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A Tracer-Based Method for Classifying Groundwater Dependence in Boreal Headwater Streams

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A Tracer-Based Method for Classifying Groundwater Dependence in Boreal Headwater Streams

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Abstract

Ecosystem protection requires a better definition of groundwater (GW) dependence and tools to measure this dependence. In this study, a classification method for the GW dependence of headwater streams was devised based on the fact that GW affects discharge, thermal regime, and water quality. The method was tested in three boreal headwater streams discharging from two esker aquifers. Spatial and temporal variability of GW dependence were studied in the stream continuum at several locations, by combining continuous measurements of temperature, electrical conductivity, and discharge with discrete sampling of environmental tracers (e.g., stable water isotopes, silica, chloride). The stream tracer index method developed was used to classify stream sections into GW-dominated, GW-surface water (SW) transition, and SW-dominated zones. We found that, spatially, GW dependence along the stream varied widely, with calculated stream tracer index values ranging from 33 to 94%. The GW-dominated areas extended at least 745, 1682, and 4202 m downstream from the main GW discharge points in the three streams studied. A stream located in a pristine peatland-dominated catchment was more prone to rapid change from GW- to SW-dominated than two streams located in catchments dominated by peatland forestry. These results suggest that to evaluate the GW dependence of streams, it may be sufficient to sample stream sections only once, during summer low-flow conditions. The proposed method can serve as a water management tool, especially for streams of exceptional ecological importance or in places where anthropogenic activities are expected to change local hydrology and ecology.

Keywords: stable water isotopes, environmental tracers, groundwater-dependent ecosystems, headwater streams
1 Introduction

Headwater streams have a large effect on downstream hydrological and geochemical processes and ecological functions [Freeman et al., 2007; Finn et al., 2011]. Groundwater (GW) is generally a major contributing factor to maintaining the baseflow of headwater streams [Sophocleous, 2002; Winter, 2007] and has specific geochemical, physical, and biological characteristics that differ from surface water (SW) [Bertrand et al., 2012]. Therefore, any changes in GW discharge to headwater streams can have a major impact on stream water quality and volume, with the most pronounced effects occurring in areas that are highly influenced by GW. In order to reduce the impacts on groundwater-dependent ecosystems (GDEs), tools are needed for their classification, management, and protection [EC, 2006; Richardson et al., 2011; Rohde et al., 2017]. However, GDE classification of headwater streams is not straightforward because standard procedures are lacking and the GW-SW transition zones and ecotones can vary temporally and seasonally.

Dynamic environmental factors govern the healthy functioning of freshwater ecosystems and are categorized as: flow patterns, sediment and organic matter inputs, temperature and light penetration, chemical and nutrient conditions, and plant and animal assemblages [Younger, 2006]. In GW-dependent stream ecosystems, many organisms rely on conditions sustained by GW. These conditions are i) discharge volume, ii) stable thermal regime, and iii) water quality [Bertrand et al., 2012]. During sensitive summer and winter low-flow periods in particular, GW input to headwater streams provides important refuges maintaining stable discharge [Younger, 2006] and thermal conditions in these streams [Dugdale et al., 2013; Snyder et al., 2015]. As GW-dominated streams provide more stable conditions for stream ecosystems than SW-dominated streams [Webb et al., 2008], these ecosystems will become even more important in supporting thermal refuges in a changing climate. However, GW-dominated headwater streams can be sensitive to local anthropogenic actions such as agriculture, drainage for forestry, and GW abstraction [Ramchunder et al., 2012; Rossi et al., 2012, 2014; Saarinen et al., 2013; Eskelinen et al., 2016], which can lower GW levels, alter GW discharge patterns to headwater streams, and change water quality and the ecology of streams [Poff and Zimmerman, 2010]. This emphasizes the need to classify these ecosystems, in order to better protect and manage them and the connected GW systems.
Use of environmental tracers, such as stable water isotopes and water chemistry, is an efficient and flexible method to study dynamic and spatially varying GW-SW interactions in water courses and streams [Leibundgut et al., 2009; Bertrand et al., 2014]. However, past tracer approaches have often focused on only one location in a stream [Kendall and Coplen, 2001; Litt et al., 2015; Soulsby et al., 2015; Niinikoski et al., 2016] or on intensive sampling for a rather short period [Klaus and McDonnell, 2013]. Thus, these studies cannot give a full spatial and temporal picture of GW dependence in the stream continuum. Recent studies highlight the importance of spatially dense sampling to determine stream water chemistry [Zimmer et al., 2013] and stable water isotopes [Singh et al., 2016]. The specific geochemistry of different landscape units in the catchment can alter the chemical composition of stream water [Blumstock et al., 2015]. A study by Zimmer et al. [2013] suggests that GW contributions from distinct soil types control the spatial similarities found in stream water chemistry in varying flow conditions. The catchment structures (i.e. catchment “forms”, the hydrogeological setup of the catchment) also cause small-scale differences in baseflow stable water isotopes [Singh et al., 2016]. In general, variations in stream water quality can result from changes in mixing proportions of GW and SW, and spatial or temporal changes in water quality, which can complicate interpretation of tracer data [Kirchner, 2016a, 2016b].

Recent tracer modelling approaches have focused particularly on studying the water age distributions in catchments [e.g., Birkel and Soulsby, 2015; Soulsby et al., 2015; Huijgevoort et al., 2016; Ala-aho et al., 2017]. These modeling efforts are increasingly being supported by continuous measurement of isotope data [Tweed et al., 2016], which has improved estimates of young water fractions [Stockinger et al., 2016] and thus also estimates of GW fractions in streams. However, at this point high-resolution data cannot be obtained cost-effectively from several locations along the stream, which would be necessary for assessing spatial variations in GW dependence. Although low-resolution isotope data have uncertainties when estimating water
fractions during large events [Soulsby et al., 2015], it can be sufficient to assess GW dependence during low flows and small events, which account for the majority of the hydrological year and sustain the ecological functions of streams. Thus, many tracer-based studies discuss GW-SW interactions in streams [e.g., Hagedorn and Whittier, 2015; Scholl et al., 2015; Duvert et al., 2016]

but none has proposed a generalized method for water management purposes that could be used to evaluate the GW dependence in headwater streams.

In this study, we combined continuous measurements of discharge, temperature (T), and electrical conductivity (EC) with use of stable water isotopes and other environmental tracers to study the GW-SW transition zones in three boreal streams known to have high proportions of GW from esker aquifers. The esker aquifer systems studied are of a type commonly found in areas covered by the last glaciation and are of great importance in the Northern hemisphere as a source of potable water [Kløve et al., 2017]. Typically, headwater streams originate from esker boundaries (esker-peatland interaction). We expected to find a transition zone within which a spring-originated stream turns into a SW-dominated system. By definition, SW is the water in surface storage units (e.g., lakes, streams, rivers, wetlands) and GW is the water underground.

However, since our aim was to study the transition and mixing between these in streams, we applied the term SW to water that is already modified by surface processes, i.e., river water or water originating from surrounding peatlands. Our specific objectives were to determine the GW dependence along the stream continuum, study the spatial and temporal changes in mixing zones in the three streams, and develop a tool and guidelines for the use of different environmental tracers in evaluating the GW dependence of streams. This work addresses the following research questions: i) How can headwater stream sections be classified to GDEs? ii) What measurements should be made, and from where, to obtain a sound GDE classification for headwater streams? iii) Is it possible to evaluate the GW dependence of a stream based on a single sampling campaign?
2 Materials and methods

2.1 Study sites

The three streams selected for the study are located in Rokua and Viinivaara esker aquifer areas and are 60 km from each other. Eskers are one of the most common aquifer types in deglaciation areas in Finland, Sweden, and Eastern Canada [Britschgi et al., 2009; Nadeau et al., 2015; Berthot et al., 2016; Holmlund et al., 2016; Quillet et al., 2017]. The study sites belong to a mid-boreal coniferous forest belt. The Rokua study area represents disturbed ecosystems and Viinivaara contains nearly pristine ecosystems (Fig. 1). In the Rokua esker area, we selected two streams, Siirasoja and Lohioja, where surrounding peatlands are intensively drained for forestry. In contrast, Mesioja stream, discharging from Viinivaara esker aquifer, represents a pristine stream and flows through undisturbed peatland. The average channel widths and average maximum depths along the streams studied are presented in the Supporting Information Table S1.

2.1.1 Siirasoja and Lohioja streams in Rokua esker aquifer

Rokua esker aquifer, with a recharge area of 92 km², is a post-glacial sand and gravel deposit rising on average 30-40 m above the surrounding peatlands (max. 90 m). The aquifer itself is unconfined, but the heavily drained peatlands in the surroundings partly confine the GW [Rossi et al., 2012]. On the northern side of the esker, the headwater streams Siirasoja and Lohioja discharge to the river Oulujoki. The catchments are located next to each other and the land use consists mainly of peatland forestry and some agricultural land (Table 1). Due to varying land use in the surroundings, different sections of Siirasoja and Lohioja streams show differences in channel shading, which can affect stream water temperature. Prior to this work, several studies have clarified the GW-SW interactions in the Rokua esker aquifer area [Ala-aho et al., 2013, 2015; Rossi et al., 2014; Eskelinen et al., 2015; Isokangas et al., 2015], and two have investigated the
hydrology of Siirasoja stream, revealing complex GW discharge patterns [Rossi et al., 2012; Eskelinen et al., 2016]. Siirasoja and Lohioja streams have tributaries that are also connected to ditches in the area (Fig. 1). Some of the ditches in Siirasoja catchment have no flow and some fully penetrate the peat layer and reach the mineral soil beneath, causing increased GW discharge to the stream. GW discharge has been found to be either diffuse seepage or point type, and is induced by high pressure underneath the peat layer (Rossi et al. 2012). Eskelinen et al. (2016) concluded that the GW discharge and thick snow pack prevent the formation of soil frost in Siirasoja catchment, which results in snowmelt water infiltration into the soil and a higher flux of weathering products than at sites with soil frost.

Fig. 1. Maps showing the location of the three study streams (Siirasoja, Lohioja, Mesioja) discharging from Viinivaara and Rokua esker aquifers, their catchment area, and the sub-catchments of the measurement points. Measurement points with no identifiers represent “dense sampling points” and points with identifiers (with a letter indicating the stream, followed by a sample number) represent “detailed sampling points”. The letter Q shows locations of continuous water level measurements (see section 2.2 for more details).
Table 1. Stream and watershed characteristics of the three headwater streams analyzed in this study

<table>
<thead>
<tr>
<th>Stream</th>
<th>Length (km)</th>
<th>Watershed area (km²)</th>
<th>Drained for forestry (%)</th>
<th>Agricultural land (%)</th>
<th>Q\textsubscript{max} (m³ s⁻¹)</th>
<th>MQ (m³ s⁻¹)</th>
<th>Q\textsubscript{min} (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesioja</td>
<td>3.0</td>
<td>2.6</td>
<td>0.6</td>
<td>0.0</td>
<td>0.018</td>
<td>0.007</td>
<td>0.001</td>
</tr>
<tr>
<td>Lohioja</td>
<td>5.4</td>
<td>13.6</td>
<td>59.9</td>
<td>5.8</td>
<td>1.186</td>
<td>0.177</td>
<td>0.051</td>
</tr>
<tr>
<td>Siirasoja</td>
<td>7.2</td>
<td>24.0</td>
<td>32.9</td>
<td>3.4</td>
<td>0.706</td>
<td>0.234</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Note. Discharge values for Siirasoja and Lohioja streams are the highest annual discharge (Q\textsubscript{max}), mean annual discharge (MQ), and lowest annual discharge (Q\textsubscript{min}) (hourly data 2010-2015). Discharge values for Mesioja stream are from in situ measurements made during study periods 15.5.2013-14.10.2013 and 12.5.2014-10.11.2014, and are the highest discharge (Q\textsubscript{max}), mean discharge (MQ), and lowest discharge (Q\textsubscript{min}).

2.1.2 Mesioja stream in Viinivaara esker aquifer

Viinivaara esker is a smaller aquifer than Rokua esker and has a recharge area of 15 km². This sandy aquifer is also surrounded by peatlands, which have remained partly in pristine condition. Our study stream, Mesioja, discharges from a spring located at the break of slope where the sandy aquifer meets the peat formation and flows partly underground between measurement locations M2 and M3 (Table 1). The lower catchment area is mostly pristine peatland with bog-type vegetation. The GW dependence of the peatland area varies widely; spatial isotope studies by Isokangas et al. (2017) showed that the stable isotopic composition of the peatland pore water is not uniform near Mesioja stream, with δ¹⁸O values ranging between approximately -8‰ and -13‰ at 10 cm depth during the period 4-11 August 2014.

2.2 Field measurements

In the three streams, two disturbed and one pristine, EC and temperature were continuously measured during 2013-2014 using Hobo loggers (EC and temperature logger U24-001, accuracy 5 µS/cm and 0.1°C) installed at on average 1-km intervals in the stream, to study the spatial and
temporal variations in these variables along the streams (i.e., “detailed sampling points”, Fig. 1).

In Mesioja stream, four Hobo loggers were installed along the stream and one (measurement point M5) was positioned at the outlet stream from Lake Sarvilampi, where Mesioja stream discharges. Hobo loggers were installed at four locations in Lohioja stream and at five locations in Siirasoja stream. An additional Hobo logger was installed at a small tributary of Siirasoja stream (measurement point S3), since this reach is protected by the Natura 2000 program because its grove area has remained in a more natural state than the rest of the upper catchment. Water level was monitored continuously at one location in each of the streams (point Q, Fig. 1). Discharge was measured with a current meter at all stream measurement points during the eight field measurement campaigns. Rating curves for the streams studied were developed using continuously measured and barometrically compensated water levels (Solinst Levelogger Gold) and the discharge measured with current meters (Mini Air 20, Schiltknecht) during the field work and in campaigns prior to this study (Siirasoja and Lohioja). As the field campaigns did not capture the highest recorded water levels, rating curves for Siirasoja and Lohioja were extrapolated using discharge rates obtained from fully integrated surface-subsurface flow modeling with HydroGeoSphere [Ala-aho et al., 2014]. Rating curves were used to obtain continuous discharge values for the streams.

The streams were sampled quarterly during 2013 and 2014 for stable isotopes of water (δ18O, δ2H), nutrients (P, PO43−-P, total inorganic carbon (TIC), dissolved organic carbon (DOC)), water quality parameters (T, pH, EC, O2), geochemical parameters (dissolved SiO2, SO42−, K+, Na+, Ca2+, Mg2+, Mn2+, Sr2+, Al3+, Cl−, S, Fe), and alkalinity. The samples were taken from four, four, and six locations in Mesioja, Lohioja, and Siirasoja stream, respectively (i.e., “detailed sampling points”, Fig. 1). For stable water isotopes and water quality parameters, additional water samples were taken from five, four, and six locations in Mesioja, Lohioja, and Siirasoja stream, respectively (i.e., “dense sampling points”, Fig. 1). Monthly cumulative samples for stable isotopes of water were also taken from local precipitation at Rokua, approximately 4 km from the studied streams, and near Viinivaara (Nuoritta site), 17 km from Mesioja stream.

Stable isotopic composition of water samples was analyzed using cavity ring-down spectroscopy with a Picarro L2120-i analyzer and the isotope ratios were expressed in δ notation relative to Vienna Standard Mean Ocean Water (VSMOW), with precision for δ18O and δ2H
values of ±0.1‰ and ±1.0‰, respectively. Water quality parameters were measured using a field meter (WTW Multi 350i meter, accuracy: pH ±0.005, O₂ ±0.5% of the measured value; ±1 mV for EC and ±0.1 °C for T). Nutrients, alkalinity, and geochemical parameters were analyzed using Finnish national standards in an accredited (SFS-EN ISO/IEC 17025:2005) laboratory at the Finnish Environment Institute (SYKE) [National Board of Waters, 1981].

2.2.1 Local groundwater and surface water quality

Local GW and SW quality data were acquired for use as reference values to evaluate the potential of different water quality tracers to separate GW from SW (Supporting Information Table S2). The measurement locations are presented in the map in Supporting Information Fig. S1. In Viinivaara, local GW was sampled quarterly in 2014 at one location approximately 1 m below the GW level and analyzed for stable isotopes of water (δ¹⁸O, δ⁶H), nutrients (P, PO₄³⁻-P, TIC, DOC), water quality parameters (T, pH, EC, O₂), geochemical parameters (dissolved SiO₂, SO₄²⁻, K⁺, Na⁺, Ca²⁺, Mg²⁺, Mn²⁺, Sr²⁺, Al³⁺, Cl⁻, S, Fe), and alkalinity. The nearest SW sampling locations of SYKE are situated 27 km (Nuorittajoki suu station) and 9 km (Nuorittajoki Töntönkoski station) from Mesioja catchment. SW was sampled during the open water season from Nuorittajoki suu station four times per year during 2013-2014 and from Töntönkoski station one to four times per year during 2006-2011. Most of the parameters were analyzed using samples from Töntönkoski station and, although the measurements were performed before our stream sampling campaign, the data were assumed to be representative for the study period because there had not been any major changes in land use in the area. The SW sampling location of Nuorittajoki suu station is located rather far from our study stream but, as the land use is relatively similar to that in Mesioja catchment (Supporting Information Fig. S1), the data were assumed to be representative for the study area. In Rokua, local GW in the esker and also under the peat layer in the discharge zone was sampled four times a year during 2010-2012 and analyzed for stable isotopes of water, P,
PO₄³⁻-P, EC, pH, dissolved SiO₂, K⁺, Na⁺, Ca²⁺, Mg²⁺, and Cl⁻. In addition, SO₄²⁻, Mn²⁺, Fe, and alkalinity were determined by SYKE in four GW pipes (MEA 206, MEA 506, MEA 806, and MEA 1006) in Rokua esker in January 2007. In Rokua, the measurements by SYKE were also used as a reference for SW. Sampling was carried out generally once a month during 2013-2014 in the river Oulujoki, into which the studied streams discharge (at Jylhämä station, located approximately 6 km upstream from the study catchments).

2.3 Data analysis

Watersheds were delineated in an ArcGIS 10.2 environment using a 2 m resolution digital elevation model (DEM) produced by the National Land Survey of Finland. Statistical parameters (standard deviation, mean, and coefficient of variation) for continuous temperature and EC measurements were calculated with R [The R Foundation, 2019]. The data were grouped into two subgroups before analysis: warm season (June-September) and cold season (April, May, October, and November).

To graphically compare the chemistry in different water samples, piper diagrams were formed using the R package ‘Hydrogeo’ [English, 2017]. If the measured concentration of the substance was below the limit of detection (LOD), it was assigned a value of LOD divided by 2, which is a common procedure used to assign values for sample sets with less than 15% of the samples below the detection limit [United States Environmental Protection Agency, 2000].

To reduce the dimensionality of the dataset while retaining as much of its variation as possible, we performed principal component analysis (PCA) for the stream data (chemical and physical water quality parameters and discharge). We used the R function prcomp from the Stats package, which employs singular value decomposition (SVD) [R Core Team, 2019]. It is preferred over the princomp function because of its better numerical accuracy [Anderson, 2013]. A constant was added to isotope values to transform them to positive values (13.3‰ for δ¹⁸O and 95.8‰ for δ²H).

To eliminate skewness, we log-transformed the data. We also scaled and centered the data using the prcomp function. We performed the analysis for two datasets; the average values of all measurements for each site and the average values for the low-flow situation (July measurements). One of the basic assumptions of PCA is that the measurements are independent [Demšar et al., 2013]. However, the measurements in this study were made at several locations along the same
streams and thus there was some spatial autocorrelation between the measurements. However, as each stream had almost the same number of sampling locations, they had similar weighting in the analysis and PCA was deemed suitable for use, although the autocorrelation between samples was borne in mind when analyzing the results. We included three PCA components, which explained 85% (all measurements) and 88% (low flow measurements) of the variation in the data set.

2.3.1 The stream tracer index method

To classify the observed GW dependence of the three streams, we developed a stream tracer index method. This was used to classify the stream sections into GW-dominated, GW-SW transition, and SW-dominated zones, based on three properties: i) GW volume in streams, ii) thermal properties of streams, and iii) stream water quality. GW amount in streams can be evaluated based on discharge and stable water isotopes, thermal properties based on the temporal variations in stream T, and water quality based on the GW tracers chosen to be suitable for the specific stream. The stream tracer index (S) was calculated as:

\[ S(\%) = 100 \times \frac{x_{gw} + x_{temperature} + x_{chemistry}}{3} \]  

where \( x_{gw} \) is the classification value based on stable water isotopes and discharge (GW volume), \( x_{temperature} \) the classification value based on temperature, and \( x_{chemistry} \) the classification value based on water quality. Due to local variations in land use and in bedrock and soil chemistry, the same water quality tracers may not be applicable at all locations. The tracers were chosen based on the assumptions that: i) the chemical signature of GW and SW stays relatively stable within a catchment and ii) upstream locations are more GW-dominated and thus the upstream tracer values should be closer to GW than SW reference values (see section 2.2.1). In practice, the stream water tracer values (median values) also had to be between the GW and SW reference values in order to be chosen as tracers. Stream water tracer values not related to the reference values can be the
result of deviating GW and/or SW quality in the catchment area. SW tracer concentrations in
particular can change markedly due to different kinds of land uses and catchment properties.
However, as there is hardly any detailed information about the SW quality of different land units,
in our method only tracers with behavior associated with the available reference values are used.
Thus, the best suited catchment-specific tracers must be first determined for each site (see section
3.3) and then the classification value based on water quality can be calculated as:

\[ x_{\text{chemistry}} = \frac{x_{\text{variable 1}} + x_{\text{variable 2}} + \ldots + x_{\text{variable n}}}{n} \]  

(2)

where \( x_{\text{variable}} \) is the classification value based on the chosen water quality variable. The
classification values are determined by evaluating whether the tracer in question indicates a clear
GW signal (\( x=1 \)), a mixture of GW and SW (transition zone, \( x=0.5 \)), or a clear surface water
signal (\( x=0 \)). After the appropriate values are chosen, the stream tracer index values can be
calculated using equations (1) and (2). Measurement locations with stream tracer index values \( S_i <
50\% \) are interpreted as SW-dominated zones, those with \( S_i = 50\% \) as transition zones, and those
with \( S_i > 50\% \) as GW-dominated zones.
3 Results

3.1 Stream discharge and its origin

The discharge in the three streams studied varied temporally and spatially, with a generally increasing trend downstream (Figs. 2 and 3). Baseflow was highest for Siirasoja stream (approximately 15 L s$^{-1}$ km$^{-2}$), considerably higher than for Lohioja stream (7.5 L s$^{-1}$ km$^{-2}$). The baseflow in Mesioja was approximately 1.3 L s$^{-1}$ km$^{-2}$, which was only 9% of that in Siirasoja. Siirasoja and Lohioja streams responded similarly to precipitation events and with a similar timing and magnitude of the response (Fig. 3). However, the maximum peak discharges were higher in Lohioja. In general, high flows occurred during autumn and after snowmelt in spring. During these events, the spatial variations in discharge along the stream continuum were at their highest. The coefficient of variation for discharge was greatest for Mesioja (87%) in October 2013 and for Lohioja (75%) and Siirasoja (77%) in November 2014. The lowest flows were observed during winter and occasionally during summer. The discharge at the upstream locations stayed relatively stable during all seasons.

Based on the stable water isotope dataset, the water origin in all three streams was mainly GW (Fig. 6 and Supporting Information Fig. S2). The average isotopic composition of GW in Viinivaara and Rokua esker areas is -13.0 and -94.3 ‰ [Isokangas et al., 2017] and -13.1 and -95 ‰ [Isokangas et al., 2015], respectively, for δ$^{18}$O and δ$^{2}$H. In Siirasoja and Lohioja streams at Rokua, the isotopic composition remained relatively stable except during the rain events in November 2014 (Fig. 3), when the isotopically more enriched SW increased the delta values of the streams. Summer evaporation also slightly modified the isotopic composition of stream water. In Mesioja, the water isotope responses were more complex than in Lohioja and Siirasoja. At upstream locations, the isotopic composition resembled GW, but further downstream the delta values increased, indicating larger contributions from enriched surface runoff and soil water. However, at
the furthest downstream locations, the delta values were again more negative, indicating GW discharge into the stream also at downstream locations (Fig. S2).

Fig. 2. Stream discharge (Q) measured with a current meter at different distances from the stream start point in Mesioja, Lohioja, and Siirasoja streams during field campaigns.

Fig. 3. Continuous stream discharge obtained using water level measurements in Mesioja (MQ), Lohioja (LQ), and Siirasoja (SQ) streams and local precipitation data obtained from the Finnish Meteorological Institute weather stations Pudasjärvi Airport (Mesioja) and Pelso (Lohioja and Siirasoja). Dotted vertical lines indicate the sampling times.
3.2 Spatial and temporal variations in stream water temperature

During summer, water temperature generally increased from headwater to downstream in all streams (June-September, mean air T at Pudasjärvi airport 14.0 °C and at Vaala-Pelso station 13.3 °C). However, the streams generally had different diurnal variations (Fig. 4). During colder periods (spring and autumn), the upstream locations generally had a somewhat higher water temperature (mean 4.7 °C) than the downstream locations (mean 4.4 °C). The coefficient of variation for temperature was smallest for headwater locations in both warm (June-September) and cold (April, May, October, November) seasons. For the warm season, the values were 17.8%, 14.5%, and 13.7% for locations M1, L1, and S3, respectively, while for the cold season they were 46.1%, 39.1%, and 35.7%, respectively (Supporting Information Table S3). This shows that GW sustains stable thermal regimes in both warm and cold seasons. Although there was a clear increase in water temperature in the Mesioja stream continuum, at the last measurement location it still differed noticeably (5 °C on average in the warm season) from the SW reference, i.e., Lake Sarvilampi outlet (M5). In Lohioja and Siirasoja streams, water temperatures at different measurement points were more similar than in Mesioja. In Siirasoja, water temperature of one tributary (S3, warm season mean 6.9 °C) was mostly GW-influenced, whereas in Mesioja (M1, warm season mean 7.4°C) and Lohioja (L1, warm season mean 6.4°C), the GW impact was most pronounced at the most upstream locations (Table 2).
Fig. 4. Water temperature at different points in Mesioja, Lohioja, and Siirasoja streams, and local air temperature obtained from the Finnish Meteorological Institute weather stations Pudasjärvi Airport (Mesioja) and Pelso (Lohioja and Siirasoja). Dashed grey
line indicates mean spring water temperature in Finland and Sweden [Jyväsjärvi et al., 2015] and dotted vertical lines indicate the sampling times.
3.3 Spatial and temporal variations in stream chemical properties

Stream water chemical properties varied spatially and temporally in all streams. Continuously measured EC of water reflects the total amount of ions in water and thus can be used to observe temporal changes in water chemistry. The average EC was highest in Siirasoja (43 μS cm⁻¹) and lowest in Mesioja (19 μS cm⁻¹) during both warm (June-September) and cold (April, May, October, and November) seasons (Fig. 5). The average EC of Lohioja water was 27 μS cm⁻¹. In Mesioja, EC values generally decreased downstream, on average from 23 to 15 μS cm⁻¹, indicating SW input to the stream (SW reference value 3 μS cm⁻¹; Supporting Information Table S1). The behavior of EC in Lohioja and Siirasoja catchments was more complex. The lowest average EC values were found at upstream measurement points L1 (20 μS cm⁻¹) and S2 (36 μS cm⁻¹), and the highest at points L2 and L3 (30 μS cm⁻¹) and S1 (50 μS cm⁻¹). In general, the EC values in Lohioja and Siirasoja indicate that SW increased EC, unlike in the Mesioja catchment, although the SW reference values were the same in both areas (Supporting Information Table S2). This is supported by the relatively low GW reference values in Rokua, which ranged from 2.9 to 7.8 μS cm⁻¹ depending on measurement location (Supporting Information Table S2).
Fig. 5. Electrical conductivity (EC) at different points in Mesioja, Lohioja, and Siirasoja streams. Dotted vertical lines indicate the sampling times. Some of the data were filtered out due to unreliable results (compared against field measurements) caused by biofilm growth on loggers.

Based on piper diagrams, the dominant water type was Ca-HCO$_3$ for Siirasoja, Ca-HCO$_3$ to Ca-SO$_4$ for Lohioja, and Na-HCO$_3$ to Na-SO$_4$ for Mesioja (Fig. 6). Finnish streams usually have Ca-HCO$_3$ as the dominant water type, with dark water color and high organic matter and Fe content [Lahermo et al., 1996]. The piper diagrams showed that Mesioja had significantly different water chemistry than Siirasoja and Lohioja streams. However, Siirasoja and Lohioja also differed slightly from each other. Siirasoja had the most stable water chemistry, based on the piper diagram.
Furthermore, stream water chemistry varied spatially in Mesioja, Lohioja, and Siirasoja streams (Fig. 6). In Mesioja water, several substances decreased downstream (TIC, K, Ca, Mg, S, Sr, SO$_4^-$, and SiO$_2$) and only DOC increased in the Mesioja stream continuum. The chemistry of Lohioja and Siirasoja water varied less regularly. Stream water chemistry was compared against the local GW and SW composition (Supporting Information Table S2). The variables that changed along the stream continuum which could be best related to these reference values were conventionally used environmental tracers SiO$_2$ and Cl$^-$ and,
in addition, DOC, TIC, and PO₄³⁻-P. Thus, these variables were chosen for use as GW tracers in this study (see section 3.4). However, not all these variables could be used for tracing GW in all streams. In general, the change in GW dominance was more easily associated with the tracer concentrations in Mesioja stream than in other streams.

In the Mesioja stream continuum (from M1 to M4), the DOC values rose from the GW reference value (1.0 mg L⁻¹) to the SW reference level (23 mg L⁻¹) (Fig. 7). Therefore, the DOC values indicated that the first measurement location (M1) had a clear GW signal, the next two (M2 and M3) belonged to the transition zone, and the last measurement location (M4) had a clear SW signal. In Lohioja stream, all DOC values were higher than the GW and SW reference values and DOC could not be used to indicate GW dependency. In Siirasoja stream, most of the measured DOC values fell between the reference values and those of all other measurement locations, except for S2, which was in the GW-SW transition zone.

TIC decreased by approximately half in the Mesioja stream continuum, from near its GW reference value to near its SW reference value. However, the transition occurred earlier than for DOC and already at the M3 location the stream had a clear SW signal. There was no available information about TIC in GW in the Rokua esker, so the Viinivaara esker reference value was used as an estimate. Based on TIC, all the locations in Lohioja stream were in the GW-SW transition zone. Furthermore, in Siirasoja only the first measurement location S1 had a clear GW signal and the others fell between GW and SW reference values to the transition zone.
In Mesioja stream, SiO$_2$ concentrations decreased downstream, indicating gradual SW input to the stream. The first three measurement points were located in the GW-SW transition zone, with gradually increased SW downstream, and the last point had a clear SW signal. In Lohioja, the SiO$_2$ concentration stayed relatively stable throughout the stream continuum and indicated a mixture of GW and SW. In Siirasoja, the second measurement location S2 belonged to a GW-SW transition zone, whereas the other measurement locations had a clear GW signal.

In Lohioja, Cl$^-$ concentrations indicated that the first measurement location (L1) had a clear GW signal and the other locations were in the GW-SW transition zone. In Siirasoja, the first three locations had Cl$^-$ concentrations near to the GW reference value, the next two belonged to the GW-SW transition zone, and the last measurement location had a clear SW signal. In Mesioja, Cl$^-$ concentrations showed no consistent variation and could not be used to trace GW.

PO$_4^{3-}$-P was not useful as a tracer in Mesioja, as the reference values of GW and SW were very close to each other in the Viinivaara area. However, in the Rokua area the reference values showed a clear distinction from each other. Due to the high phosphate content of the aquifer sand, the GW had a high phosphate content and all the measurement locations in both Lohioja and Siirasoja streams belonged to the GW-SW transition zone. The behavior of total P was similar to that of PO$_4^{3-}$-P.
Fig. 7. Stream water chemical variables represented as box plots for each measurement point, where M is Mesioja, L is Lohioja, and S is Siirasoja. Vertical axes for SiO$_2$, PO$_4^{3-}$-P, and P are rescaled and the plots do not show all outliers. Continuous lines indicate local groundwater (average of esker groundwater and groundwater...
under the peat layer at discharge zone in Rokua), dotted lines represent surface water (see Table 2), and dashed lines represent summer precipitation.

PCA was applied to average values of all measurements and to average values of low-flow measurements (July samples). We observed no notable dissimilarities between the PCA results of these two sampling seasons (Table 2). For all measurements, 75% of the variation in the data was explained by the first two principal components (PCs), while for low-flow measurements these two PCs explained 79% of the variation. In both cases, all three streams were distinctly separated from each other when plotted along the first two PCs (Fig. 8). Mesioja had the greatest variance between measurement locations, while in Lohioja and Siirasoja the variance along the first two PCs was much smaller. On examining the component loadings of different variables, it was possible to find physical interpretations for different PCs. The first PC could be connected with GW, since many of the variables known to be associated with GW, e.g., pH, alkalinity, PO_{4}^{3-}, P, and SiO_{2} (see section 4.3), had high negative PC1 loadings. Thus, generally low PC1 loadings indicated high GW influence. The second PC could be associated with peatland water, since DOC in particular is correlated with increased peatland surface water contribution. Therefore, negative PC2 loading could indicate a high amount of peatland SW in a stream. The third PC was associated with discharge and temperature and was therefore related to the GW amount and the thermal regime of the streams.
Table 2. Summary of principal component (PC) results for the stream data showing the eigenvalues, percentages and cumulative percentages of explained variances, and component loadings for different parameters.

<table>
<thead>
<tr>
<th></th>
<th>All measurements</th>
<th>Low-flow conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PC1</td>
<td>PC2</td>
</tr>
<tr>
<td>Eigenvalue</td>
<td>12.97</td>
<td>6.50</td>
</tr>
<tr>
<td>% explained</td>
<td>49.90</td>
<td>25.00</td>
</tr>
<tr>
<td>Cumulative % explained</td>
<td>49.90</td>
<td>74.90</td>
</tr>
<tr>
<td>EC</td>
<td>-0.259</td>
<td>0.047</td>
</tr>
<tr>
<td>pH</td>
<td>-0.248</td>
<td>0.102</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>-0.256</td>
<td>0.072</td>
</tr>
<tr>
<td>SiO₂</td>
<td>-0.200</td>
<td>0.130</td>
</tr>
<tr>
<td>P</td>
<td>-0.243</td>
<td>-0.150</td>
</tr>
<tr>
<td>PO₄³⁻-P</td>
<td>-0.249</td>
<td>-0.151</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>-0.254</td>
<td>0.100</td>
</tr>
<tr>
<td>Ba²⁺</td>
<td>-0.248</td>
<td>-0.154</td>
</tr>
<tr>
<td>Ca²⁺</td>
<td>-0.271</td>
<td>-0.074</td>
</tr>
<tr>
<td>Mg²⁺</td>
<td>-0.251</td>
<td>0.145</td>
</tr>
<tr>
<td>Mn²⁺</td>
<td>-0.265</td>
<td>-0.053</td>
</tr>
<tr>
<td>S</td>
<td>-0.253</td>
<td>0.077</td>
</tr>
<tr>
<td>Sr²⁺</td>
<td>-0.195</td>
<td>-0.156</td>
</tr>
<tr>
<td>Al³⁺</td>
<td>-0.020</td>
<td>-0.370</td>
</tr>
<tr>
<td>TIC</td>
<td>-0.131</td>
<td>0.246</td>
</tr>
<tr>
<td>DOC</td>
<td>0.173</td>
<td>-0.247</td>
</tr>
<tr>
<td>Fe</td>
<td>-0.157</td>
<td>-0.255</td>
</tr>
<tr>
<td>Ti</td>
<td>-0.027</td>
<td>-0.361</td>
</tr>
<tr>
<td>δ¹⁸O</td>
<td>0.111</td>
<td>-0.127</td>
</tr>
<tr>
<td>δ²H</td>
<td>0.119</td>
<td>-0.165</td>
</tr>
<tr>
<td>K⁺</td>
<td>-0.180</td>
<td>0.187</td>
</tr>
<tr>
<td>Na⁺</td>
<td>-0.121</td>
<td>0.317</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>-0.129</td>
<td>-0.207</td>
</tr>
<tr>
<td>Q</td>
<td>-0.117</td>
<td>-0.244</td>
</tr>
<tr>
<td>T</td>
<td>0.097</td>
<td>0.188</td>
</tr>
<tr>
<td>Dissolved O₂</td>
<td>-0.154</td>
<td>-0.236</td>
</tr>
</tbody>
</table>

Note. The highest loadings for each PC are shown in bold.
Fig. 8. Principal component analysis results for low-flow measurements (July samples) in Mesioja, Lohioja, and Siirasoja streams, plotted against the first two principal components (PC1, PC2).

3.4 Groundwater and surface water dominance of streams

The stream tracer index method was developed to combine the various types of information obtained during this study (see section 2.3.1.). The transition between the GW-dominated and SW-dominated sections occurred in the middle of
Mesioja stream, between locations M2 and M3, and at the end of Lohioja and Siirasoja streams. The upper parts of the streams were classified as zones with a clear GW signal (Table 3). Thermal properties (warm and cold seasons) were used to give T-based classification values (see section 3.2). The set of water quality variables used to obtain the water quality classification values were specifically customized for each stream (see section 3.3).

The calculated stream tracer index value $S_i$ ranged from 33 to 94% for Mesioja, 50 to 88% for Lohioja, and 50 to 90% for Siirasoja. High $S_i$ values indicate strong GW dependence, which was expected as the streams discharge from esker aquifers. Based on the index values, Lohioja and Siirasoja streams were more affected by GW than Mesioja stream. Mesioja was also the only stream where SW dominated in part of the stream. However, both in Lohioja and Siirasoja there was a clear shift from a GW-dominated to a SW-dominated system and the downstream locations were classified as GW-SW transition zones ($S_i=50\%$).

As the results of PCA for the whole dataset and for the low-flow situation resembled each other, the classification was reproduced using only the low-flow measurements (Supporting Information Table S4). The final classification results were almost identical except for location M3 in Mesioja, which belonged to a transition zone, not a SW-dominated zone, in the classification with low-flow measurements. On average, $S_i$ values determined from the low-flow measurements were only 3.6% higher than the values determined from all measurements.
Table 3. Use of the stream tracer index ($S_i$) method and classification values ($x_i$) to spatially classify the different parts of Mesioja, Lohioja, and Siirasoja headwater streams into groundwater-dominated (GW, $S_i >50\%$) or surface water-dominated (SW, $S_i < 50\%$)

<table>
<thead>
<tr>
<th>Location</th>
<th>GW amount</th>
<th>Thermal properties</th>
<th>Water quality</th>
<th>$S_i$ (%)</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$x_{gw}$</td>
<td>$x_{temperature}$</td>
<td>$x_{DOC}$</td>
<td>$x_{TIC}$</td>
<td>$x_{SO_2}$</td>
</tr>
<tr>
<td>Mesioja</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>M3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>M4</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lohioja</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>L2</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>L3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>L4</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Siirasoja</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>S3</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>S4</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>S5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>S6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

Classification values: 1 - Clear groundwater signal, 0.5 - Transition zone, 0 - Clear surface water signal.
4 Discussion

4.1 The role of groundwater in boreal streams

Groundwater plays an important role in boreal headwater systems as the main source of base flow, providing unique biodiversity due to its cool and stable temperature and supply of good-quality water [Ilmonen et al., 2012; Jyväsjärvi et al., 2015; Lehosmaa et al., 2017]. Classification of streams and aquifers is needed to protect these systems and manage water abstraction and land use activities that influence the GW source [Laini et al., 2012; Nadeau et al., 2015; Rossi et al., 2015] or the stream continuum itself [Jyväsjärvi et al., 2014]. In this study, discharge, continuous measurements of EC and temperature, and tracer measurements (e.g., stable water isotopes, ions) were successfully used to trace the amount of GW in a stream continuum and classify the GW dependence of boreal headwater streams.

As expected for gaining streams, discharge increased towards downstream reaches due to increased GW exfiltration and/or SW input. GW maintained the flow in the small streams also during the dry season, when a constant isotopic composition was observed. During high flows in autumn and spring, surface water runoff from peatlands was observed and indicated by stable water isotopes, especially at downstream measurement points. The discharge at upstream locations close to the eskers stayed relatively stable throughout the year.
While GW dominated the first stream sections, differences among sites were noted in downstream reaches. In Mesioja, stable water isotope data showed more variations throughout the year than in Lohioja and Siirasoja streams. This variation can be the result of fractionation by evaporation from the stream channel or significant SW flow to the stream. However, based on the discharge and stable water isotopes, all the streams are first GW-dominated, and then SW starts to contribute more and the downstream locations are classified into GW-SW transition or SW-dominated zones (Table 2).

Our results show that boreal headwater streams can be highly GW-dependent. Changes in GW discharge would particularly affect the position and length of the GW-SW transition zone in the stream continuum and could thus alter stream ecosystems. As GW supports stream flow, especially at upstream measurement locations, our study streams would most probably dry out without GW input at least occasionally. In future, stream discharge in the Viinivaara study area will probably decrease considerably due to planned GW abstraction for the city of Oulu, as a large proportion of the annual recharge will be extracted [Rantala et al., 2014]. Earlier snowmelt due to climate change may also lower GW levels in the region during summer months, exacerbating the impacts of drought [Okkonen et al., 2010; Okkonen and Kløve, 2011]. These potential changes in stream discharge pose a threat to the viability of aquatic ecosystems [Mustonen, 2016] and highlight the importance of GW-dominated streams in boreal landscapes for supporting ecological biodiversity.
4.2 Thermal properties change radically in the stream continuum

Water temperature can be a simple and affordable indicator of GW exfiltration. In the streams studied here, stream temperature generally changed rapidly from upstream to downstream sections. During summer, the measurements revealed drastic changes in stream water temperature from cold (3 °C) to warm (up to 19 °C) occurring within a few kilometers in the boreal stream continuum. In general, the temperature provided an approximation of GW amount, except during autumn and spring seasons when GW and air temperature were similar.

The variations in stream water temperature were smallest at upstream locations M1, L1, and S3 (classified as having a clear GW signal), where GW sustained stable thermal regimes in both warm and cold seasons. Water temperature at downstream locations still deviated from that in a local surface water body (Lake Sarvilampi). The average temperature increase during the warm season was 4.3, 3.7, and 2.6 °C in Mesioja, Lohioja, and Siirasoja, respectively. The low values in Siirasoja stream were most likely due to higher discharge rate and greater GW volume than in the other streams. The temperature-based GW-SW transition zone started before 745 m and 1682 m distance from the beginning of the stream in Mesioja and Lohioja, respectively, while in Siirasoja even the first measurement location belonged to the transition zone and only the small tributary (S3) had a GW-influenced thermal regime. Although we did not have a complete set of winter temperature measurements, the cold season results provide an indication of the conditions in winter. They show that the stream sections
which were most GW-influenced during the warm season were also the most GW-influenced in winter. A GW influence on streams was also clearly visible during winter, as the highly GW-dependent locations did not freeze due to the stable GW temperature (approximately 4-6 °C). This provides specific conditions for aquatic biota and can be vital for their survival. Unreported winter-time observations (2010-2012) in Siirasoja stream supported our conclusion that the GW-influenced section stays the same in winter, as the upper part of Siirasoja was mostly unfrozen.

Our results showed that GW plays a major role in the thermal sensitivity of the streams studied, such that GW-dependent areas were less sensitive to changes in air temperature, although still responded to it. For example, the water temperature at these locations still showed diurnal variations and during exceptionally warm days the water temperature increased. Fortunately, these events were relatively short (some days) and the highest temperatures were only short-term mid-day events (e.g., on 1 July 2013, T in Siirasoja stream, location S3, increased to 10 °C for 45 minutes). Changes in water temperature can be critical for highly sensitive freshwater ecosystems [Yvon-Durocher et al., 2011]. For example, Jyväsjärvi et al. (2015) showed that even a 1 °C increase in mean water temperature of springs can affect the species present in water and alter bryophyte and macroinvertebrate communities in streams discharging from springs. In addition, salmonid fish in particular have been found to be extremely sensitive to the current warming trend and thermal refuges are becoming even more important for preserving their populations [Isaak et al., 2015]. However, stream biota can
have very different responses to temperature changes and therefore it is difficult
to give an overall estimate of a critical temperature limit. In addition, increasing
stream temperatures may not only reduce the amount of thermally suitable areas
available, but may also increase stream network fragmentation through thermal
barriers that reduce local ecological viability [Isaak et al., 2012, 2015; Orr et al.,
2015; Snyder et al., 2015].

4.3 The applicability of local groundwater and surface water
reference values

The water quality of the three streams studied showed clear differences, despite a
similar geological formation being the main water source. Therefore different
water quality tracers were chosen for each of the streams (see sections 3.3. and
3.4). Changes in stream water quality can result from changes in mixing
proportions of GW and SW, or changes in GW and/or SW water quality spatially
or temporally. These kinds of variations can complicate interpretation of tracer
data [Kirchner, 2016a, 2016b]. In general, GW is assumed to have more stable
water quality than SW, but seasonal variations in GW quality can stem from
snowmelt or storm events [James and Roulet, 2006]. Furthermore, the hyporheic
processes and interchanges between GW and SW can increase the contact time
between stream water and subsurface material and intensify biochemical activity,
which can be seen in changes in water quality [Sophocleous, 2002].
In the present case, some of the GW and SW reference water quality variables, mostly the SW variables, were not suitable and did not represent the actual GW and/or SW observed in the catchment area. SW quality is dependent on several factors, including local geology, soil properties, and land use. For example, even within the same catchment, peat porewaters can have differing geochemical signals caused by e.g., substance accumulation in peat, vegetation uptake, variations in water source and GW level and its fluctuations, temperature, and matrix diffusion [Tahvanainen et al., 2002; Levy et al., 2016; Isokangas et al., 2017; Menberu et al., 2017]. Isokangas et al., [2017] showed that peatland surface water quality in the Viinivaara area is variable, e.g., near Mesioja stream, δ¹⁸O values were found to range between approximately -8‰ and -13‰ and SiO₂ values between 0 and 30 mg L⁻¹ during the period 4-11 August 2014. This large range in values results mainly from differences in peatland water source, as some parts of the peatland are GW-dependent and some are rainwater-dominated. In the present study, we opted to use a nearby river water as a local SW reference, instead of studying and determining the small-scale variations and features of the immediate, actual peatland water surrounding the stream. Thus, the water quality signal was a mixture of the deviating SW quality found in the area. Furthermore, although it is still possible that the SW reference value does not fully represent the SW of the studied catchment, at the moment this is the best available option for management purposes.

Moreover, GW quality reflects the local geology. In geologically homogeneous settings, as in Viinivaara and Rokua esker aquifer areas, GW
quality is often assumed to be spatially variable rather uniform. However, our
results from Rokua show that there are some variations in GW quality, as the
quality of esker GW deviates from the quality of GW under the peat layer
(Supporting Information Table S2). Spatial variations in GW quality in Rokua
esker aquifer area were investigated more closely using data from 13 piezometers
sampled for three of the water quality tracers used in this study (SiO$_2$, Cl$^-$ and
PO$_4^{3-}$-P) during previous studies in the area [Ala-aho et al., 2013, 2015]. The
piezometers were sampled quarterly during 2010-2012. In general, SiO$_2$ and Cl$^-$
were more stable spatially and temporally than PO$_4^{3-}$-P (Supporting Information
Fig. S3). The average coefficient of variation for Cl$^-$, SiO$_2$, and PO$_4^{3-}$-P measured
in the different piezometers was 17.6, 12.5, and 68.6 %. This suggests that SiO$_2$
and Cl$^-$ are more reliable tracers in this area. In addition, temporal variations in
GW and SW quality were detected in both the Rokua and Viinivaara areas.
However, the chosen catchment-specific tracers for the areas showed generally
reasonably steady behavior. The average coefficient of variation for the GW
reference variables used (excluding PO$_4^{3-}$-P) was 7.5% and that for the SW
reference variables was 17.4%.

4.4 Surface water input causes changes in water quality in the
stream continuum

As the processes affecting stream water quality are catchment-specific, relatively
conservative tracers for a certain catchment can be challenging to distinguish. In
this study, we handled this problem by developing a method that overcomes the uncertainty of using a single tracer by applying multiple tracers. The selected catchment-specific GW tracers in this study were: DOC, TIC, SiO$_2$, Cl$^-$, and PO$_4^{3-}$. Although selection of these variables was not governed by their reputation as GW tracers, many of them have been used previously to study GW-SW interactions [e.g., Kalbus et al., 2006; Ala-aho et al., 2013; Bertrand et al., 2014].

A clear effect of peatland water sources was shown by elevated DOC in stream water. Soils, especially riparian and organic-rich soils like peatlands, together with forested areas, are generally the main source of DOC to headwater streams [Laudon et al., 2011; Marx et al., 2017]. The typical brownish waters of boreal streams and rivers are the result of high DOC concentrations, which also affect the physio-ecological conditions in streams [de Witt et al., 2016]. In this study, the peatlands surrounding the stream in Mesioja catchment released high amounts of DOC along the stream continuum. In Siirasoja stream, higher DOC concentrations at measurement point S2 could again be explained by a relatively higher proportion of peatlands in this upstream subcatchment. In addition, the decreasing amount of TIC downstream observed in all streams studied can be related to atmospheric outgassing of carbon dioxide or SW input, as in headwater streams TIC mostly originates from GW [Marx et al., 2017].

Fertilizers and manure from agriculture can raise Cl$^-$ concentrations in surface waters [Granato et al., 2015]. This is the most probable reason for the increased chloride concentrations observed downstream in Lohioja and Siirasoja streams, where the proportion of agricultural land in the catchment is higher than at
upstream locations. The impact of the esker aquifers could also be seen in the tracer dataset. The high concentrations of dissolved SiO$_2$ found in all streams resulted from leaching of SiO$_2$ from the sandy soils of the eskers and the relatively long flow paths to the discharge zone, enabling long contact time with soil. For example, in the Rokua area the average SiO$_2$ concentration of the esker GW increased towards the discharge zone (Table 2). In the Rokua area, phosphate also leaches from the soil and GW acts as a phosphate source for lakes and streams [Ala-aho et al., 2013]. Interestingly, however, the first measurement location in Lohioja had relatively low phosphate concentrations. This might be due to uptake of phosphate by biological processes, which could be more pronounced at this upstream location with relatively low discharge.

Most of the other water quality parameters tested (alkalinity, SO$_4^{2-}$, K$^+$, Ca$^{2+}$, Mg$^{2+}$, and Na$^+$) decreased downstream in Mesioja due to SW dilution. Alkalinity values dropped downstream from an ecologically good (>0.2 mmol L$^{-1}$) to a poor level (<0.01 mmol L$^{-1}$) [Oravainen, 1999]. In Lohioja and Siirasoja, this drastic drop in alkalinity was not observed and therefore it is likely that the pristine peatland area surrounding Mesioja affected the SW and caused alkalinity to decrease. These results suggest that GW sustains high alkalinity at the study sites, which make the streams less sensitive to changes in pH and thus protects the aquatic biota.

Although temporal variations in water quality are important for aquatic biota and habitats, the results from our PCA analysis indicated that snapshot sampling during low-flow periods was sufficient to reveal GW dominance in the streams.
The PCA results for the whole dataset and for the low-flow situation resembled each other, which suggests that it could be sufficient to sample streams only in summer during low-flow conditions, which would make field studies more cost-effective. Furthermore, the classification and $S_i$ values were similar, irrespective of whether the summer temperature measurements or the whole temperature dataset were used. In fact, mid-summer can be considered the optimum time to detect the GW impact on water temperature, because at that time the deviation between upstream and downstream water temperatures was found to be most pronounced. Overall, these results answer our research question (iii), by confirming that it is possible to obtain a reliable GDE classification based on a single sampling campaign conducted under low-flow conditions during a rainless period.

4.5 Using the stream tracer index method to determine GW-SW transition zones – Implications for practical management

When the GW dependence of a stream is studied, it is also important to consider aspects other than the actual amount of GW in the stream, which is determined using stable water isotopes in many cases. From an ecological perspective, water temperature, water quality, and water amount are important. Therefore, we developed our stream tracer index method to combine the information we considered most important for evaluating GW dominance and transition zones towards SW-dominated sections in streams (Fig. 9). The method answers our
723 research question (i), by showing how headwater stream sections can be classified 724 to GDEs. Method development was guided by the recommendation to use a 725 combination of different tracers to understand ecosystem GW-SW interactions 726 and to estimate the anthropogenic influence on these systems [Bertrand et al., 727 2014]. In this study, we determined the stream tracer index value ($S_i$) for Mesioja, 728 Lohioja, and Siirasoja streams, and found that it ranged between 33 and 94%, 50 729 and 88%, and 50 and 90%, respectively. As high $S_i$ index values indicate strong 730 GW dependence, we concluded that Lohioja and Siirasoja streams are more GW- 731 dependent than Mesioja. The transition zones between GW and SW occurred at 732 the end of Lohioja and Siirasoja streams and approximately in the middle of 733 Mesioja. This suggests that streams discharging from esker aquifers located in 734 pristine peatland-dominated catchments may be more prone to rapid change from 735 GW to SW systems than streams located in catchments dominated by peatland 736 forestry.

737 This study shows that the combined use of environmental tracers can serve as 738 a general water management tool. The method is especially suitable when there is 739 a clear temperature difference between local GW and SW. During the warm 740 season, GW temperature is lower than SW temperature, which can be used to 741 trace GW (Fig. 9). Furthermore, the method is particularly suitable for sites where 742 there is a well-defined, rather homogeneous aquifer as a source of GW (Fig. 9). 743 This set-up increases the probability of stable GW quality and isotopic 744 composition and reduces the uncertainty of the classification. One of the 745 assumptions for the method is that the chemical signature of GW and SW stays 746
relatively stable within a catchment. However, our case study showed that the method can still be applied even when water quality displays some variation (Supporting Information Table S2 and Fig. S3). We analyzed a number of water quality parameters, instead of just a few, increasing the likelihood of some of the tracers analyzed having rather uniform and stable behavior, and thus being suitable for further evaluation.

Based on our results and findings in the literature, we recommend use of SiO$_2$, DOC (especially in peatland-dominated catchments), TIC, and Cl$^-$ (in catchments with agricultural land) as tracers, although bearing in mind that their applicability has to be decided case-by-case. In addition, as the classification is not based solely on water quality, but also on water quantity and temperature, deviating results can be spotted and further analyzed, providing more credible classification. For example, in a case with an additional major GW source from a different geological formation affecting the stream further downstream, this would be evident in changing water temperature. In that case, it would be possible to analyze the chemistry of this other GW formation and adapt the classification as indicated. Finally, we must emphasize that our method is developed for headwater streams, for which we believe it is reliable enough to produce sensible estimates of the GW dependence.

A clear benefit of the proposed method is its simplicity, which makes it easy to use in water management. A disadvantage is that expert knowledge is needed to choose appropriate tracers for a selected area and the classification values for those tracers. However, the method resembles other management tools, such as
analytic hierarchy process [Subramanian and Ramanathan, 2012], so in that regard it should be rather easy to adopt in decision making. Furthermore, the stream tracer index method could be especially helpful in the intense monitoring programs required in areas of exceptional ecological importance [Bertrand et al., 2014]. The method could also be applied in places where anthropogenic actions are expected to change the local hydrology and affect stream ecosystems. In addition, available historical data could be applied in some cases if there have not been any major changes in the catchment area.

Fig. 9. Conceptual illustration of the stream tracer index method (see section 2.3.1 for more details).
5 Conclusions

Spatial and temporal aspects of the groundwater dependence of three boreal headwater streams were studied using environmental tracers and a novel tool for classification and management of groundwater-dependent stream ecosystems was developed. Our stream tracer index method combines the ecohydrologically important characteristics dominated by groundwater, namely groundwater volume in streams, thermal properties of streams, and stream water quality. As water quality tracers are site-specific, they need to be specifically chosen for each stream, using reference measurements of local groundwater and surface water.

We found that spatially, the groundwater dependence in the three streams studied varied widely, with groundwater-dominated areas reaching at least 745, 1682, and 4202 m from the main groundwater discharge points located at the stream head. Groundwater sustained flow in the streams during the whole hydrological year and the groundwater dependence was similar during summer and winter seasons. Generally, stream temperatures changed rapidly from upstream to downstream and the most pronounced effects of groundwater on stream water temperatures were observed during summer. Furthermore, water quality analyses revealed that, even though the boreal headwater streams studied all discharge from esker aquifers, they have very different characteristics. Therefore different water quality tracers were chosen for each of the streams.

It is important to classify boreal headwater streams, owing to their ability to act as refuges, supporting stable conditions vital for specific aquatic biota in a
changing climate. The results of this study suggest that it might be sufficient to sample stream sections only once, during summer low-flow conditions, when evaluating the groundwater dependence of streams. The stream tracer index method could serve as a useful management tool, especially at sites of exceptional ecological importance or at sites where anthropogenic measures are expected to change the local hydrology.
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**Abstract:**

Ecosystem protection requires a better definition of groundwater (GW) dependence and tools to measure this dependence. In this study, a classification method for the GW dependence of headwater streams was devised based on the fact that GW affects discharge, thermal regime, and water quality. The method
was tested in three boreal headwater streams discharging from two esker aquifers. Spatial and temporal variability of GW dependence were studied in the stream continuum at several locations, by combining continuous measurements of temperature, electrical conductivity, and discharge with discrete sampling of environmental tracers (e.g., stable water isotopes, silica, chloride). The stream tracer index method developed was used to classify stream sections into GW-dominated, GW-surface water (SW) transition, and SW-dominated zones. We found that, spatially, GW dependence along the stream varied widely, with calculated stream tracer index values ranging from 33 to 94 %. The GW-dominated areas extended at least 745, 1682, and 4202 m downstream from the main GW discharge points in the three streams studied. A stream located in a pristine peatland-dominated catchment was more prone to rapid change from GW- to SW-dominated than two streams located in catchments dominated by peatland forestry. These results suggest that to evaluate the GW dependence of streams, it may be sufficient to sample stream sections only once, during summer low-flow conditions. The proposed method can serve as a water management tool, especially for streams of exceptional ecological importance or in places where anthropogenic activities are expected to change local hydrology and ecology.

**Highlights:**

- A novel index method was developed to classify stream sections
• The classification was based on water quantity, quality, and stable isotopes
• As a result the groundwater dependence of stream sections can be determined
• Groundwater dependence in studied headwater streams varied spatially and temporally
• The proposed method improves monitoring and impact assessment in headwater streams

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: