 and 006, see Table 3), but average rates of outseepage were distinctly different for these locations (Fig. 6). The observed differences in seepage rates can be accounted for different hydrogeological settings, as the hydraulic gradient between surface water and groundwater and lake bed hydraulic conductivity were presumably somewhat different for each location. Even though the average outseepage rate varied between individual locations, the strong correlation between locations implied a common underlying control in the outseepage rate.

The behavior of inseepage location 003 differed markedly from that of other locations (Table 3). Even though a statistically significant correlation was not found, a persistent negative value for correlation coefficient was observed for 003 and other locations. If the same underlying mechanism had caused the changes in the measured seepage rates, a positive correlation would have prevailed for all measurement locations. In that case, a rise in e.g. lake stage with respect to surrounding groundwater level would have increased the absolute value of outseepage (a change towards a larger negative value) and decreased the absolute value of inseepage (a change towards a less positive value). The negative co-variation, although not statistically significant, showed a different temporal pattern for the groundwater inflow and suggested that the location of groundwater inflow may have been affected by another groundwater flow system than the locations of groundwater outflow. We hypothesize that inseepage originated from a regional groundwater flow system that was less affected by short-term temporal changes in water levels, and the assumption could be further verified with groundwater flow modeling or additional hydrological observations.

At location 005, measured seepage rates were low (Fig. 6) and no co-variation was found with other points. The lack of co-variation with other points can be explained with (1) stagnant flow situation or (2) poor installation and therefore failure of measurements at the location. Distribution of seepage rates in the lake is heterogeneous (Fig. 5) and therefore the location 005 may well have been in the zone of minimal seepage. However, location 005 was the most challenging in terms of seepage meter installation, with a steep slope and abundant debris and loose organic sediment on the lake bed. Therefore unsuccessful installation of the seepage chamber was a potential reason for the measured low flow rates and lack of correlation on this rather steep shore. In addition, location 005 lay between the strongly correlated locations 006 and 004, but showed no correlation to either one.

4.3. Correlation analysis outlining groundwater flow systems at local scale

The correlation analysis for seepage rates and lake and groundwater levels reinforced the hypothesis that inseepage followed the dynamics of a different hydrogeological regime than outseepage. Outseepage at locations 001 and 006 co-varied with the groundwater levels in piezometers MEA506 and MEA1907 (Fig. 2). Thus outseepage rate appeared to be affected by changes in groundwater levels in the direction of outseepage as would be expected. Location 004 with low seepage rates correlated with lake level and piezometer 1807, where the changes in level dynamics were more rapid. The location 003 shows again negative correlation with the hydrological measurements thus deviating from other locations, though the correlation is still not statistically significant.

Cumulative precipitation preceding the seepage measurement day in question was negatively correlated with amount of outseepage (Fig. 8). This negative co-variation could be explained by precipitation raising the lake stage faster than the groundwater level, leading to increased outseepage rates. At all locations, the negative correlation increased up to a time lag of 15–25 days. This result was not expected, because precipitation affects lake level almost immediately, so the negative correlation could be expected to be strongest with short time lags. The location of inseepage was positively correlated with cumulative precipitation, but only after a time lag of over 20 days. These results further support the previous hypothesis that inseepage at location 003 was influenced by a different flow system than outseepage at other locations.

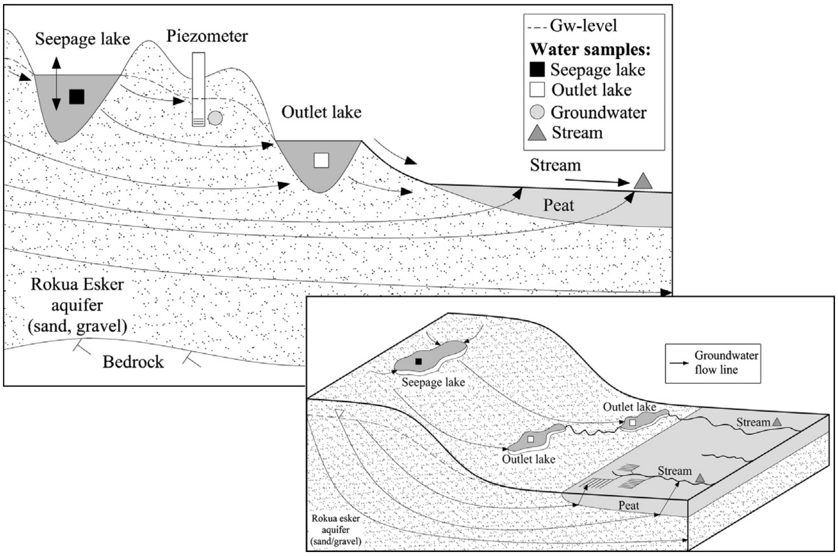

Fig. 9. Conceptual model for the Rokua esker aquifer explaining water level fluctuations in some lakes and the eutrophic state of others. Our hypothesis is that seepage lakes receive most of their water from precipitation or local groundwater flow systems, so their levels are more sensitive to climate variability. Outlet lakes are more eutrophic and have more stable levels, because they receive a constant, nutrient-rich groundwater inflow.

4.4. Novel conceptual model for lakes in the study aquifer

Using data obtained in natural tracer and seepage meter measurements, we developed a novel conceptual model to explain the peculiar behavior of kettle hole lakes embedded in the aquifer (Fig. 9). The landscape position of lakes, based on the theory of regional and local groundwater systems (Toth, 1963), was used to explain the periodic water level decline in some lakes and the eutrophic state of others.

According to the results from the natural tracer analysis, water in the close basin lakes with periodically declining water table is poor in solutes and close to precipitation compared to solute concentrations of lakes with outlets. Nevertheless measured inseepage for one such lake using seepage meters and solute concentrations higher than in precipitation provided evidence that closed basin lakes are not totally hydraulically mounded, but rather interact with the groundwater system. Low solute concentrations in the closed basin lakes in comparison to lakes with outlets lakes could be explained by (1) lower concentration of solutes in the groundwater inseepage because shorter subsurface flow paths or (2) smaller contribution of groundwater in the closed basin lake water balance.

Both of the reasons above can be used to explain the periodically declining water level in the closed basin lakes. If the contribution of steady groundwater inflow to lake water balance is small, the lake levels are highly susceptible to decline during years of low precipitation. This explanation as the sole reason was questioned by Anttila and Heikkinen (2007) as they observed that lake response to droughts has not been rapid and consistent between different lakes as would be expected if the lakes relied completely on precipitation as a source of inflow. The scenario where lakes receive a significant part of their water input as groundwater inflow from local flow systems with short residence time and low solute concentrations would better explain the dissimilar response of lakes to years of low precipitation. Water table configuration surrounding lakes is somewhat different for each closed basin lake and variable amounts of groundwater inflow from local flow systems would buffer the tendency of water table decline during dry years. However, the local groundwater flow system may be depleted as the groundwater table declines further, which may consequently be seen as lake level drop with some delay after drought. It is likely that both of the reasons above act coincidently with different intensity for different lakes, suggesting that periodical water table minimums are strongly related to natural climate variability.

The conclusion, that lake stages are a function not only of climatic conditions but also of groundwater level, indicate that changes in the aquifer can potentially be reflected in lakes. Rossi et al. (2012) demonstrated the potential of land use surrounding the esker aquifer to affect groundwater levels in the aquifer. Thus changes in the groundwater level induced by land use may also be reflected in the groundwater flow systems surrounding the lakes. That is to say, that even though periodic water table minimums would be caused mainly by climate variability a general trend of declining groundwater table would increase the “depth” of such minimum conditions. This is in agreement with other observations that changes in groundwater flow systems around seepage lakes may alter groundwater inflow and nutrient fluxes to lakes (Kenoyer and Anderson, 1989; Anderson and Cheng, 1993; Webster et al., 1996).

Natural tracers were present in similar concentrations in eutrophic lakes with outlets and in groundwater, implying nutrient and cation input to certain lakes from groundwater discharge. Surface or near surface runoff is often considered an important transport route for nutrients to surface water bodies (Holman et al., 2010), but at the study site highly permeable soils and a lichen layer covering the soils make the surface runoff at the area negligible. If the subsurface flow is adopted as the main route of nutrient transport, the source providing the nutrients to groundwater is essential to distinguish. Because land-use practices and habitation in catchment areas of both lake types, closed basin lakes and lakes with outlets, are similar and nutrient inputs to the system from precipitation almost non-existent, subsurface origin by leaching, dissolution, weathering or desorption remains the most credible source providing nutrients and cations to the lakes.

A considerable body of research reports similar inputs of dissolution and weathering products to lakes via long, regional groundwater flow paths (see e.g. Brock et al., 1982; Kenoyer and Anderson, 1989; Kenoyer and Bowser, 1992; Webster et al., 1996). In the Rokua aquifer area stream outlets are a vital component in enabling and sustaining a steady, nutrient-rich groundwater inflow to the drainage lakes. This holds true especially for the first lakes in the chain of lakes which have no inlets, but discharge water constantly via outlets. These outlets convey the nutrient-rich water seeping from groundwater through the chain of lakes, affecting the water quality of the whole lake chain. Stets et al. (2010) have reported similar settings where regional groundwater flow system provided inflow to headwater lakes connected with streams.

Finding of this study is especially interesting in terms of phosphate, because even small differences in phosphate inputs can change the ecological structure of sensitive surface water bodies. The subsurface is traditionally considered as a dilution system for phosphate, as in the study by Devito et al. (2000) which suggests that total phosphorus loading caused by forestry logging and ending up in lakes is lower for lakes which receive groundwater via long subsurface flow paths. Sorption processes responsible for dilution along long flow paths can be expected if phosphorus concentration in the infiltrating water is for whatever reason elevated significantly above natural back ground concentration. Our results, on the other hand, provide support for the claim made by Holman et al. (2010) that the subsurface can act as a source of phosphate in certain geological settings. This is seen best in the correlation of phosphate with tracers indicating long residence time in the subsurface (Fig. 4).

5. Conclusions

Natural tracers (Ca^{2+}, SiO_2 and PO_4^{3-}) together with seepage meter measurements were successfully used to develop a novel conceptual model for a complex glacial aquifer system with interconnected lakes and streams. The natural tracer data indicated that lakes could be categorized as drainage lakes or seepage lakes according to their chemical composition, presence of surface water outlets and landscape position. Progressively higher concentrations of natural tracers at lower altitudes and finally in stream samples located in the groundwater discharge area supported the hypothesis that long subsurface flow paths are reflected in elevated concentrations of dissolution and weathering compounds. Of the tracers silica provided the most consistent signal of long subsurface flow path in the studied silicate aquifer; a finding which further encourages the use of silica as a tracer for groundwater age in similar hydrogeological settings. Although phosphate is a chemically active compound, its concentrations correlated with landscape position in a similar way to calcium and silica. Furthermore, a positive correlation was found between tracers know to indicate groundwater flow path length (SiO_2 and Ca^{2+}) and phosphate concentrations. This suggests that phosphate can be transported to lakes via subsurface flow paths, and these fluxes may have ecological consequences for phosphate-limited inland lakes.

Seepage meter measurements confirmed the interaction between lakes and the aquifer thus verifying the hypothesis that lake water quantity and quality can be affected by groundwater seepage. In addition to traditional use of seepage meters in determining spatial and temporal distribution of lake seepage, time series of seepage measurements were used to distinguish groundwater flow systems affecting the lake seepage. Statistical analysis of time series of seepage meter data and hydrogeological observations gave ground to hypotheses of two different groundwater flow systems controlling water exchange with the study lake, one in the direction of inseepage and the other controlling outseepage.

The conceptual model developed to explain periodical decline in level and the trophic state of different lakes with groundwater flow systems may be useful in water resources management in the area. Conventional restoration procedures for eutrophic lakes would most likely prove inefficient in the study area, as the subsurface flow paths will continue to provide nutrients to the lakes. The drainage lakes in the area will likely uphold a steady water level because if they are fed from a more regional groundwater flow system and are thus less sensitive to groundwater level fluctuations. They will keep receiving groundwater inflow despite small changes in groundwater levels and the flow is further sustained by stream outlets. Therefore the drainage lakes in the Rokua area can be expected to remain eutrophic with a steady water table.

According to our understanding, climate variability is likely the primary cause of periodic water level decline in closed basin lakes located at Rokua aquifer. However land use practices affecting the groundwater level may have the potential to alter groundwater–surface water interactions in the area. Because the closed basin lakes are an internal part of the aquifer system, lowering the groundwater table would be reflected in lake levels. Groundwater inflow may be more important inseepage lake water budgets in drought years than in average hydrological years. If inseepage flux is diminished due to lowered groundwater levels in the flow system providing inflow, the water level in the lakes will most probably decline further. Even though the oligotrophic closed basin lakes are low in solutes and nutrients, their nutrient balance is partially dependent on groundwater inflow. Therefore droughts might have negative impacts not only on their water quantity but also their water quality. During low precipitation periods larger portion of the lake water budget is comprised of nutrient rich groundwater inseepage. Eutrophication risk is most pronounced in lakes with small water volume because the buffering effect of the total water volume, which evens quality variations in conditions of changed inflow and outflow fluxes, is small.

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