Groundwater−surface water interactions in snow-type catchments: integrated resources

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Abstract

Groundwater (GW) and surface water (SW) have been studied as separate resources in most previous hydrological or hydrogeological studies in Finland. This traditional research approach has both underestimated the commonness of natural exchange between GW and SW systems and oversimplified the management of water resources. This thesis research investigated the previously poorly recognized GW−SW interactions in two boreal snow-type catchments, Lake Pyhäjärvi and River Vantaa, with physical methods, isotopic and chemical tracers and thermal methods, particularly low-altitude aerial infrared (AIR) surveys. The aim of the work was to identify the GW−SW interactions sites, to define the ubiquity of these interactions, to assess the applicability of the used methods, to provide baseline data on seasonal variation in isotopic and chemical tracers in the studied catchments and to provide new insights into more integrated water resources management.

The field studies performed in Lake Pyhäjärvi revealed that the direct GW discharge areas are associated with the esker deposits and focused on the 10-km NE shoreline of lake. The direct GW discharge was spatially highly variable due to the heterogeneous substrate in lake shoreline area. The results from the various methods correlated and confirmed the GW discharge into Lake Pyhäjärvi at the NE shoreline.

The baseline data on isotopic patterns and hydrogeochemistry in the hydrological cycle were provided by a one-year monitoring survey in the Lake Pyhäjärvi catchment. The results revealed strong seasonality in general water chemistry, stable isotopes and dissolved silica concentrations of different water bodies on the catchment scale that should be considered in GW–SW interaction studies in northern high-latitude regions with snow-type hydrology. Samples taken during the spring thaw and high-precipitation events could be problematic in terms of both sampling and interpreting the results.

In the River Vantaa and its tributaries (a 203-km-long river channel altogether), around 370 GW discharge sites were located with two catchment scale AIR surveys in two consecutive years. The identified interaction locations in the proximity of 12 municipal water intake plants during the low-flow seasons should be considered as potential risk areas for water supply during flood periods and/or with high pumping rates and taken under consideration in water resources management.

This work revealed that the GW−SW interactions are a far more general phenomenon in the studied catchments than has thus far been acknowledged, and these two resources should be integrated as one entity in hydrological studies. The GW−SW interaction should be taken account in water resources management, especially in changing climate conditions. This work highlighted the importance of an integrated approach that applied detailed local field measurements combined with chemical and isotopic sampling, as well as AIR surveys on the catchment scale.

Tiivistelmä (in Finnish)

Pohja- ja pintavettä on aikaisemmissa hydrologisissa ja hydrogeologisissa tutkimuksissa tarkasteltu erillisinä vesivarastoina. Tämä perinteinen lähestymistapa on sekä aliarvioinut pohjavesi–pintavesi vuorovaikutuksen yleisyyttä että yksinkertaistanut vesivarojen hallinnoimiseen liittyviä tekijöitä. Tässä väitöskirjatyössä selvitettiin aikaisemmin huonosti tunnettua pohjavesi–pintavesi vuorovaikutusta Pyhäjärven ja Vantaanjoen valuma-alueilla. Tutkimuksessa hyödynnettiin fysikaalisia, kemiallisia (pääionikoostumus, liuennut silikaatti, happi- ja vetyisotoopit) sekä termisiä menetelmiä, erityisesti helikopterista toteutettua lämpökamerakuvausta. Tutkimuksessa pyrittiin paikantamaan vuorovaikutuskohdat, selvittämään vuorovaikutuksen voimakkuus ja laajuus, arvioimaan käytettyjen tutkimusmenetelmien soveltuvuutta sekä hankkimaan perustietoa kemiallisten muuttujien vuodenaikaisesta vaihtelusta tutkituilla valuma-alueilla sekä tarjoamaan menetelmiä aikaisempaa kokonaisvaltaisemman vesienhallinnan tueksi.

Pyhäjärven valuma-alueella kenttätutkimukset osoittivat pohjaveden purkautumisen suoraan järveen tapahtuvan pääasiassa järven koillisrannan 10 km pituisella osuudella ja liittyvän harjumuodostumiin. Pohjaveden purkautumisnopeus vaihteli paikallisesti paljon järven heterogeenisestä pohja-aineksesta johtuen. Eri menetelmillä saadut tulokset tukivat toisiaan ja vahvistivat pohjaveden purkautuvan järveen koillisrannalla, mutta myös järviveden imeytyvän akviferiin järven pohjoiskulmassa.

Vuoden kestävä seurantaohjelma toi perustietoa veden stabiilien isotooppien ja hydrogeokemiallisten muuttujien vuodenaikaisvaihtelusta Pyhäjärven valuma-alueella. Veden peruskemiassa, isotooppisuhteissa ja liuenneen silikaatin pitoisuuksissa havaittiin voimakas vuodenaikainen vaihtelu vesistön eri osissa. Tätä saatua tietoa vuodenaikaisvaihtelun systematiikasta voidaan hyödyntää pohjavesi–pintavesi vuorovaikutustutkimuksissa pohjoisilla alueilla. Kevätsulannan ja rankkasateiden aikana kerätyt näytteet voivat olla sekä näytteenotollisesti ongelmallisia että tulkinnallisesti moniselitteisiä.

Vantaanjoessa ja sen sivu-uomissa tunnistettiin 370 pohjaveden purkautumispaikkaa kahtena perättäisenä vuotena lennetyissä lämpökamerakuvauksessa. Kunnallisten vesilaitosten läheisyydessä havaittuja vuorovaikutuspaikkoja voidaan pitää potentiaalisina riskeinä vedenottamoille sekä tulva-aikoina että alivirtaamakaudella suurilla pumppausmäärillä, ja vuorovaikutuspaikat tulisi ottaa huomioon vesivarojen hallinnassa muuttuvissa ilmasto-oloissa.

Tämä työ havainnollistaa pohjavesi–pintavesi vuorovaikutuksen olevan paljon aikaisemmin luultua yleisempää tutkituilla valuma-alueilla. Tutkimus osoitti, että vesivarojen hallinnassa tulisi pyrkiä aikaisempaa kokonaisvaltaisempaan lähestymistapaan. Vuorovaikutus on dynaaminen ilmiö sekä ajallisesti että paikallisesti, ja se myös vaihtelee suuruudeltaan ja suunnaltaan. Tulevaisuudessa muuttuvat ilmasto-olosuhteet tulevat korostamaan kokonaisvaltaisen tutkimusnäkökannan tarpeellisuutta vesivarojen hallinnassa. Tämä väitöskirjatyö korostaa useamman tutkimusmenetelmän samanaikaisesta käyttämisestä saatavaa hyötyä.

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Contents

List of original publications

This thesis is based on the following publications:

- I Rautio, A. & Korkka-Niemi, K. 2011. Characterization of groundwater-lake water interactions at Pyhäjärvi, a lake in SW Finland. Boreal Env. Res. 16, 363–380.
- II Korkka-Niemi, K., Kivimäki, A.-L., Lahti, K., Nygård, M., Rautio, A., Salonen V.-P. & Pellikka, P. 2012. Observations on groundwater–surface water interaction at River Vantaa, Finland. Management of Env. Quality 23, 222–231.
- III Rautio, A. & Korkka-Niemi, K. 2015. Chemical and isotopic tracers indicating groundwater/surface-water interaction within a boreal lake catchment in Finland. Hydrogeol. J. 23, 687–705.
- IV Rautio, A., Kivimäki, A.-L., Korkka-Niemi, K., Nygård, M., Salonen, V.-P., Lahti, K. & Vahtera, H. Vulnerability of groundwater resources to interaction with river water in a boreal catchment. Hydrol. Earth Syst. Sci. (submitted to Hydrol. Earth Syst. Sci. Discuss.).

The publications are referred to in the text by their roman numerals.

Author's contribution

- I. Mainly designed and performed the field study. Wrote the paper and prepared the figures, which were commented on by the co-author.
- II. Designed and performed the fieldwork with the co-authors. Analysed the samples. Wrote part of the text and prepared some of the figures in the paper.
- III. Mainly designed the study and performed the fieldwork. Analysed the water samples, interpreted the results, and wrote the paper, which was commented on by the co-author.
- IV. Designed and performed the fieldwork with the co-authors. Analysed the samples and AIR data. Interpreted the results and mainly wrote the paper and prepared the figures, which were then commented on by the co-authors.

Abbreviations

GW	Groundwater
SW	Surface water
DGW	Discharging/discharged groundwater
LW	Lake water
RW	River water
AIR	Aerial infrared
EC	Electrical conductivity
GDE	Groundwater-dependent ecosystem
GDTE	Groundwater-dependent terrestrial ecosystem
GDSE	Groundwater-dependent surface water ecosystem
TIR	Thermal infrared

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1. Introduction

1.1. Integrated approach in water resource management

The management of water resources in Finland has traditionally focused on either SW or GW bodies, and interactions between the water resources have not been systematically studied. However, it is apparent that nearly all SW bodies (lakes, rivers, wetlands) interact with GW (Winter et al. 1998), and the exchange between GW and SW is one of the most important processes in most watersheds (Hayashi & Rosenberry 2002, Rosenberry 2003). The management of one component of the hydrological system is usually only partially effective, because each hydrological component is in continuing interaction with others, and the development or contamination of one also commonly affects the others (Winter et al. 1998, Rosenberry & LaBaugh 2008).

In Finland, the public water supply mainly relies on GW, and it is generally assumed that GW is safe and clean for consumption without treatment. GW quality has usually been good and constant, while SW quality has been more variable, and some issues with decreased water quality have existed (Silander et al. 2006, Suhonen & Rantakokko, 2006). However, contaminated SW might form part of the source water in GW abstraction wells near the stream, and treatment or filtration of GW is therefore needed (Winter et al. 1998). Unconfined shallow esker aquifers form the foundation for large-scale water supply in Finland (Britschgi et al. 2009), and also support GW-dependent ecosystems (GDEs) (Kløve et al. 2011). According to Winter et al. (1998), GW−SW interactions have a major role in affecting chemical and biological processes in SW bodies, and the water quality of the hydrological system is therefore influenced if variables such as pH, temperature and dissolved oxygen are altered. Winter et al. (1998) concluded that DGW can have major effects on aquatic environments, therefore, changes in natural GW−SW exchange processes caused by human activities can potentially degrade the aquatic environment.

GW−SW interactions will be sensitive to climate variability, as the shallow aquifers responsible for the majority of GW−SW interactions are also the most sensitive ones (Winter et al. 1998). The impacts of climate change will not be uniform within Finland, as flooding will decrease in some parts of the country but increase due to the increased precipitation in central lakes and their outflow rivers, as well as in some southern watersheds (Veijalainen et al. 2010). The frequency of summer floods due to the extreme precipitation and of winter floods due to mild winters is expected to increase in southern Finland (Veijalainen et al. 2009). Statistical analysis of the frequency and intensity of floods in Finland during the last 50 years indicates that the frequency of winter floods has already increased throughout the country. In northern Finland, winter floods mainly occur in December, whereas in southern Finland, floods can be witnessed throughout the winter months (Kuusisto 2015). The potential impacts of climate variability and climate change on SWs have been studied in detail, but little is known about how GW will respond to climate change coupled with human activities (Green et al. 2011, Holman 2006, Bovolo et al. 2009), and the projections of the direct impacts of climate change on GW systems are highly uncertain (Taylor et al. 2013). GW recharge projections are closely related to projected changes in precipitation, and these indicate an increase in recharge in Northern Europe (Taylor et al. 2013). As the GW and SW resources change, so will the GW−SW interactions. The changes in GW−SW interactions could result in changes in river flows, the degradation of GDEs, GW droughts, GW-induced floods (indirect overflow as the result of GW recharge to exceeding store capacity of aquifer; Négrel & Petelet-Giraud 2005), the mobilization of pollutants and saline intrusion of coastal aquifers.

Recognition of GDEs in the European Union (EU) is as important as GW quality and quantity for sustainable GW management (Danielopol et al. 2004). GDEs are endangered and valuable ecosystems, and the EU Groundwater Directive requires them to be characterized to define their quality status (EC 2006). GW-dependent terrestrial ecosystems (GDTEs) and GW-dependent surface water ecosystems (GDSEs) are included as part of the national classification of exploitable aquifers in Finland, and these aquifers supporting the terrestrial or SW ecosystems will be classified as E-class in approved legislation (Government of Finland 2014). GDEs can be found where GW directly or indirectly sustains ecosystems by providing them with a stable water flow, temperature or chemical environment (Winter et al. 1998, Kløve et al. 2011).

Water resources are difficult to manage as one entity due to the multiple-scale of interactions, their complexity, the difficulty in defining the boundaries of GW watersheds, superimposed GW flow systems and the shifting of GW divides in response to the dynamic climate and precipitation (Winter et al. 2003). To manage a catchment as a single resource, the small-scale processes need to be understood, and their integration and scaling up lead to a broader understanding of the catchment (Rosenberry et al. 2003). This understanding is needed by environmental agencies to undertake more holistic watershed planning and management of resources (Winter et al. 1998). The integration of multi-scale results includes uncertainty, which is inherited by models based on these data. The need for GW protection from contamination within vulnerable aquifers is widely recognized, but the situation can be the opposite. For example, GW having high nutrient concentrations increases the eutrophication of the receiving SW body (Belanger et. al 1985, Ito et al. 2007). Furthermore, severe contamination of a GW body with persistent contaminants can affect SW quality, leading to damage to the aquatic flora, microorganisms and fish species (Hancock et al. 2005). More integrated water supply management practices are needed in order to secure the water supply and sustain the biodiversity of GDEs in future.

1.2. Groundwater−surface water interactions

GW−SW interaction studies have a history of over a century, starting from studies dealing with alluvial aquifer and stream water (Boussinesq 1877). Since then, the research has encompassed a wide variety of research questions in different environments, from mountains to the sea (Winter 1995). The discipline is continuously developing via technical progress in monitoring devices, remote sensing applications and software, and the research itself has moved towards a more interdisciplinary approach (Hayashi & Rosenberry 2002).

GW−SW interactions are complex and exchange rates are both spatially and temporally highly variable (Winter et al. 1998), depending on shoreline and bed substrates, aquifer characteristics, topography and meteorological conditions (Schneider et al. 2005, Rosenberry & LaBaugh 2008).

According to Winter et al. (1998) lakes can interact with aquifers by receiving GW discharge throughout their bed, recharging GW throughout their bed but probably the majority of lakes receiving GW inflow through part of their bed and recharging GW through the other parts.

The seepage meter approach (Lee 1977) has provided information on both the spatial variability and distribution of seepage flux rates and amounts into lakes (McBride & Plannkuch 1975, Brock et al. 1982, Woessner & Sullivan 1984, Schafran & Driscoll 1990, Shaw & Prepas 1990a, Schneider et al. 2005, Kidmose et al. 2011, Ommen et al. 2012, Kidmose et al. 2013). Many studies have found connections between the seepage fluxes and lake substrate (Krabbenhoft & Anderson 1986, Schafran & Driscoll 1990, Guyonnet 1991, Kidmose et al. 2011). However, spatial variability in seepage fluxes is not always straightforwardly connected to the substrate material, as Schneider et al. (2005) demonstrated. They observed that localized influences of the substrate were overridden by strong hydraulic gradients connected to the complex GW system. Moreover, large rainfall events and snowmelt can increase the measured seepage fluxes (Shawn & Prepas 1990a, Sebestyen & Schneider 2001, Schneider et al. 2005), and temporal variability in GW seepage rates has been observed (Downing & Peterka 1978, Connor & Belanger 1981, Kenoyer & Anderson 1989, Shaw & Prepas 1990a, Sebestyen & Schneider 2001, Rosenberry & Morin 2004).

Large lakes are more likely than small lakes to exhibit variation in shoreline substrates, aquifer characteristics, topography or meteorological conditions that influence GW seepage processes (Schneider et al. 2005). Previous studies on large lakes have revealed considerable variability in GW contributions, with some having negligible GW exchange (Lenters 2004), some being dominated by GW (Schwalb et al. 1999), and others having a variable net GW flux varying from partial GW discharge (Zacharias et al. 2003) to partial recharge (Ayenew & Gebreegziabher 2006). Hayashi and Rosenberry (2002) found that GW discharges to a lake might have a significant role locally in shaping the shore environment through direct or indirect effects on environmental factors, even if the net GW flux is a relatively small component of the lake's water balance.

River channel interactions with underlying the aquifer can be classified into gaining, losing, parallel flow and flow-through (Winter 1998, Woessner 1998), and they can vary through time within a year (Winter 1998). GW–LW interactions have the following fundamental differences compared to GW–river water (RW) interactions: the water levels of lakes are rather constant, and the bank storage effect therefore has smaller importance in lakes; there is an absence of hyporheic exchange flows in lakes; evaporation generally has a greater effect on lakes; the magnitude of turbulent mixing is smaller in lakes; and the volumes of organic deposits are commonly greater in lakes (Winter et al. 1998).

Evidently, discharging GW (DGW) has an important role in maintaining stream flow, thermal buffering, water quality and providing a beneficial habitat for fish and freshwater aquatic life in SW bodies (Hansen 1975, Kenoyer & Anderson 1989, Stanford & Ward 1993, Sinokrot et al. 1995, Brunke & Gonser 1997, Boulton et al. 1998, Woessner 2000, Hayashi & Rosenberry 2002, Sebestyen & Schneider 2004, Loheide & Gorelick 2006).

The hyporheic zone was defined in 1993 by White as the saturated interstitial space below the stream bed and adjacent stream banks, containing a proportion of the channel water. The hyporheic zone provides a unique environment that differs significantly from the surrounding GW and SW, and is highly active biogeochemically in the conversion of nutrients and attenuation of pollutants (Triska et al. 1989a,b). It is an important habitat and refuge for highly specialized organisms (Stanford & Ward 1998). The hyporheic zone is a critical component of stream ecosystems, and more interdisciplinary research has focused on this interface due the close interrelation between the ecology, biogeochemistry and hydrology.

1.3. Research aims and hypothesis

The main aim of this thesis was (1) to identify GW−SW interactions and gain a general understanding of their significance in the Lake Pyhäjärvi and River Vantaa catchments (Fig. 1). Various methods (thermal, physical, isotopic, chemical tracers) were used to investigate the interactions in different geological environments and at different spatial research scales.

The second objective was (2) to define the most applicable methods to investigate the exchange of GW and SW bodies in the snow-type catchments. The multi-method approach was used to achieve a reliable and comprehensive understanding of this exchange and its commonness, and to assess the applicability of the methods in two catchments with different properties and dimensions.

The third aim was (3) to provide baseline data on isotopic and geochemical patterns in the hydrological cycle with monitoring survey data and to provide essential information on the optimal sampling time in GW–SW interaction studies in the boreal snow-type catchments with distinct seasons. Such baseline data and evaluation of the seasonality effect will also be useful in other northern high-latitude regions. The isotopic composition of Finnish GW and atmospheric precipitation, as well as their seasonal variation, are known after Kortelainen and Karhu (2004). However, available data on the isotopic composition of SW is both spatially and temporally limited, and more detailed information is needed on the effect of strong seasonality on geochemical and stable isotopic patterns of different SW bodies on the catchment scale, in order to be able to use them as tracers for estimating GW–SW interactions in northern high-latitude regions.

The application target of the study was (4) to improve the general understanding of GW−SW interactions and the potential vulnerability of municipal abstraction wells due to the infiltration of SW, potentially affecting quality of the GW utilized by waterworks.

The thesis hypothesis was that GW–SW exchange could be more general phenomenon and important factor affecting the quality of shallow aquifers and SW bodies as thus far has been acknowledged in studied catchments. Also, the thesis hypothesis that GW–SW exchange could be an important factor affecting the quality of water in municipal water intake plants, where a hydraulic connection between the SW body and the aquifer exists. Many GW abstraction wells are located in close proximity to main river channels or lake shorelines and are potentially vulnerable to RW contamination during high peak flow or LW infiltration through the shoreline sediments. The high pumping rates of intake wells close to SW bodies can also lead to the contamination of the wells during low flow conditions. Flooding and heavy rain have the potential to induce the contamination of municipal water extraction wells via both overland flows entering the wells and bank infiltration into the aquifer.

1.4. Research motivation

Paper I was motivated by the need to evaluate and quantify the GW flux into Lake Pyhäjärvi (Fig. 1.) Therefore, different methods were tested to find the most applicable ones for working in the Lake Pyhäjärvi study area. The study was also motivated by the need to better understand the hydraulic connections between the lake and two municipal water intake plants with pumping wells close to the lake shoreline.

The motivation of Paper II, focused on the large River Vantaa catchment (Fig. 1), was (1) to identify the sections and branches of river systems where significant hydraulic connections between GW and RW exist, and (2) to test applicable research methods in GW–RW interaction studies in studied catchment.

The motivation of Paper III was to assess the applicability and validity of the major ions, $\delta^{18}O$, δD and DSi as tracers for estimating GW–SW interaction in different parts of the hydrological cycle (rivers, lake) in the Lake Pyhäjärvi catchment. Of particular interest was the applicability of DSi as a tracer to define the relative share of GW in the catchment. A further motivation of Paper III was to provide baseline data on the isotopic and geochemical patterns in the hydrological cycle with over one year of monitoring survey data in the boreal snow-type catchment.

The motivation of Paper IV was to gain a better understanding of aquifer−river channel interaction and the potential vulnerability of municipal water intake plants in the River Vantaa catchment. The motivation was also improve the general understanding of GW−RW interactions in the boreal snow-type catchment under different weather conditions, potentially affecting the quality of GW utilized by waterworks. Moreover, the temporal and spatial variations in GW−RW interactions between two consecutive years were studied and compared.

2. Summaries of the papers

In Paper I, the applicability of the physical and chemical methods used to locate GW−SW interaction sites were compared and the results obtained from Lake Pyhäjärvi were evaluated. The study focused on a 10-km section of the NE shoreline of Lake Pyhäjärvi, where the potential GW discharge areas are associated with esker aquifers. This study represented the first attempt in Finland to collect detailed observations on GW−SW interactions. The results from the various methods correlated and confirmed the GW discharge into Lake Pyhäjärvi at the NE shoreline.

In Paper II, the focus was on identifying the GW discharge locations at the catchment scale with a low-altitude aerial infrared (AIR) survey in the River Vantaa and its tributaries, and with isotopic tracers and field measurements to verify the observed sites. The study was the first attempt to identify and locate the GW−SW interactions in a river system at the catchment scale in Finland. The field measurements agreed with the AIR survey results and highlighted the abundance of GW discharge locations in the study catchment. The commonness of GW−SW exchange in the River Vantaa catchment indicated that this water resource connection may have a far more significant impact on water quality and quantity than has thus far been acknowledged. The study also noted that the observed GW discharge sites should be considered as potential risk areas during flood periods (GW quality deterioration due to bank infiltration of RW), as a preferential flow path between the river and aquifer exists.

In Paper III, the Lake Pyhäjärvi study was extended to the catchment scale with isotopic ($\delta^{18}O$, δD) and chemical tracers (dissolved silica (DSi), major ion composition), which were used to indicate GW−SW interaction between the

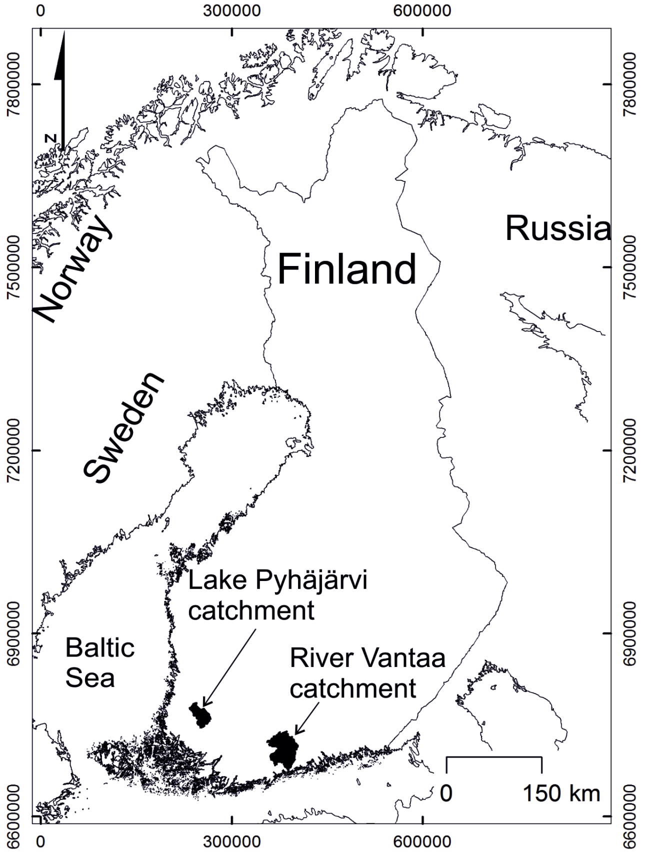

Figure 1. Location of the studied Lake Pyhäjärvi and River Vantaa catchments. (Basemap Database © National Land Survey of Finland 2010; Watershed Database © SYKE 2010).

aquifers, the rivers and a lake. The baseline data on isotopic patterns and hydrogeochemistry in the hydrological cycle were provided by a one-year monitoring survey in this rural snow-type catchment area. The stable isotope composition and DSi concentrations of different water types revealed significant differences and proved to be useful tracers, and thus the proportions of GW could be calculated in the rivers, the lake inshore area and in GW abstraction wells. DSi appeared to be a significant tracer in the river environment, whereas stable isotopes were more applicable in the lake environment. The study demonstrated both the GW discharge into the SW bodies and also the infiltration of the LW into the aquifer. This infiltration of LW into the intake wells presents a potential risk for household water quality. In GW–SW interaction studies, the spring thaw and high-precipitation events could be problematic, in terms of both sampling and interpretation of the results.

Paper IV evaluates the vulnerability of GW in the urban catchment of the River Vantaa. An AIR survey was conducted to identify the hydraulic connections between the aquifers and rivers, and to map spatial surface temperature patterns along the boreal rivers. Stable isotopes, chemical tracers and field studies were used to verify the observed GW discharge into the river system. Altogether, around 370 GW discharge sites were located along the main river channel and its tributaries. Two consecutive AIR surveys revealed the spatial and temporal changes in GW discharge sites on the catchment scale.

The longitudinal RW temperature patterns and the isotopic and DSi composition of the studied rivers differed noticeably. The observed significant vertical thermal stratification could lead to an underestimation of the extent and magnitude of the GW discharge, and should be taken into account in AIR surveys during low-flow conditions in the summer. The results of this study support the use of the multi-method approach (AIR and hydrogeochemical variables) to survey and confirm GW–RW interaction as well as to assess the potential vulnerability of intake plants in proximity of main stream channels due to the RW infiltration. The interaction locations in the proximity of 12 municipal water intake plants during the low-flow seasons should be considered as potential risk areas for water intake plants during flood periods, and taken under consideration in river basin and water resources management under changing climatic situations in the future. The study emphasized the ubiquity of GW−SW exchange processes and the need for more integrated water resource management in the future.

3. Description of the study sites

3.1. Lake Pyhäjärvi catchment

Lake Pyhäjärvi is highly valuable, and the largest lake (155 km^2) in southwestern Finland (Figs 1 and 2). It is classified as a mesotrophic lake and has been intensively studied for decades. In the 1970s and 1980s, Lake Pyhäjärvi was impacted by eutrophication associated with high levels of nutrient loading from the catchment

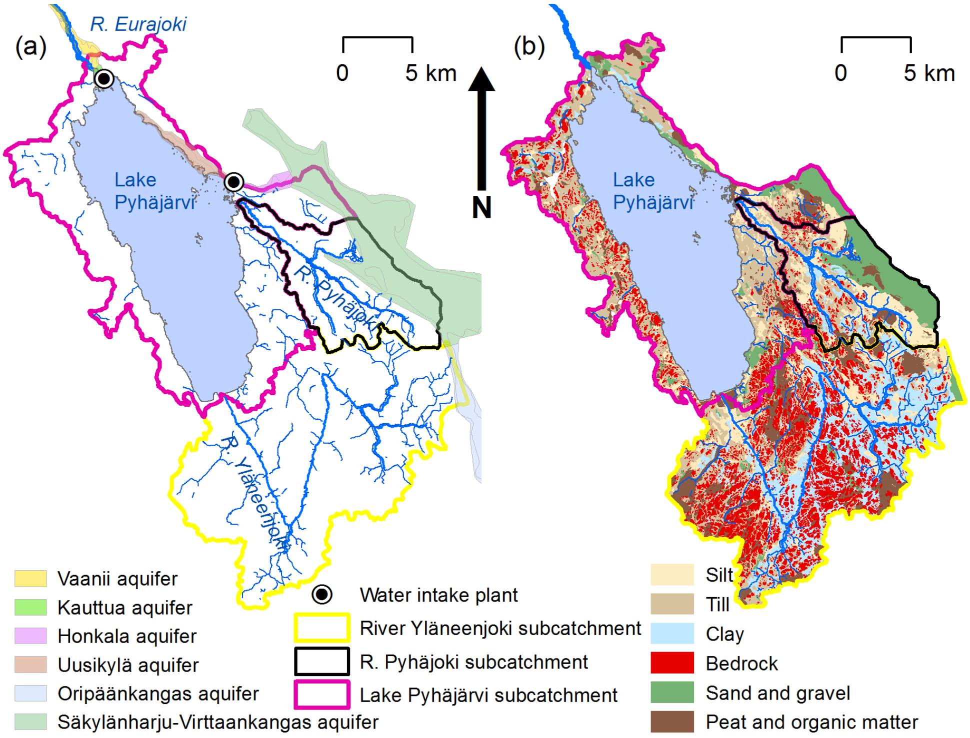

Figure 2. (a) The Lake Pyhäjärvi catchment and its subcatchments. (b) Quaternary deposits in the Lake Pyhäjärvi catchment. (Basemap Database © National Land Survey of Finland 2010; Quaternary Deposits Database © Geological Survey of Finland 2008; Watershed Database © SYKE 2010). Modified from Paper III.

(Räsänen et al. 1992). Hence, the lake and the catchment have been an object of comprehensive restoration since the 1990s (Ventelä et al. 2007, 2011, Kirkkala 2013). Lake Pyhäjärvi is used for recreational activities, as a commercial fishery, and as a water source for local industrial processes. However, all these activities have become seriously threatened by eutrophication during recent decades (Ventelä et al. 2007). Furthermore, the restoration activities have been hindered by increasing temperatures, a shortened ice-cover period and an increased winter nutrient load from the catchment related to the predicted climate change (Ventelä et al. 2011).

The Lake Pyhäjärvi catchment has a large central lake (Fig. 2). The drainage basin area including the lake is 616 km^2, which is quite a small area compared with the surface area of the lake (Fig. 2). Lake Pyhäjärvi is shallow, the mean depth of the lake being 5.5 m, and the only depression in the lake is 26 m deep and is located on the western side. Two major rivers discharge into Lake Pyhäjärvi, the Rivers Pyhäjoki and Yläneenjoki (Fig. 2). The River Eurajoki, on the northern corner of the lake, forms the only outflow from the lake (Fig. 2).

The Precambrian bedrock is covered by a layer of unconsolidated sediments varying in thickness from a few to some tens of metres. The glacial sediments of the research area consist of deposits formed during the Late Weichselian deglaciation of the Scandinavian Ice Sheet and include till, sand, gravel, and glacial and post-glacial clay deposits (Fig. 2b). Esker aquifers are connected to the northern and northeastern sides of Lake Pyhäjärvi (Fig. 2a). These eskers

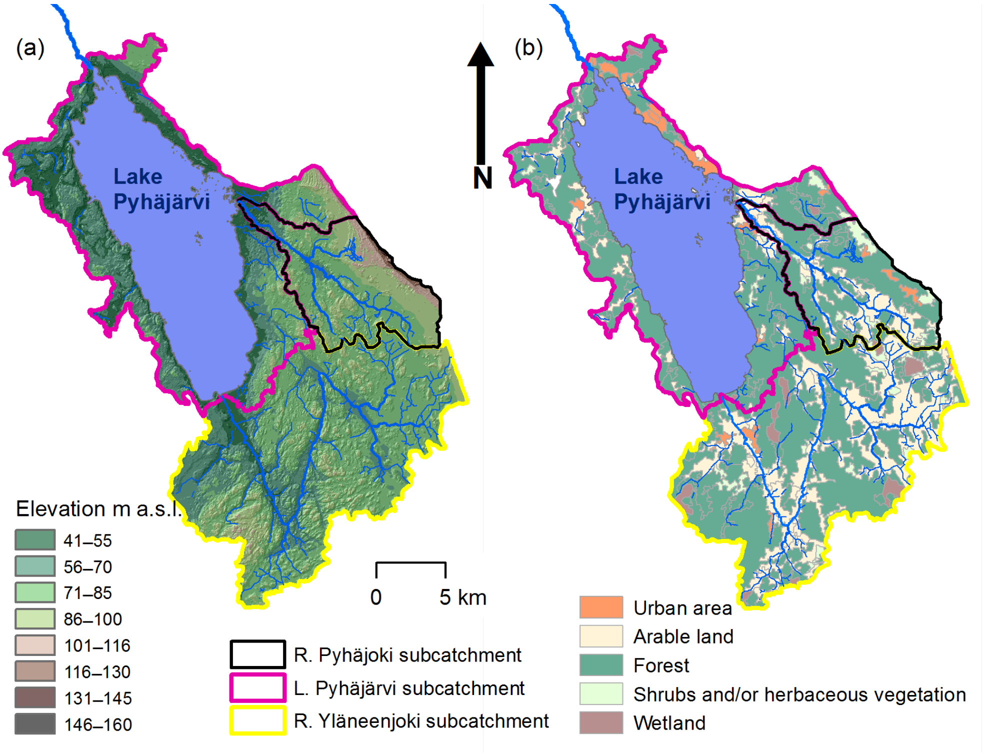

Figure 3. (a) Elevation model of the Lake Pyhäjärvi catchment. (b) Land use in the Lake Pyhäjärvi catchment. (Basemap Database © National Land Survey of Finland 2010; Watershed Database © SYKE 2010; Topographic Databas © National Land Survey of Finland 2010; Corine land cover © National Land Survey of Finland 2010). Modified from Paper III.

can enhance the GW discharge to the SW and contribute to the exchange between GW and SW due to the coarse grained esker sediments with a high permeability. In the River Pyhäjoki subcatchment, the soils mainly consist of sand, silt and till, whereas the soils of the River Yläneenjoki subcatchment mainly consist of clay, tills and peat (Fig. 2b). The subcatchments of the Rivers Yläneenjoki and Pyhäjoki are located on coastal plains. The landscape topography ranges in elevation from 40 m (the outlet of the River Eurajoki) to 145 m above sea level (a.s.l.) (Virttaankangas complex) (Fig. 3a). The average lake level is 44.9 m a.s.l., and the level is regulated via a dam at the outflowing River Eurajoki.

There are two water intake plants for municipal supply purposes with pumping wells close to the lake shoreline (Fig. 2a). The Lohiluoma water intake plant on the Kauttua aquifer is located in the northernmost corner of Lake Pyhäjärvi (Fig. 2a). The Honkala intake plant in the easternmost part of the lake has been closed since 1998 because of PCE contamination (Artimo 2002) (Fig. 2a). A more detailed study site description is provided in Papers I and III.

3.2. River Vantaa catchment

The River Vantaa is one of the water reserves for Finland's capital region (ca. 1 million inhabitants) (Fig. 4a). The total catchment area of the River Vantaa is 1 685 km^2. The water quality of the River Vantaa and its tributaries has regularly been monitored since the 1970s in order to identify the incoming load of nutrients and contaminants. During heavy rains and the spring thaw, the RW has generally high nutrient concentrations and poor hygienic quality in the catchment (Vahtera

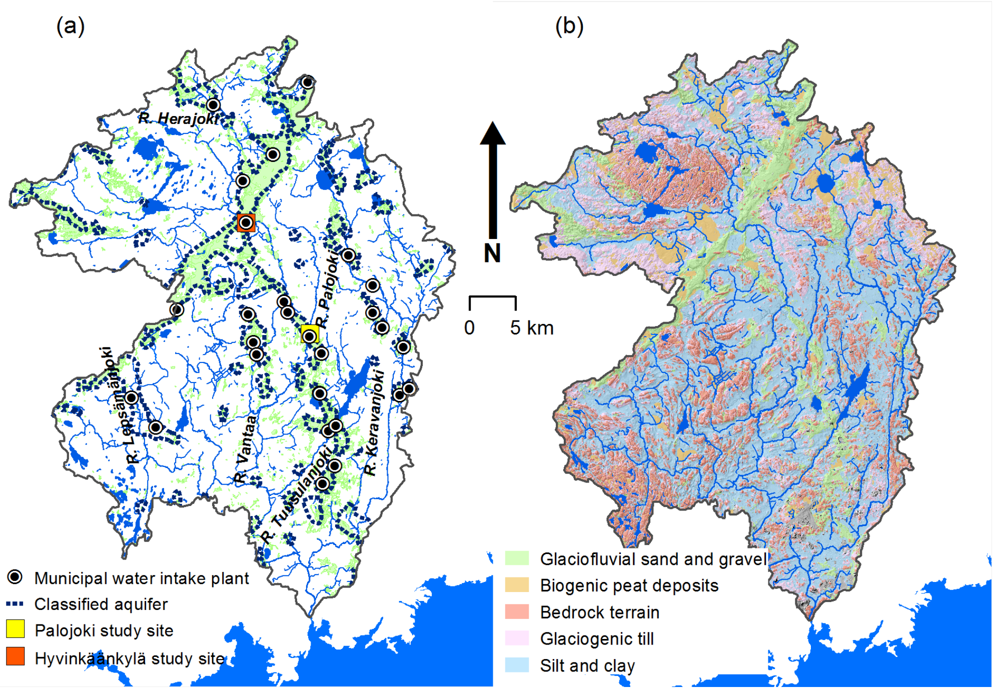

Figure 4. (a) The study sites, municipal water intake plants and classified aquifers in of the River Vantaa catchment. In Finland, mapped aquifers are classified into three classes according to their priority. (b) Quaternary deposits in the River Vantaa catchment. (Basemap Database © National Land Survey of Finland 2010; Quaternary Deposit Database © Geological Survey of Finland 2008; Watershed Database © SYKE 2010). Modified from Paper IV.

et al. 2014). Within the catchment, 29 aquifers in close vicinity to river beds are classified as important ones that are used for municipal supply (Fig. 4a). The relatively high flooding sensitivity of the studied catchment is related to large fluctuations in the river flow rates, the low percentage cover of lakes, the high relative percentage of headwater lakes, the flat topography and generally poor infiltration rate of the soils (Mäntylä & Saarelainen 2008) (Figs 4 and 5). The continuous development and construction of new areas in the densely populated capital region has additionally increased the flood risk during peak flow periods (Suhonen & Rantakokko 2006) (Fig. 5b). In the studied river catchment, this has been acknowledged in a number of recent surveys in which riparian areas vulnerable to floods have been identified (i.a. Mäntylä & Saarelainen 2008).

The dominant geomorphological relief types are bedrock terrain and glacigenic deposits forming cover-moraine sheets and end-moraine ridges in the northern part of the study area where the elevation ranges from +100 m to +160 m a.s.l. (Tikkanen 1989) (Fig. 5). The majority of the central and southern parts of the catchment are lower than +80 m a.s.l. due to the relatively smooth elevation decrease towards the south. Quaternary marine and lacustrine silt and clay cover 39% of the entire catchment area and dominate the lower areas (Helsinki-Uusimaa Region 1997) (Fig. 4b). Riverbeds generally pass along bedrock fracture zones covered by thick clay layers and only sporadically overlap glaciofluvial sand and gravel formations (Tikkanen 1989). Land use varies between the River Vantaa and its tributaries, as the headwater

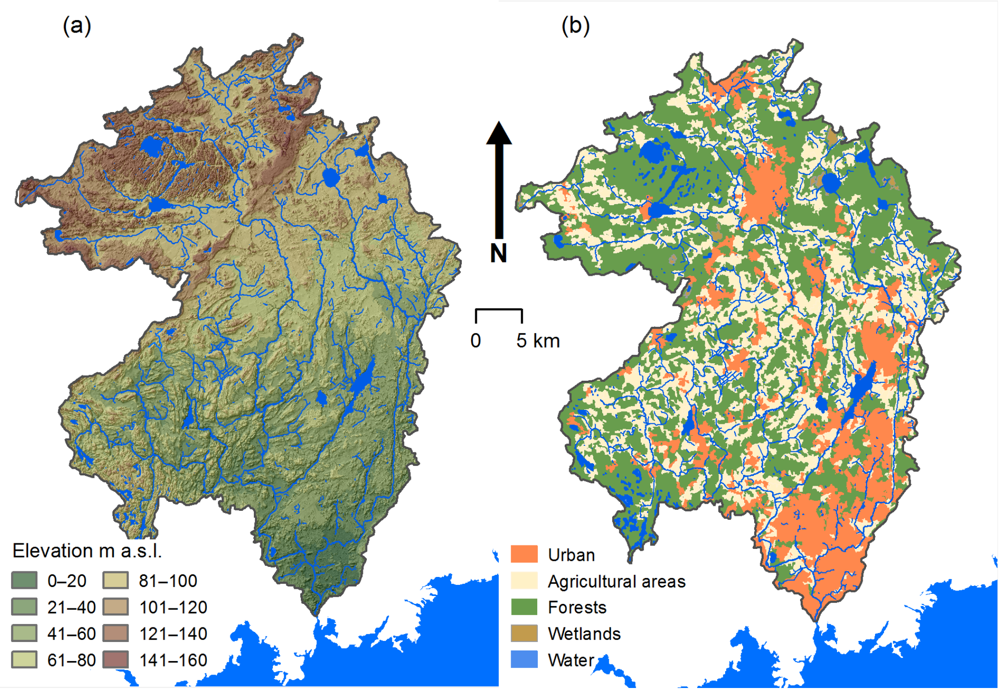

Figure 5. (a) Elevation model of the River Vantaa catchment. (b) Land use in the River Vantaa catchment. (Basemap Database © National Land Survey of Finland 2010; Watershed Database © SYKE 2010; Topographic Database © National Land Survey of Finland 2010; Corine land cover © National Land Survey of Finland 2010). Modified from Paper IV.

areas are dominated by forestry and the southern areas by urban land use (Fig. 5b).

The major differences between two studied catchments are:

- The River Vantaa has a catchment area (1 685 km^2) considerably larger than that of Lake Pyhäjärvi (616 km^2) (Fig. 1).
- The River Vantaa has a considerably lower percentage cover of lakes (2.25%), the largest lake having a total area of 6.0 km^2 (Seuna 1971, Ekholm 1993) compared to Lake Pyhäjärvi (26%).
- The River Vantaa has a considerably higher percentage of urban land use (20%) compared to Lake Pyhäjärvi (2.4%) (Figs 3b and 5b).
- The Lake Pyhäjärvi is dominated by till (33%) compared to River Vantaa, which is dominated by marine and lacustrine silt and clay (39%) (Figs 2b and 4b).

The major similarities between two studied catchments are:

- The climate: The mean annual air temperature is close to 5.0 °C in the studied catchments (Finnish Meteorological Institute 1991). Approximately 10–20% of the precipitation falls as snow in southern Finland (Karlsson 1986). The mean annual precipitation at the River Vantaa (670 mm a^{-1}) is slightly higher than at Lake Pyhäjärvi (app. 600 mm a^{-1}).
- The snow-type hydrology of studied boreal catchments are characterized by strong snow-dominated seasonality, and major floods can be caused by either snowmelt or heavy rain events (Veijalainen et al. 2010).
- The highest river flow rates typically occur during the spring and late autumn months due to snow melt (spring thaw) and heavy rains in the autumns.
- The surveyed rivers were slow to moderate flowing streams, and contained straight and meandering channel types in a gently undulating glacial landscape.
- Major GW reserves are associated with glaciofluvial eskers mainly hosting unconfined aquifers (Figs 2a and 4a). However, semi-confined or confined parts of aquifers also occur in places.

4. Materials and methods

Multiple methods were tested, as the geological environments, research scale and the prevailing conditions were highly variable. The methods are divided into three types: (1) thermal methods, (2) physical field methods and (3) chemical and isotopic tracers. The multi-method approach was used to achieve a reliable and comprehensive understanding of GW−SW exchange and its commonness, and to assess the applicability of the methods in two snow-type catchments with different properties and dimensions.

4.1. Thermal methods (I, II & IV)

In this work, temperature was used (1) to identify areas of discrete and diffuse discharge of GW into the rivers and the lake based on the temperature contrast between SW and GW, (2) to verify the GW−SW exchange between the SW and aquifers, and (3) to demonstrate the spatial distribution of seepage fluxes near the shoreline (for full details, see Papers I & IV). Temperature can be used as a GW−SW exchange tracer due to the relatively stable temperature of GW compared to diurnally and annually fluctuating SW temperatures (Stonestrom & Constantz 2003, Anderson 2005). GW discharge zones into a SW body have been located by searching for anomalies in temperature (e.g. Lee 1985, Silliman & Booth 1993, Conant 2004, Blume et al. 2013) near the sediment–water interface. Thermal methods require a sufficient flow through the substrate to allow advective processes to be significant relative to conductive temperature signals (Rosenberry & LaBaugh 2008). Temperature is a natural, robust, and easily measured and interpreted variable (Stonestrom & Constantz 2003).

4.1.1. Winter mapping (I)

The temperature of GW (4–8 °C in southern Finland) keeps shoreline areas of lakes and rivers unfrozen during winter if the DGW flux is high enough. Unfrozen and open water shoreline areas were mapped during one field campaign by skiing on the lake ice along a 15-km stretch of the NE shoreline of Lake Pyhäjärvi. It was based on visual observations of a lack of lake ice or weakened ice strength/thawing patterns of the ice-cover. This preliminary mapping was used as a guide for fieldwork in summer 2009.

4.1.2. River bed and lakebed temperature measurements (I, II &IV)

Lake-bed temperature measurements were performed from July to August in both catchments, when the annual maximum contrast between GW and SW temperatures (4–8 °C and 20–24 °C, respectively) exists and the conditions were most favorable for using temperature as a tracer (for full details, see Papers I, II & IV). A YSI model 600XLM-V2-M multiparameter probe (YSI Inc., Yellow Springs, Ohio, USA) was used to measure *in situ* temperature values near the sediment–water interface and in the SW column along the studied transects in the Lake Pyhäjärvi and River Vantaa catchments (for full details, see Papers I & IV). The sediment temperature measurements were performed 5 cm below the water–sediment surface with a stainless steel temperature probe (Therma Plus, Electronic Temperature instruments Ltd, Worthing, West Sussex, UK, accuracy ±0.10 °C). In addition, continuous temperature measurements of RW were taken to demonstrate the temporal variability in GW discharge into the river in the River Vantaa catchment (for full details, see Paper IV).

4.1.3. Aerial infrared surveys (II & IV)

AIR has proved to be a feasible method for identifying GW discharge locations in previous hydrological studies (e.g. Torgersen et al. 2001, Loheide & Gorelick 2006, Davis 2007, Conant & Mochnacz 2009, Loheide & Deitchman 2009). Furthermore, AIR provides a method for collecting spatially continuous patterns of river temperatures in an entire river over a short period of time (Faux et al. 2001, Torgersen et al. 2001, Cristea & Burges 2009, Dugdale et al. 2015).

In Finland, the conditions are most favorable for AIR studies from July to August, when the annual maximum temperature contrast exists between GW and RW. Altogether, the AIR surveys covered 203 km of rivers as well as the riparian areas alongside the channels of the River Vantaa and its tributaries during the low-flow period in 2010 and 2011 (Fig. 2 in Paper IV). The weather conditions were ideal for detecting GW discharge locations in summers 2010 and 2011 due to the preceding warm weather and low precipitation conditions. The technical details and designs of the AIR surveys in 2010 and 2011 have been reported in Papers II and IV, respectively.

The main difference between the AIR surveys in 2010 and 2011 was in the design. In 2010, the infrared camera (FLIR Thermo Vision A40) was mounted in a pod on the side of a helicopter together with a Nikon D1X digital camera. The results from first AIR survey were very promising and inspiring, and an improved AIR system was therefore developed (in the Department of Geosciences and Geography) (Fig. 6) to more efficiently address the challenges in river surveys. The improvements and adjustments to the system were (1) the simultaneous use of an HDR-CX700 digital video camera with an infrared camera and (2) the cameras being held in a near vertical position on the side of the helicopter. Later improvements allowed easier fine-scale adjustments to the flight path and altitude made visually by the pilot in cooperation with the FLIR operator. A third difference between the surveys was the flight altitude, as in 2011 the altitude was higher to capture both the rivers and a significant proportion of the riparian areas on either side of the channels. Both thermal cameras used in AIR surveys had a pixel resolution of 320 × 240, a spectral range of 7.5–13 µm and a field of view of 24 × 18 degrees. The FLIR system was capable of detecting temperature differences of ±0.08 °C with an accuracy of ±2.0 °C or ±2.0% of the reading, as reported by the manufacturer.

AIR surveys were mainly conducted in an upstream direction during the early afternoon hours in calm and cloudless weather conditions. Meteorological data on the air temperature and relative humidity during the aerial surveys were obtained from the two nearest weather stations. The flight altitude of 100–300 meters above grouond level (m a.g.s.) produced a ground resolution from 0.15 m to 0.5 m. The ground speed varied between 50 km h^{-1} and 90 km h^{-1}, depending on the stream width and intensity of meandering. The canopy cover from riparian vegetation ranged from nearly completely closed to wide open and varied within and between the rivers surveyed.

Figure 6. The low altitude aerial infrared system. (a) The on-board computer and remote control with LCD display. (b) A FLIR ThermaCAM P60 together with an HDR-CX700 digital video camera. (c) AIR surveys were acquired with A Raven R44 II helicopter. (d) The cameras held in a near vertical position on the side of the helicopter. Figures by Kirsti Korkka-Niemi. Modified from Rautio et al. 2014.

Reference measurements were collected as discrete manual measurements with a YSI 600 XLM-V2-M multiparameter probe simultaneously with AIR survey to compare the kinetic water temperature (T_k) measured 5 cm below the surface using a thermometer with the radiant water temperature (T_r) measured remotely using a thermal sensor in 2010 and 2011 (see full details from Paper IV).

In post-processing, the T_r values were calculated for the emissivity of natural water (0.96) and with inputs of air temperature, relative humidity and path length. The spatially continuous profiles of minimum radiant water temperature (T_{minr}) were produced by individually analyzing the thermal images and manually sampling the T_{minr} from each thermal image of the main stream channel, and selecting the lowest value of T_{minr} for each second. T_{minr} was selected to more efficiently localize the anomalous cold temperatures in the main stream channel than with extraction methods based on the median values of selected points or the histogram of contiguous water pixel temperatures (image sampling or weighted averages) used in previous studies (Torgersen et al. 2001, Cristea & Burges 2009) (see full details from Paper IV).

4.2. Physical field methods (I)

4.2.1. Seepage meter measurements (I)

Seepage meter measurements have been performed to quantify the seepage flux through lake beds (Lee 1977, Lee & Cherry 1978, Carr & Winter 1980, Shaw & Prepas 1990a, 1990b, Avery 1994, Duff et al. 1999, Kidmose et al. 2011, Ommen et al. 2012, Kidmose et al. 2013). Seepage measurements were performed in the Pyhäjärvi catchment in order to (1) verify the GW−SW exchange between the lake and aquifer, (2) define the spatial distribution of seepage fluxes near the shoreline, and (3) sample discharging GW for chemical and isotopic analysis in Lake Pyhäjärvi. The seepage meters used in this study were built based on the classic design of Lee (1977) with some slight modification (for full details, see Paper I). All four seepage meter designs including the half-barrel, collection bag and the connection hose between the barrel and bag were used at Lake Pyhäjärvi.

4.2.2. Mini-piezometers (I)

The mini-piezometer measurements were performed to (1) measure the head differences, (2) characterize the direction and magnitude of the vertical hydraulic gradient (VHG), and (3) collect water samples from the Lake Pyhäjärvi study site. The mini-piezometer design in Paper I consisted of a small-diameter translucent, plastic tube (ID 4 mm, OD 6 mm) ending in a screen and a short (length 5 cm, ID 10 mm, OD 12 mm) perforated section (approximately 14 holes 4 mm in diameter), surrounded by a suitably fine mesh (300 µm). Mini-piezometers were hand driven into the lakebed, using the bolt method described by Lee & Cherry (1978) (for full details, see Paper I).

4.3. Isotopic and chemical tracers (I, III & IV)

Isotopic and chemical tracers have been applied in different hydrologic studies for several decades. Here, isotopic and chemical tracers were applied to examine GW−SW interactions at both the local scale (Paper I) and the catchment scale (Papers III & IV). The tracers were used to (1) identify the GW–SW interaction in different parts of the hydrological cycle (river, lake) in the lake (Papers I & III) and in the river (Paper IV) catchments, (2) estimate the level of GW–SW interaction in different parts of the hydrological cycle (Papers III & IV) and (3) calculate the GW contributions for different water types (Paper III). A monitoring survey extending over one year was conducted to (4) provide baseline data on the isotopic and geochemical patterns (Paper III) and (5) estimate the applicability of isotopic and chemical tracers in defining GW–SW interaction in the hydrological cycle in the boreal snow-type catchment (Papers I, III & IV). Isotopic and chemical tracers were used to (6) gain a better understanding of aquifer–river channel interaction and the potential vulnerability of municipal water intake plants in the studied catchment (Paper IV), (7) improve the general understanding of GW–SW interactions in boreal catchments under changing climatic conditions, which will potentially affect the quality of GW utilized by waterworks (Papers III & V) and (8) evaluate the effect of exchange on the quality of the receiving water resource (Papers III & IV).

In this work, two sampling strategies were used at the catchment scale. In Lake Pyhäjärvi, the RW sampling points were evenly distributed between the headwater area and the river mouth. Samples were taken from LW, lake-shore water, intake wells, DGW and GW. Water samples were mainly taken at one-month intervals during the 15 monitoring months. Details of the sampling procedure and analysis methods are provided in Paper III. In River Vantaa catchment, by comparison, sampling was focused on locations where the riverbeds overlap the glaciofluvial deposits during low and high flow seasons. The sample locations at each study site were selected in order to detect changes in RW chemistry: (1) sample sites upstream from potential GW discharge to the river, (2) GW discharge sites based on the geological location (riverbed overlaps glacigenic sediments) and (3) sample sites downstream from GW discharge sites. Details of the sampling procedure and analysis methods are provided in Paper IV.

4.3.1. Electrical conductivity and pH measurements (I, III & IV)

GW discharge zones into the SW body have been located by searching for anomalies in electrical conductivity (EC) values (e.g. Lee 1985, Vanek & Lee 1991, Harvey et al. 1997) near the sediment–water interface. Fresh SW and more mineralized local GW commonly differ with respect to their EC levels and temperatures. EC and pH measurements were performed in order to (1) identify the GW discharge locations, (2) verify the GW−SW exchange between the SW and aquifers, (3) demonstrate the spatial distribution of seepage fluxes near the shoreline and (4) demonstrate the temporal variability in GW discharge into the river with continuous measurements in the River Vantaa catchment (for full details, see Papers I, III & IV). A YSI model 600XLM-V2-M multiparameter probe (YSI Inc., Yellow Springs, Ohio, USA) was used to measure in situ EC and pH values near the sediment–water interface and in the SW column along the studied transects in the Lake Pyhäjärvi and River Vantaa catchments (for full details, see Papers I, III & IV).

4.3.2. General water chemistry (III)

The major ion composition (Na, K, Ca, Mg, F, Cl, NO_3, SO_4), pH, EC and alkalinity were analysed to (1) study the main ion composition of different water types, (2) provide baseline data on the geochemical patterns in the hydrological cycle with over one year of monitoring survey data from the boreal snow-type catchment (Paper III) and (3) estimate the GW–SW interaction in different parts of the hydrological cycle (rivers, lake) in the snow-type lake catchment (Paper III) (for full details, see Paper III).

4.3.3. Stable isotopes (I, III & IV)

The method is based on isotopic fractionation between the lighter (^{16}O, ^{1}H) and heavier (^{18}O, D) species of oxygen and hydrogen. As water evaporates, the evaporated SW becomes relatively enriched in ^{18}O and D compared to the mean annual precipitation or shallow GW (Craig 1961); therefore, the evaporated isotope signature of LW can be used as a tracer in GW–LW interaction studies (Krabbenhoft et al. 1990). In precipitation, the δD and $\delta^{18}O$ values are strongly related following the Global Meteoric Water Line (GMWL) (Craig 1961). Studies on shallow GW in temperate climates have demonstrated that the isotope ratios of oxygen and hydrogen closely follow those in mean annual precipitation (Fritz et al. 1987, Ingraham & Taylor 1991, Clark & Fritz 1997).

Previous studies have used the stable isotopes to resolve the contributions from different water sources and other hydrologic processes to rivers (Rock & Mayer 2007, Koeniger et al. 2009, Brooks et al. 2012). Precipitation and GW are the main components of water in most rivers, and the stable isotopic composition of RW is the outcome of the temporally variable proportions of precipitation and GW, as well as changes in the isotopic composition of sources over time (Kendall & Coplen 2001). With increasing basin size, the isotopic compositions of rivers are increasingly affected by subsequent alterations in the different runoff components and precipitation, mixing with GW, and by evaporation (Kendall & Coplen 2001).

Isotopic tracers were used to (1) confirm the GW discharge to the lake and rivers (Papers I, III & IV), (2) examine the impacts of GW discharge on RW chemistry at the GW discharge locations identified with AIR in 2010 and 2011 (Paper IV), (3) estimate the fraction of GW in intake wells and shoreline water with a mass balance approach utilizing $\delta^{18}O$ in a binary system (Paper III) and (4) provide baseline data on the seasonal isotopic patterns at the catchment scale (Paper IV) and (5) compare the isotopic patterns of different rivers (Papers III & IV). The deuterium excess (*d*-excess) was calculated as an index of the evaporation effect and used to compare evaporation in different rivers (Papers III & IV).

4.3.4. Dissolved silica (III & IV)

DSi was selected as a tracer because of its near zero concentration in precipitation, whereas in GW the arithmetic mean DSi in shallow wells in Finland is 6.5 ppm (Lahermo et al. 2002). DSi concentrations are dependent on the GW residence time and the grain size of aquifer media (Sandborg 1993, Soveri et al. 2001). Streams show systematic variation in the DSi concentration as a function of flow, with higher concentrations under baseflow conditions and the lowest concentrations under high flow (Neal et al. 2005). Therefore, DSi could serve as a potential tracer to estimate the contribution of GW to river flow, as earlier observed by Hinton et al. (1994). Some previous studies have utilized DSi in different geological settings (oligotrophic temperate lake, karst water system, steep head water system) as a GW tracer (e.g. Hurley 1985, Asano et al. 2003, Gao et al. 2010).

DSi was used as parallel tracer with stable isotopes. In two papers (III & IV), the results of these tracers were compared to define their applicability in lacustrine and riverine environments. Similarly to stable isotopes, the DSi concentrations were used to (1) confirm the GW discharge to the lake and rivers (Papers III

& IV), (2) examine the impacts of GW discharge on RW chemistry at the GW discharge locations identified with AIR in 2010 and 2011 (Paper IV), (3) estimate the fraction of GW in intake wells, lake-shore water and rivers with a mass balance approach and (4) provide baseline data on annual silica patterns at the catchment scale (Paper III) and compare the silica patterns of different rivers.

4.3.5. Statistics (III & IV)

Statistical analyses (Excel 2010, STATISTICA 9.0 and AquaChem 2010.1) were performed with data on isotope and chemical analysis from the Lake Pyhäjärvi catchment. The variable distributions were studied and tested for normality and log-normality prior to the analysis, as suggested by Reimann & Filzmoser (2000). The non-parametric Mann-Whitney U-test for two unrelated or independent populations (Rock 1988, Ranta et al. 1991) was used to examine the differences in water chemistry in Lake Pyhäjärvi and River Vantaa catchments (full details in Papers III & IV). Principal component analysis (PCA) was conducted with the water chemistry variables to identify the variables related to specific geochemical or environmental processes and the importance of elements was evaluated by examining the factor loadings, communalities and eigenvalues (e.g. Frapporti 1994, Jayakumar & Siraz 1997, Korkka-Niemi 2001). The factor scores for the individual samples were used to examine the causative factors underlying the water chemistry (full details in Paper III).

5. Results

5.1. Thermal methods (I, II & IV)

5.1.1. Winter mapping (I)

Different types of unfrozen areas were detected along and further from the shoreline of Lake Pyhäjärvi (Fig. 7) (see full details in Paper I). Three types of area were detected, indicating GW discharge of some amount into Lake Pyhäjärvi: unfrozen shore without open water present, unfrozen shore and open water present along the shoreline (springs) and areas of soft and wet lake ice further from the shore (for full details, see Paper I) (Fig. 7).

5.1.2. River bed and lakebed temperature measurements (I, II, & IV)

The temperature measurements detected distinct temperature anomalies in the shoreline water and lake sediment temperatures, indicating several focused GW discharge areas having a lake bed sediment temperature lower than the surrounding area in Lake Pyhäjärvi (Fig. 7). The temperature and EC measurements at the selected field sites in the River Vantaa catchment are presented in the following section (5.1.3) together with AIR results. The shallow depths (5 cm) of the river bed temperature measurements may have influenced to the accuracy of mapping GW discharge sites as the shallow depth will decrease the reproducibility of measurements and only the strong GW discharge locations are identified (Conant 2004).

5.1.3. Aerial infrared surveys (II & IV)

In the River Vantaa catchment, approximately

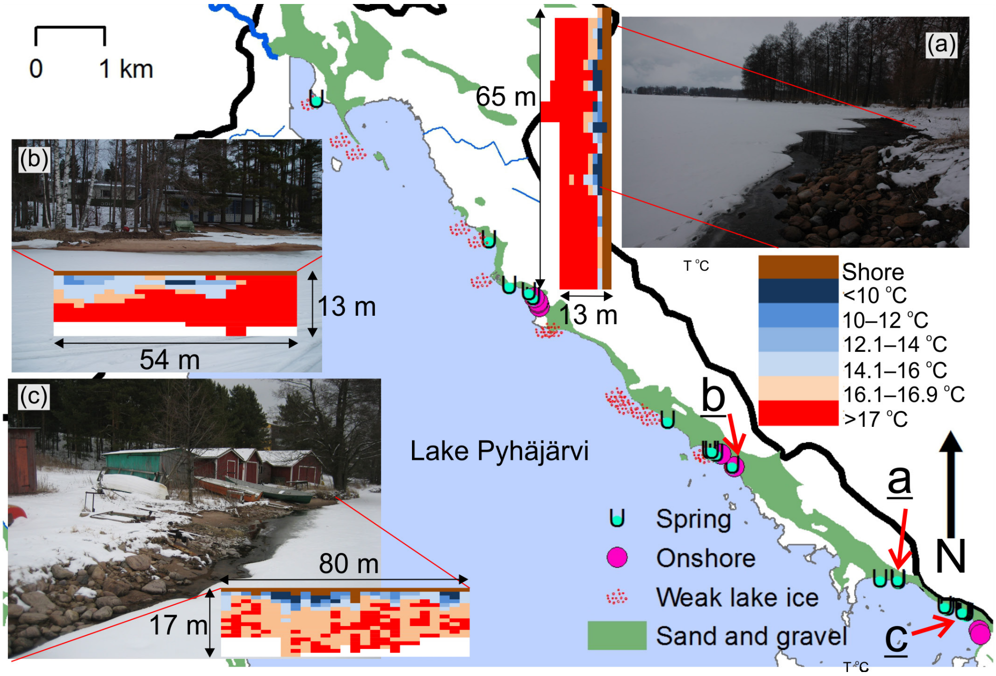

Figure. 7. Locations of potential GW discharge areas after winter mapping. Measured sediment temperatures (a) in springs, (b) in unfrozen onshore area, and (c) in spring compared to the winter condition. (Basemap Database © National Land Survey of Finland 2010; Quaternary Deposit Database © Geological Survey of Finland 2008; Watershed Database © SYKE 2010).

40 000 thermal images were acquired during the AIR surveys in 2010 and 2011. Altogether, 374 thermal anomalies were identified along the 203-km course of the studied rivers (River Vantaa catchment) in 2010 and 2011 using AIR (Fig. 4 in Paper IV). In Paper II, thermal anomalies were classified as discrete or multiple springs, cold creeks discharging into the river, diffuse sources by the shoreline, and diffuse and wide seepage areas. However, in paper IV, the anomalies were classified into three categories (Fig. 8, Table 2 in Paper IV) and a thermal anomaly was defined as a difference of at least 0.5 °C between the T_{minr} in the main channel and the observed anomaly. Two discrete categories (springs and cold creeks) were the same as in Paper II, but the two previously presented diffuse categories were merged to form one diffuse category in Paper IV, because both contribute to the diffuse discharge of GW in the riparian zone. Category three, diffuse anomalies, had a variable areal coverage ranging from separate small diffuse anomalies to wetlands with a large areal coverage. The discrete anomalies in category one (springs) were mostly (59 %) connected to medium- and coarse-grained Quaternary deposits (glaciofluvial silt, sand and gravel, glacigenic till), whereas anomalies in categories two and three were not directly connected to them (Paper IV, Fig. 4a). The differences in thermal anomalies among the studied streams can partly be explained by the shape of the river beds and composition of the river bed sediments (Paper IV).

There were some variations in the observed anomalies between the consecutive years, possibly related to annual differences in the hydraulic heads, as the hydraulic heads of the aquifers were generally at a higher level in the study area in July 2010 than in July 2011 (Finnish Environmental Administration, 2015). This illustrates the temporal as well as the spatial variation in GW discharge locations in the studied rivers. Moreover, the differences observed between years were partially related to the different design of image acquisition and missing some short sections of the strongly meandering study rivers.

There was significant variation in the longitudinal profiles of T_{minr} between the studied rivers and the revealed patterns of spatial variability in T_{minr} provided a means to characterize the thermal signatures of the individual rivers (Fig. 5 in Paper IV). In longitudinal temperature profiles, the observed smaller peaks and troughs (1−2 °C fluctuations) in T_{minr}, were connected to the inputs from tributaries, dams, rapids, narrowing of the channel and meandering bends. The large-scale patterns, such as gradual warming and cooling trends covering several kilometers in studied rivers, are related to physical geomorphic, riparian and hydrological processes at the catchment scale according to Torgersen et al. (2001).

The values of T_r, detected with AIR, were within ±0.6 °C of the reference measurements of T_k (n = 29) in subsequent years. The average absolute temperature difference between T_r and T_k was 0.22 °C. In this work, the focus was more on the relative temperature differences than the

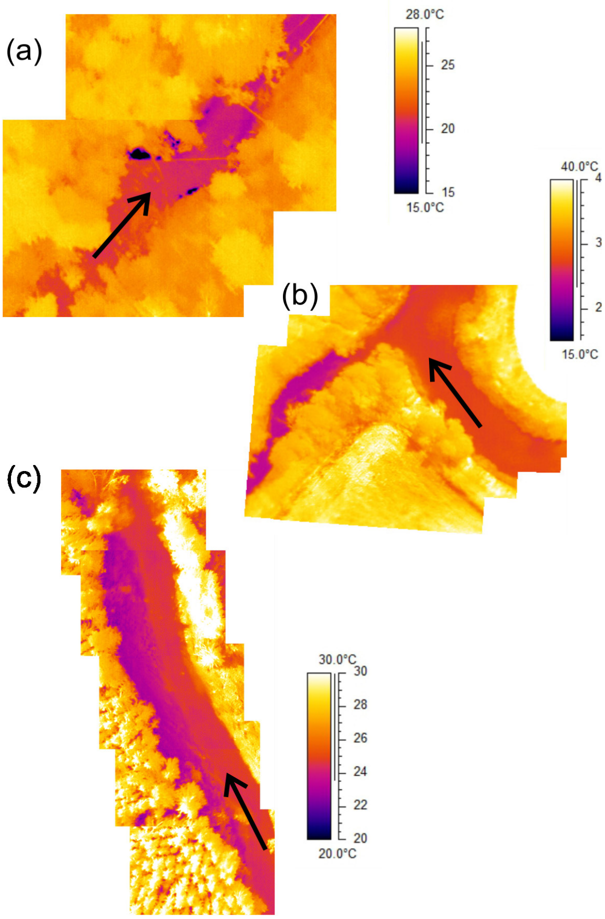

Figure 8. Categories of discrete and diffuse thermal anomalies; (a) springs (River Palojoki), (b) cold creek discharging into the river (River Vantaa) and (c) diffuse discharge (River Keravanjoki). The arrows indicate flow directions.

absolute temperature values.

The GW discharge locations identified using AIR were confirmed with the temperature and EC measurements of river bottom water and RW at selected field sites (see full details from Paper IV) (Fig. 9). The lower EC values had a statistically significant and very strong positive correlation with the lower temperatures on the river bottom and in RW, respectively (Fig. 9) (See full details from Paper IV). Moreover, the GW discharge into the rivers in the low-flow period was demonstrated by Brander (2013) with river flow rate measurements (YSI FlowTracker HandHeld-ADV, SonTek; RiverSurveyor M9 Acoustic Doppler Current Profiler, SonTek).

The field studies demonstrated the considerable vertical thermal stratification of RW in River Vantaa (Fig. 9d) and River Palojoki study sites. Vertical thermal stratification was strongest (as high as 17 °C) at the points where the river bed perpendicularly cuts the esker ridge and the highest volumes of GW were observed to discharge to the river (cross-sections from G–GG' to I–II') (Fig. 9c). Thermal stratification is an outcome of both the influx of cold water and retention of cold and dense water at the bottom of the river channel pools where the cold and less turbulent lower water regime can be isolated as long as the inflow of cold water is sufficient or/ and the river flow rate is slow enough, accord-

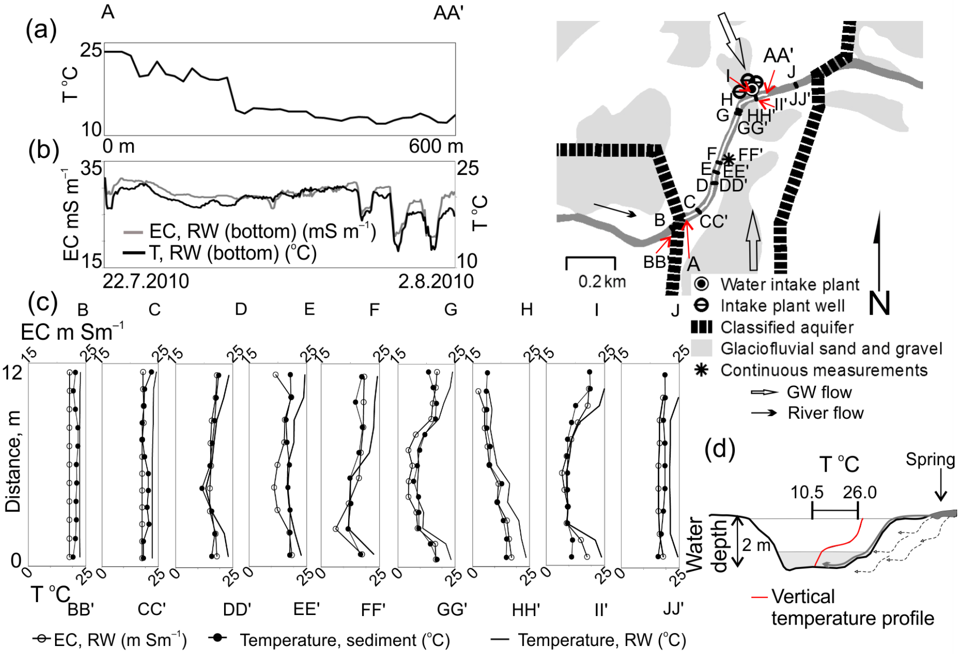

Figure 9. Field studies at the Hyvinkäänkylä study site (see Fig. 4) in the low-flow period in July 2010: (a) longitudinal profile of RW temperatures (A–AA') near the sediment–water interface; (b) continuous measurements of temperature and EC in RW 0.3 m above the river bottom (monitoring period from 22 July to 2 August 2010); (c) cross-sectional profiles (from B–BB' to J–JJ') of temperature and EC in RW near the sediment-water interface and temperature in the sediment (water depth ranging from 0.10 to 2.0 m) and (d) schematic figure of vertical thermal stratification and the vertical RW temperature profile in the middle of the River Vantaa at cross-section F–FF'. The grey array represent the GW sinking down by the river bank and the dashed lines represent the subsurface preferential GW flow paths into the river. Reprinted with permission from CC Attribution 3.0 License.

ing to Nielsen et al. (1994). The cold and dense water originates from both GW sinking down by the river bank and possibly through subsurface preferential GW flow paths into the lower part of the river channel (Fig. 9d).

5.2. Physical field methods (I)

5.2.1. Groundwater discharge fluxes (I)

The average (arithmetic mean) (GW) seepage flux rates measured at the Lake Pyhäjärvi shoreline varied from 4.69×10^{-5} cm s^{-1} to 4.80×10^{-3} cm s^{-1}. The seepage rates measured were moderate to high compared with the wide range of seepage flux rates reported in other lakes (Shaw & Prepas 1990b). The highest fluxes were measured in the vicinity of the shoreline and the average GW seepage velocity diminished with increasing distance from the shoreline. The detected thin clay lenses beneath sand, gravel and pebbles e.g. the geological heterogeneity was the most likely explanatory factor for the spatial variability in flux across the sediment–water interface. The seepage meter designs used in this work were similar to the properties of seepage meter design with correction factor 1.05 reported by Rosenberry (2005). A correction factor (e.g. Rosenberry & LaBaugh 2008) was not used in this work and the measured fluxes could have slightly underestimated the true seepage fluxes.

5.2.2. Hydraulic gradients (I)

The measured vertical hydraulic gradients (0.011–0.128) indicated GW discharge into the lake in northeastern side of the Lake Pyhäjärvi. All comparisons of head differences, the vertical hydraulic gradient and horizontal hydraulic gradient were carried out at approximately the same time. The GW discharge could not be verified with the mini-piezometers in locations where the lake ice was softened and weak further from shore, and no open water was detected on the shoreline in winter mapping.

5.3. Isotopic and chemical tracers (I & IV)

5.3.1. Electrical conductivity and pH measurements (I, III & IV)

The EC measurements were the easiest and most applicable method to verify the GW discharge into Lake Pyhäjärvi, as the EC values of GW were usually 1.5–4 times the magnitude of the EC values. Furthermore, the EC values were rather constant regardless of the season in Lake Pyhäjärvi. The pH values varied greatly both temporally and spatially in LW, being more constant in GW. The very coarse substrate partly prevented sediment temperature, seepage meter and hydraulic head measurements at NE shoreline of the lake.

The field measurements in the River Vantaa catchment, including the EC measurements at the selected field site, are summarized in chapter 5.1.3 together with AIR results, and full details are provided in Paper IV.

5.3.2. General water chemistry (III)

In the Lake Pyhäjärvi catchment, water types could mostly be classified as Ca-HCO_3 water, the exception being a few of the stream and RW samples representing Ca-NO_3-dominant waters. RW generally has higher NO_3 concentrations than other water types. The main chemistry of RW samples showed clear seasonal differences, as samples taken in the low-flow season had major ion concentrations close to those of GW, while in the high-flow season samples differed more from GW and spring water. This mainly reflects increased surface runoff caused by the thawing of snow or heavy rains (Fig. 10). Particularly, the EC value and NO_3 composition appears to increase, presumably indicating the NO_3 load from surface runoff of cultivated fields due to the increased leaching rates. DGW has Na, Cl, Ca, SO_4 and HCO_3 concentrations clearly higher than in other water types. The lowest amounts of dissolved solids were recorded in springs and LW. No seasonal variation occurred in spring water chemistry and only a little variation was recorded in LW chemistry. The temporal transitions between the end members (RW and GW) could be observed from the major ion chemical composition (Fig. 10), but the shares of GW in SW bodies were not calculated due to the non-conservative nature of the recorded major ions (for full details, see Paper III).

Variables Ca, NO_3, δD, $\delta^{18}O$ and DSi appeared to indicate GW–SW interaction. The differences in NO_3 concentrations between the inflowing rivers can be related to the differences in the catchment areas, the amount of runoff, surficial soil and the relative percentage of agricultural area. GW as a partial source of NO_3 loading to the river cannot be excluded due to the lack of GW samples from the River Yläneenjoki area. From the variables of the GW–SW component, calcium had a local source in the glaciofluvial and glaciolacustrine sediments of the Virttaankangas complex as dispersed, fine-

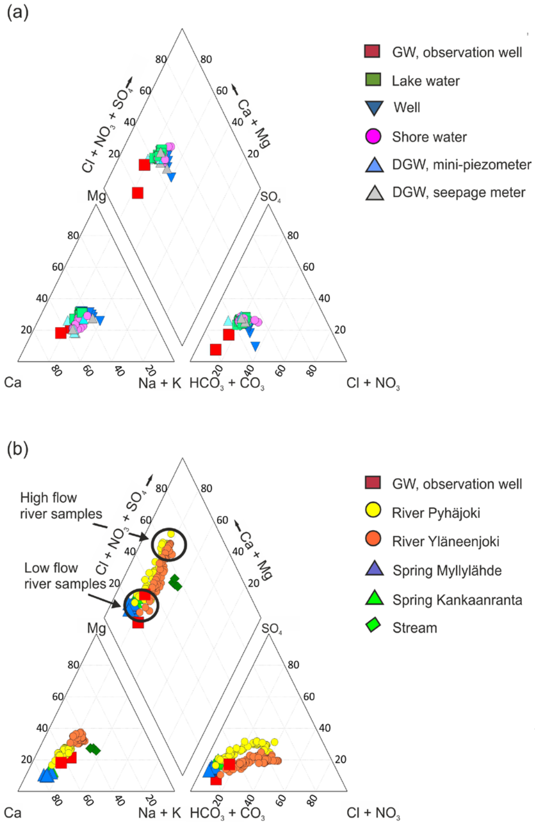

Figure 10. (a) Piper diagram for GW, LW, lake-shore water, well water and DGW samples taken with mini-piezometers and seepage meters in Lake Pyhäjärvi catchment from 2009 to 2012. (b) Piper diagram for RW, GW, spring water and stream water samples in Lake Pyhäjärvi catchment from 2009 to 2012. Reprinted with permission from Springer (III).

grained calcite (Kortelainen et al. 2007).

5.3.3. Stable isotopes (I, III & IV)

There were considerable differences in the mean δ^{18}O, δD and *d*-excess values between different water types and among the rivers in studied catchments (Tables 1−3). The measured mean δ^{18}O and δD of springs, GW and well waters from GW intake plants were mainly in close agreement with the previous studies of Kortelainen & Karhu (2004) (Table 1).

The studied rivers displayed significant differences in the stable isotope composition (Fig. 11, Table 1) and the ranked order of the mean δ^{18}O and δD values of rivers from the most enriched to the least enriched varied during the seasons (Fig. 11, Table 2). The stable isotope composition of the majority of the world's main rivers falls along the global meteoric water line (GMWL) (Rozanski et al. 2001). Most RW isotope values fell along the LMWL, indicating that RWs had not been influenced by evaporation (Fig. 11). The GMWL has a *d*-excess value of 10 ‰ (Merlivat & Jouzel, 1979), and *d*-excess values significantly below the global average of 10 ‰ indicate evaporation, since falling as precipitation (Kendall & Coplen, 2001). Approximately 14% (n = 36) of the RW samples fell 5‰ or more below GMWL; these samples were mostly collected from the Rivers Keravanjoki and Tuusulanjoki.

Among the studied rivers, the stable isotope composition of Rivers Herajoki and Pyhäjoki plotted along the LMWL (Fig. 11), with a stable isotope composition close to the GW composition, indicating GW as a source component, and the *d*-excess values indicated the smallest evaporation effects regardless of the season (Tables 1−3). In the Lake Pyhäjärvi catchment, the isotope composition of the two inflowing rivers differed more in the low flow-season than yearly (Fig. 12).

The δ^{18}O and δD values of Rivers Keravanjoki and Tuusulanjoki were significantly displaced to the right of the LMWL (Fig. 11). The more evaporated δ^{18}O, δD and *d*-excess values of Rivers Keravanjoki and Tuusulanjoki could be due to the supplementary water, the existence of headwater lakes and the dams along the river path. The Lake Päijänne water, used both as supplementary water and infiltration water (artificial GW plant/pond infiltration), has significantly evaporated δ^{18}O, δD and *d*-excess values (Table 1, infiltration water). Supplementary water was released into the Rivers Keravanjoki and Tuusulanjoki via the headwater lakes to sustain a sufficient river flow and water quality in the river channel during the summer months (Vahtera et al. 2012). The largest differences between the low-flow season and yearly values were observed in the Rivers Keravanjoki and Palojoki (Tables 1 and 2, Fig. 12). In the River Keravanjoki, this was most probably connected to the supplementary water, whereas in the River Palojoki, the isotopic enrichment of RW was probably connected to the discharging of infiltration water during the low-flow season as the RW levels declined.

In this study, the minimum and maximum δ^{18}O and δD values of RW occurred in spring and in late summer, respectively, but the magnitude of the variation varied (Fig. 12). The results are consistent with the systematics of seasonal variation observed in temperate rivers (Rozanski 2001). In general, seasonal variation in the stable isotope composition of rivers follows the mean weighted monthly composition of precipitation, but is attenuated and with a time-lag. In studied rivers, the results represent 15-months and 8-months time period in Lake Pyhäjärvi catchment and River Vantaa catchment, respectively. It should be noticed that the isotope composition of precipitation varies

Table 1. Stable isotope, *d*-excess and DSi results from the Lake Pyhäjärvi catchment during February 2011–April 2012 and in the River Vantaa catchment during 2011.

Water type			$\delta^{18}O$ ‰,	VSMOW		δD ‰,	VSMOW				DSi, ppm	
	n[a]	Mean[b]	Range	SD[c]	Mean[b]	Range	SD[c]	*d*−excess	n[a]	Mean[b]	Range	SD[c]
L. Pyhäjärvi catchment												
L. Pyhäjärvi	44	−7.32	1.28	0.34	−59.1	7.0	2.0	−0.5	41	1.5	2.8	0.9
L. Pyhäjärvi, shore	30	−9.55	4.54	1.72	−72.1	27.1	10.1	4.3	24	4.1	7.6	2.3
R. Pyhäjoki	85	−11.45	2.33	0.60	−82.4	18.3	4.5	9.2	79	5.4	5.8	1.7
R. Yläneenjoki	82	−11.12	3.93	1.10	−79.9	29.9	8.1	9.1	81	4.1	6.2	1.8
Spring, ML* and KR**	14	−12.05	0.48	0.14	−86.9	1.8	0.6	9.5	13	5.2	2.0	0.6
Lohiluoma intake plant	8	−7.82	1.33	0.46	−62.1	8.2	2.8	0.0	5	1.1	1.4	0.6
GW, observation well	3	−11.78	0.34	0.20	−84.9	2.3	1.3	9.0	3	7.0	8.2	4.1
DGW	28	−11.61	1.65	0.42	−84.3	9.9	2.5	8.6	3	8.3	3.8	2.1
Stream	6	−11.54	0.06	0.02	−83.3	0.6	0.2	9.0	–	–	–	–
R. Vantaa catchment												
Spring	6	−11.76	0.22	0.09	−83.7	2.6	0.8	10.3	6	9.2	9.5	2.9
GW	15	−11.53	1.53	0.63	−83.1	9.2	3.6	9.2	15	8.0	5.6	1.6
Well	43	−12.00	1.21	0.25	−86.2	9.8	1.9	9.9	43	8.3	1.4	1.4
Jäniksenlinna intake plant	20	−9.61	1.53	0.53	−74.6	7.3	2.5	2.2	20	4.5	6.7	2.1
Infiltration water	6	−8.93	0.25	0.07	−71.5	1.5	0.5	−0.1	6	1.3	0.7	0.2
R. Herajoki	19	−11.63	2.96	0.78	−83.6	21.9	5.8	9.4	19	6.6	7.7	2.3
R. Vantaa	19	−10.28	1.80	0.60	−76.8	13.0	4.3	5.5	19	4.0	5.2	1.1
R. Palojoki	19	−10.79	5.37	1.48	−78.6	41.5	11.1	7.0	19	3.4	6.6	2.1
R. Tuusulanjoki	17	−9.28	3.11	1.15	−74.3	19.2	6.2	0.9	17	2.2	2.8	1.0
R. Keravanjoki	19	−9.98	6.33	1.03	−73.7	37.1	10.4	3.8	19	3.7	4.7	1.8

[a] Number of analyses, [b] Arithmetic mean, [c] Standard deviation (1σ)

Table 2. Stable isotope, *d*-excess and DSi results from the Lake Pyhäjärvi and River Vantaa catchments during the low-flow and high-flow seasons in 2011.

Water type			δ18O ‰,	VSMOW		δD ‰,	VSMOW				DSi, ppm	
Low flow season	n[a]	Mean[b]	Range	SD[c]	Mean[b]	Range	SD[c]	*d*−excess	n[a]	Mean[b]	Range	SD[c]
L. Pyhäjärvi catchment												
(6−8/2011)												
L. Pyhäjärvi	9	−6.97	0.62	0.24	−57.2	4.9	1.6	−1.4	9	0.7	1.1	0.4
R. Pyhäjoki	24	−11.24	1.27	0.32	−81.5	7.4	1.7	8.5	20	5.6	1.7	0.5
R. Yläneenjoki	19	−10.37	1.64	0.62	−75.2	12.9	4.7	7.7	19	4.0	4.4	1.0
R. Vantaa catchment												
(6−8/2011)												
R. Herajoki	4	−11.18	1.33	0.54	−80.8	10.2	3.9	8.6	4	6.9	2.8	1.1
R. Lepsämänjoki	7	−10.08	0.85	0.28	−75.5	4.0	1.3	5.2	7	6.2	2.1	0.7
R. Vantaa	6	−10.12	0.98	0.38	−75.6	7.7	3.4	5.4	6	3.0	2.3	1.0
R. Palojoki	6	−9.63	2.52	0.96	−71.1	22.2	8.9	5.9	6	3.4	0.5	0.2
R. Tuusulanjoki	5	−9.29	1.31	0.56	−74.2	6.6	2.9	0.1	5	1.0	1.0	0.4
R. Keravanjoki	8	−8.84	2.59	1.15	−70.9	14.4	6.6	−0.2	8	2.1	0.7	0.2
High flow season												
L. Pyhäjärvi catchment												
(4,12/ 2011 + 3,4/2012)												
L. Pyhäjärvi	12	−7.62	0.65	0.19	−60.5	3.3	1.0	0.5	11	1.8	2.1	0.9
R. Pyhäjoki	22	−11.97	2.20	0.67	−85.9	15.9	5.5	9.9	22	3.9	4.1	1.4
R. Yläneenjoki	27	−12.30	2.48	0.85	−88.1	20.0	7.0	10.3	27	3.0	5.0	0.9
R. Vantaa catchment												
(4/2011)												
R. Herajoki	2	−13.21	0.01	−	−96.0	0.2	−	9.6	2	1.8	0.1	−
R. Vantaa	3	−11.47	0.05	0.03	−84.9	0.2	0.1	6.9	3	4.7	0.2	0.1
R. Palojoki	3	−13.39	0.54	0.29	−97.9	4.4	2.2	9.3	3	1.7	0.6	0.4
R. Tuusulanjoki	3	−11.15	0.19	0.10	−84.8	1.6	0.9	4.4	3	3.3	0.1	0.1
R. Keravanjoki	2	−13.84	0.07	−	−100.8	0.2	−	10.0	2	4.7	0.1	−

[a] Number of analyses, [b] Arithmetic mean, [c] Standard deviation (1σ)

Table 3. Stable isotope, *d*-excess and DSi results from the Lake Pyhäjärvi and River Vantaa catchments without the low-flow season and high flow season.

Water type			δ^{18}O ‰,	VSMOW		δD ‰,	VSMOW				DSi, ppm	
	n[a]	Mean[b]	Range	SD[c]	Mean[b]	Range	SD[c]	*d−excess*	n[a]	Mean[b]	Range	SD[c]
No high flow season												
L. Pyhäjärvi catchment												
L. Pyhäjärvi	32	−7.20	1.12	0.31	−58.4	6.3	1.9	−0.8	30	1.3	2.8	0.9
R. Pyhäjoki	63	−11.27	1.51	0.45	−81.2	11.2	3.3	9.0	55	5.9	5.8	1.5
R. Yläneenjoki	55	−10.54	2.38	0.63	−75.8	17.6	4.8	8.5	52	4.7	6.2	1.9
R. Vantaa catchment												
R. Herajoki	12	−11.14	1.50	0.43	−80.1	10.5	3.2	9.0	12	7.0	4.7	1.3
R. Vantaa	15	−10.05	0.98	0.31	−75.2	7.7	2.6	5.1	15	3.7	2.4	0.9
R. Palojoki	13	−9.98	2.54	0.90	−72.8	22.2	7.1	7.1	13	4.4	4.7	1.8
R. Tuusulanjoki	11	−8.75	1.74	0.62	−70.6	10.3	3.8	−0.6	11	2.1	2.7	1.0
R. Keravanjoki	14	−9.16	2.77	1.00	−71.1	14.4	5.1	2.2	14	3.1	4.7	1.6
No low flow season												
L. Pyhäjärvi catchment												
L. Pyhäjärvi	35	−7.41	1.15	0.30	−59.5	6.1	1.7	−0.3	32	1.6	2.6	0.9
R. Pyhäjoki	61	−11.53	2.28	0.66	−82.8	18.3	5.1	9.5	59	5.3	5.8	2.0
R. Yläneenjoki	63	−11.35	3.44	1.11	−81.3	26.1	8.4	9.5	62	4.1	6.8	2.0
R. Vantaa catchment												
R. Herajoki	14	−11.79	2.63	0.84	−84.5	20.1	6.4	9.8	14	6.1	7.7	2.4
R. Vantaa	13	−10.40	1.80	0.70	−85.6	11.7	4.6	5.6	13	4.5	3.3	0.8
R. Palojoki	13	−11.55	3.19	1.17	−83.6	24.4	9.0	8.8	13	5.0	6.6	2.5
R. Tuusulanjoki	12	−9.27	3.11	1.17	−73.4	19.2	7.0	0.7	12	2.7	1.9	0.7
R. Keravanjoki	11	−10.81	5.1	1.63	−79.8	32.1	11.1	6.7	11	4.9	4.5	1.6

[a] Number of analyses, [b] Arithmetic mean, [c] Standard deviation (1σ)

from year to year (Kortelainen & Karhu 2004) and, therefore, the stable isotope composition of rivers and the seasonal systematics can vary from year to year.

The proportion of the GW component varied between 4% and 99% in lake-shore water, and the water from the wells of the Lohiluoma water-intake plant was predominantly LW based on mass balance calculations of δ^{18}O.

5.3.4. Dissolved silica (III & IV)

Significant differences in DSi concentrations were recorded between different water types and among the rivers (Tables 1–3). The measured mean DSi values of springs, GW and well waters were slightly higher than in Finnish dug wells in general (Lahermo et al. 2002), except for the Myllylähde and Kankaanranta springs in the Lake Pyhäjärvi catchment (Table 1). The mean DSi concentration in LW was relatively low compared with Finnish LWs in general (Lahermo et al. 1996, range from 0.94 to 4.70 ppm). The observed seasonal variation represented the normal pattern of silicon cycling in temperate lakes (e.g. Neal et al. 2005, Nõges et al. 2008) (Fig. 13). Eutrophication-associated nutrient enrichment can additionally lower DSi concentrations (Conley et al. 1993). In the productive lakes, 80–90% of the available silicon is removed as a result of uptake by diatoms, and the seasonal variations are smaller (Neal et al. 2005). The River Pyhäjoki had a higher mean DSi concentration and a smaller range of values than the River Yläneenjoki (Table 1, Fig. 13), which was consistent with results for stable isotopes. The LW was the main component in the Lohiluoma intake-plant wells, based on mass balance calculations of DSi values as well as δ^{18}O. Lake-shore water displayed the same dynamics for DSi as for δ^{18}O and δD values.

In the Rivers Pyhäjoki, Yläneenjoki, Herajoki and Lepsämänjoki (only low-flow sampling), the observed DSi concentrations were somewhat higher than in Finnish streams in general (range from 0.80 to 6.86 ppm, mean 3.62 ppm, n = 1162, Lahermo et al. 1996), suggesting a greater GW component than typically. The Rivers Pyhäjoki and Yläneenjoki showed systematic variations in

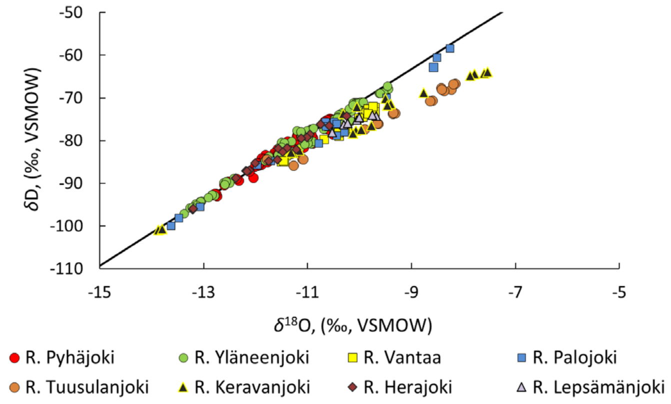

Figure 11. The δ^{18}O and δD values in the studied rivers in Lake Pyhäjärvi and River Vantaa catchments. The data are shown against the local meteoric water line (LMWL) ($\delta D = 7.67\ \delta^{18}O + 5.79‰$) defined by Kortelainen (2007).

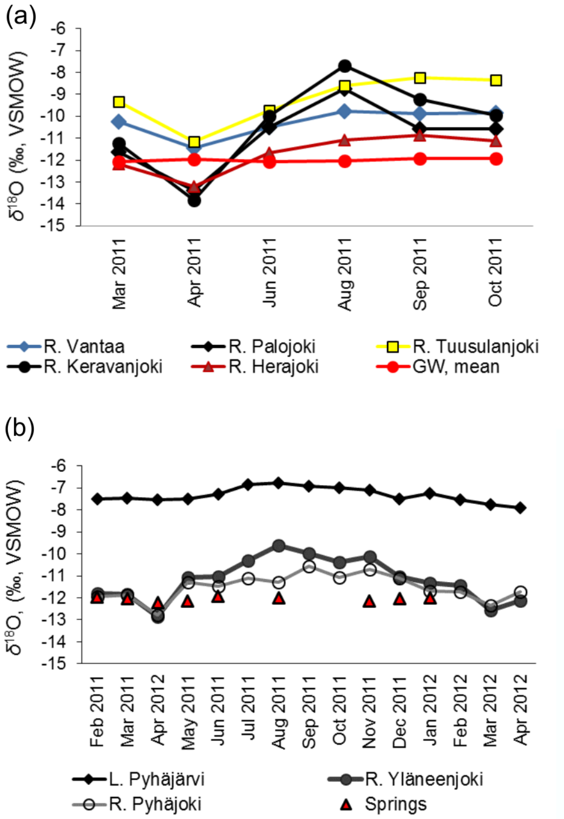

Figure 12. (a) Seasonal variation in the stable isotopic composition in GW and in the Rivers Herajoki, Vantaa, Keravanjoki, Palojoki and Tuusulanjoki. GW mean is monthly mean value of GW samples. (b) Seasonal variation in the stable isotopic composition in the Rivers Pyhäjoki and Yläneenjoki, Lake Pyhäjärvi and springs (Myllylähde and Kankaanranta springs).

the DSi concentration as a function of flow, with higher concentrations under baseflow conditions and the lowest concentrations in the high flow season, which agreed with previous studies (e.g. Scanlon et al. 2001, Neal et al. 2005, Nõges et al. 2008) (Fig. 8 in Paper III).

In the River Vantaa catchment, the rivers showed considerable variation in DSi systematics during the seasons (Fig. 13). Only the Rivers Herajoki and Palojoki showed a distinct drop in DSi concentrations during the high-flow season in spring (Fig. 13). Apart from River Herajoki, the rivers had low DSi concentrations in the River Vantaa catchment during the summer months (Fig. 13). The DSi-poor supplementary and infiltration water (Table 1) could lower the DSi concentrations in the Rivers Keravanjoki, Tuusulanjoki and Palojoki. The supplementary water release period is contemporaneous with lower DSi concentrations in the Rivers Keravanjoki and Tuusulanjoki. The lowest DSi concentrations in the River Tuusulanjoki among the all studied rivers could be related to the headwater lake, eutrophication-associated nutrient enrichment, supplementary water and a smaller GW contribution.

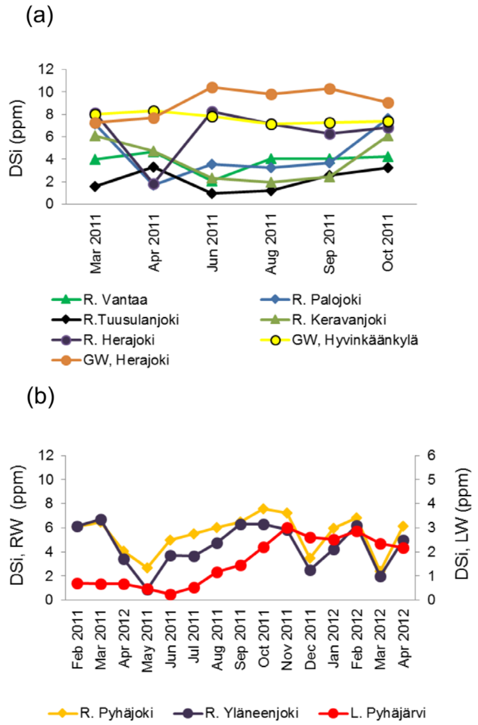

Figure 13. (a) Seasonal variation DSi concentrations in GW and in the Rivers Herajoki, Vantaa, Keravanjoki, Palojoki and Tuusulanjoki. (b) Seasonal variation DSi concentrations in the Rivers Pyhäjoki and Yläneenjoki and Lake Pyhäjärvi.

6. Discussion

6.1. Ubiquity of groundwater–surface water exchange in the boreal environment

The large numbers of thermal anomalies in the River Vantaa and its tributaries highlighted the commonness of GW discharge sites at the catchment scale, and the longitudinal temperature profiles also reflected the considerable spatial variability and dynamic nature of GW−SW exchange. These findings are supported by previous studies that have addressed the commonness of GW–SW exchange in different environments, the complexity of this interaction and the need to consider the resources as a single resource (e.g. Winter et al. 1998, Winter et al. 2003, Rosenberry & LaBaugh 2008).

The longitudinal thermal profiles of the Rivers Keravanjoki and Vantaa in consecutive summers revealed differences in the absolute temperatures, being higher in 2010, which is possibly explained by the exceptionally warm July in 2010 (Figs 5a, c in Paper IV) (Korhonen & Haavalammi 2012). However, the overall thermal patterns and amplitudes were similar in the consecutive years, which indicated that the cool and warm water sources mainly had spatially fixed locations in the Rivers Vantaa and Keravanjoki. These findings are in close agreement with earlier studies by Faux et al. (2001) and Cristea & Burges (2009). Previously, Cristea & Burges (2009) reported similar findings on the connection between elevated RW and air temperature. Additionally, they noted that differences in headwater conditions, precipitation, and main channel and tributary flow rates can influence the magnitude of the longitudinal thermal profile. Longitudinal thermal profiles along the stream can provide valuable insights into the causative factors behind the observed stream temperatures or temporal changes. The stream temperature is an important parameter in aquatic management (Poole & Berman 2001, Stonestrom & Constantz 2003), and the fundamental role of temperature in the health of rivers will be highlighted in future, as the predicted climate change will also increase the temperature of SW bodies (Graham & Harrod 2009, Dugdale et al. 2015).

Considerably strong vertical thermal stratification was observed during the field studies at study sites in the Rivers Vantaa (17 °C) and Palojoki (13.4 °C). These subsurface GW contributions to the rivers were not seen from AIR data. This is a well-known limitation of the technique, as thermal infrared (TIR) detects the surficial temperatures ("skin" layer < 0.1 mm), and only substantial subsurface GW contributions to SW bodies that reach the surface can therefore be detected (Torgersen et al. 2001). Thermal stratification can be an outcome of subsurface prefential GW flow, the influx of cold water (sinking down by the river bank) and retention of cold and dense water at the bottom of the river channel pools during low river flow rates (Matthews et al. 1994, Nielsen et al. 1994), and can lead to underestimation of GW contributions to the river (Faux et al. 2001, Torgersen et al. 2001). Strong thermal stratification has previously been observed in considerably deeper river sections or pools (depth > 3m, Nielsen et al. 1994; depth > 4.5 m, Matthews et al. 1994). The shallowness (depth < 2m) of the strongly thermally stratified river sections in this study was exceptional. This observed stratification at the field study sites supports the existence of such "hidden" GW discharge sites elsewhere in the surveyed rivers. However, thermal stratification does not exist everywhere, and moreover, dams, channel geometry changes, meander bends and rapids can disrupt the stratification, as seen in thermal mosaic images (Fig. 14). This is also supported by the findings of Wawrzyniak et al. (2012) concerning the breakdown of thermal stratification downstream of dams. However, AIR results should be considered as a minimum estimation of the amount of GW discharge in the studied rivers.

In the Lake Pyhäjärvi catchment, the results from winter mapping, seepage measurements and chemical tracers indicated that the GW discharge into the lake was focused on the NE shoreline, where the esker deposits enhanced the GW discharge. The results from AIR surveys showed that the observed springs (category one) were mostly connected to sorted Quaternary deposits in the River Vantaa catchment. According to Winter et al. (1998), the GW−SW interaction is most commonly connected to shallow aquifers. Extending the assessment outside the two studied catchments, it is realistic to assume the GW−SW exchange to be a common phenomenon, as esker aquifers are abundant in the Fennoscandia (Svendsen et al. 2004). Moreover, in northern Finland, there are coarse-grained braided rivers in which the GW contribution to the river flow from shallow aquifers can be substantial (Salonen et al. 2014).

The ubiquity and high spatial variability of GW−SW interaction is a challenge to researchers and environmental agencies. In Finland, the GW component of many existing hydrological models will need to be updated, as the GW component has previously been neglected or estimated as a residual component. In general, watershed planning as well as water resource and supply management needs a more integrated management approach. In Finland, these types of systematic catchment scale GW−SW interaction studies are necessary from the perspective of water supply management and the vulnerability of water supplies. However, this is restricted by the limited

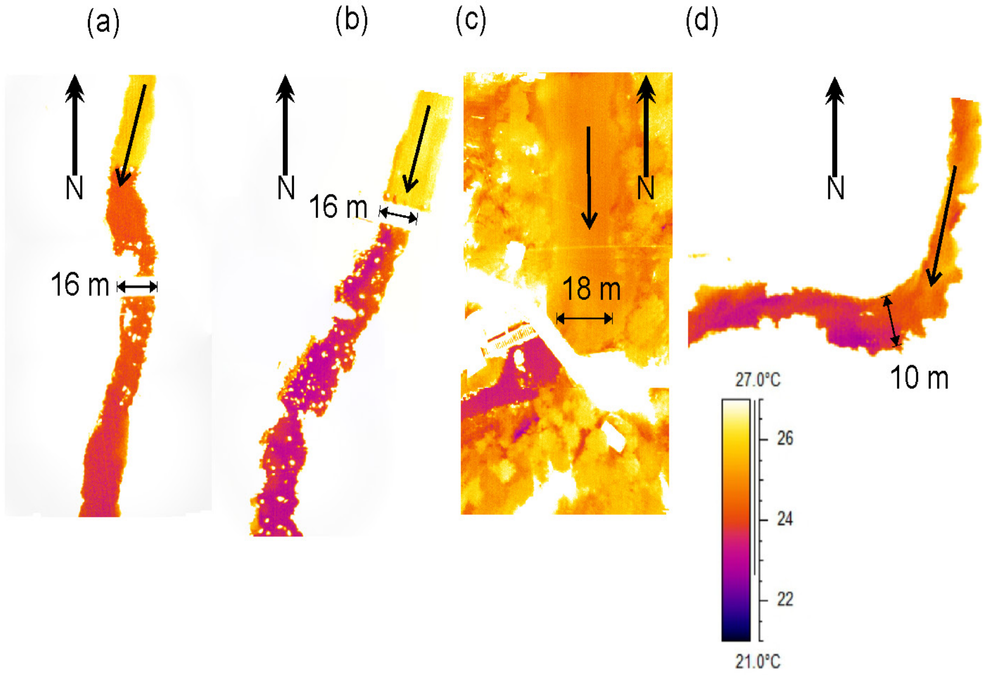

Figure 14. Example mosaic thermal images illustrating the breakdown of vertical thermal stratification downstream of (a, b) rapids in River Vantaa, (c) a dam in River Keravanjoki and (d) a meander bend in River Keravanjoki

knowledge of GW–SW interactions, their complexity and difficulties in defining the properties and dimensions of underlying GW systems (Winter et al. 2003).

6.2. Applicability of the used methods in snow-type catchments

The selection of the research method or methods has been reported as one of the most important decisions to be made when studying GW–SW exchange (Kalbus et al. 2006, Rosenberry & LaBaugh 2008). The results of this study supported this view, as the applicability of different methods was compared (Table 4). The functionality of the selected method was an outcome of several factors and was not necessarily predictable. Each method has advantages and disadvantages, and the selected method will usually be a compromise, because it is not possible to anticipate all situations in the complex natural environment.

The scale of the research area and research question will determine the appropriate methods for a specific study site. Detailed field measurements (e.g. seepage meter measurements, sediment temperature measurements) are time, labour and cost intensive if the research area is large and/or the target is a spatially-distributed estimation of the seepage flux or temperatures. Moreover, it should be noted that GW–SW exchange is temporally variable and the results obtained describe the situation only at that specific time (Tóth 1963, Rosenberry & LaBaugh

Table 4. The summary table of the used methods in studied boreal catchments and their scale, environments, applicability and limitations.

Method	**Scale**	**Environment**	**Applicability**	**Main limitation**
Winter mapping	Local	Lake	Good	Narrow time window
Temperature *in-situ* measurements	Local	Lake/river	Good	Small areal coverage
AIR	Local/catchment	Lake/river	Good	Only surficial temperatures
Mini-piezometers	Local	Lake/river	Good	Small areal coverage
Seepage meters	Local	Lake	Good	Small areal coverage
EC	Local	Lake/river	Good in lake/ Complex in rivers	End member composition variability
Main chemistry	Local/catchment	Lake/river	Limited	Non-conservative
Stable isotopes	Local/catchment	Lake/river	Good in lake/ Complex in rivers	End member composition
DSi	Local/catchment	Lake/river	Limited	GW end member variability

2008). With labour-intensive field methods, the simultaneity of measurements can be difficult or impossible to accomplish, which can produce inconsistency in the results and uncertainty in the interpretations. AIR surveys and chemical as well as isotopic tracers can provide catchment-scale data on the systematics of the watershed. It is inevitable that some detailed information will be lost at the expense of better areal coverage. The ideal research design would begin with larger scale methods (AIR), which would identify and highlight the GW discharge sites and direct more detailed studies, such as seepage flux measurements and sampling, to the most relevant locations.

The multi-method approach to identify, verify and quantify the exchange between GW and SW used in this investigation increased the reliability of the results and the confidence in the obtained results, as the results from different methods supported each other. The benefits of the multi-method approach have been acknowledged in many previous GW−SW interaction studies (e.g. Rosenberry & LaBaugh 2008, Kidmose et al. 2011, Conant et al. 2012). This is especially true for catchment-scale studies, in which the variability in the environment, circumstances and types of GW−SW exchange (GW/LW, GW/RW, GW/wetland) is a challenge and several methods have to be applied to reduce the uncertainty in the results.

Winter mapping revealed a large number of springs and possible GW discharge sites further from the shoreline (weak and wet ice) (Fig. 7), which was a simple and rapid method to identify GW discharge into the lake. Similar thawing patterns of ice-covered lakes have observed in Shingobee Lake (Rosenberry et al. 2000) and in Lake Væng (Kidmose et al. 2013). The method proved to be useful and correlated with other methods (chemical tracers, mini-piezometers, seepage meters) to locate the GW discharge zones. However the applicability is limited to early spring for ice-covered lakes, as in mid-winter only the GW discharge sites with the highest fluxes were without an ice-cover. The practical implications and success are highly dependent on the prevailing weather conditions. In riverine environment, the winter mapping is complicated by the river flow, and caution should take when interpreting the results.

AIR was found to be a time- and costs-effective method to study GW−SW interaction at the catchment scale, supporting many previous studies using TIR (Torgersen et al. 2001, Loheide & Gorelick 2006, Davis 2007, Loheide & Deitchman 2009). AIR gave an overview of the GW discharge with a good ground resolution from 0.15 m to 0.5 m (Fig. 15). The surveys were conducted in summer, when the maximum difference between GW and SW existed. This has also been a common practice in previous studies (Faux et al. 2001, Torgersen et al. 2001, Loheide & Gorelick 2006, Cristea & Burges 2009, Dugdale et al. 2015), but some studies have conducted AIR surveys additionally or only in winter (Loheide & Deitchman 2009). In Finland, winter AIR surveys would benefit from the scarce vegetation and GW upwelling, but would simultaneously be complicated by the small temperature difference between the GW and SW. The method is limited to areas without a dense canopy, as the method requires "visual" contact with the target (Torgersen et al. 2001). The AIR is further limited by that it measure only the temperature of "skin" layer and only the GW discharge zones are located.

Although AIR surveys are rapid, including the reference measurements, the post-processing of AIR data can be time-consuming and knowledge of the IR camera, flight conditions, atmospheric variables, reflections and properties of the surveyed water body is needed. The classification of AIR anomalies can be complicated due to the complex appearance and nature of the anomalies, as well as the selection of classification variable(s), which can lead to different types of classifications and interpretations. Moreover, the flight conditions (full cloud cover/cloudless/half cloudy) can have a major influence on the time needed in post-processing.

Recent studies have shown the good applicability and large areal coverage of TIR combined with spatial analysis of landscape variables to provide a very effective tool (Dugdale et al. 2015). AIR could potentially be used to localize and classify GDEs, as the method gives the temperature data, shape, size and location of the anomaly. AIR can potentially be used more extensively in environmental monitoring, such as in supporting the management of SW and GW in mining areas (e.g. Sams & Veloski 2003, Salonen et al. 2014), finding sources of thermal pollutants, as well as planning and updating hydrological models (Danielescu et al. 2009). AIR can be part of the preliminary vulnerability assessment of water intake plants located in the proximity of SW bodies. This aspect could be emphasized in the future, as flooding will increase according to the climate predictions (Veijalainen et al. 2009, Veijalainen et al. 2010).

The mini-piezometers and seepage meters could be used locally to identify the GW discharge and recharge zones. Additionally, these devices could be used to sample DGW in Lake Pyhäjärvi catchment and seepage meters could be used to measure the DGW fluxes. However, mini-piezometers and seepage meters were time consuming to install and the geological substrate (very fine or very coarse material) prevented the use of seepage meters and mini-piezometers (hand-driven), as the devices were practically impossible to install into the very hard substrate at some locations in Lake Pyhäjärvi, and other methods such as stable isotopes and winter mapping were needed to verify the GW−SW exchange. In River Vantaa catchment, the mini-piezometers and seepage meters were not used due to the too strong upward hydraulic gradient (River Palojoki) and deep water (Rivers Keravanjoki and Vantaa).

EC was applicable in both study catchments due to the sufficient difference between the EC

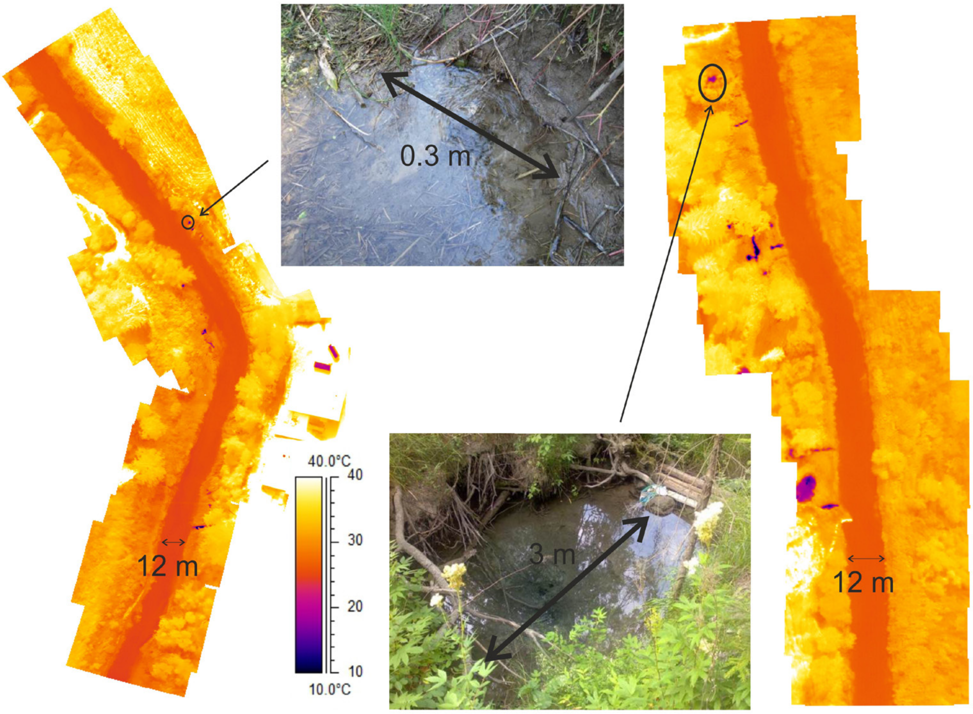

Figure 15. Thermal mosaic images and example photos illustrating the resolution of AIR from Hyvinkäänkylä in the River Vantaa catchment. Reprinted with permission from Vesitalous.

values of GW and SW (Fig. 9). These findings concerning the applicability of EC are consistent with previous studies (Lee 1985, Vanek & Lee 1991, Harvey et al. 1997) However, in the river systems, EC values ranged more spatiotemporally due to variable load from sewage treatment plants and urban areas, including residues of purified waste water and deicing chemicals (Vahtera et al. 2014). Therefore, the use of EC as a GW−RW interaction tracer was not as straightforward as it was in GW−LW interaction studies due to rather constant EC value on LW during the survey.

In Lake Pyhäjärvi, stable isotopes were applicable to identify and verify the contribution of GW to the lake and LW infiltration to the intake wells due to the strongly evaporated LW. Many previous studies (e.g. Hunt et al. 2005, Kortelainen & Karhu 2006) have used mass balance calculations to define the proportions of different water types, and the method works well in a binary system with a sufficient difference in end-member composition. The stable isotopes seemed to be the most applicable variables in estimating the GW−LW interaction of the study area in a binary systems (Lake Pyhäjärvi/GW, Lake Päijänne water as supplementary and infiltration water/GW, LW/wells). In general, some estimation of the magnitude of GW contributions in the rivers could be made, but stable isotopes were not used in the mass balance calculations of the proportion of GW in RW, because precipitation and shallow GW have a similar isotopic composition. The stable isotope method could benefit sampling the precipitation locally as well as denser sampling during the study. The strongly evaporated *d*-excess values as well as the evaporated δ^{18}O and δD values revealed the supplementary and infiltration water (Lake Päijänne water) contributions to the Rivers Keravanjoki, Palojoki and Tuusulanjoki during the low-flow season (Table 2). During the supplementary water release, the River Keravanjoki deviated strongly from the more natural Rivers Herajoki and Vantaa, and after closing the supplementary water release, the *d*-excess, δ^{18}O and δD as well as DSi values returned to more natural levels. The River Tuusulanjoki had the same systematics, but with a lower amplitude, as the DSi level is lower throughout the year. Because of the supplementary water release, the use of stable isotopes and DSi as a GW tracer was limited in the River Vantaa catchment. The usability of DSi as a GW tracer was limited by the variability in the GW end member concentrations (Fig. 13), and use of the DSi as a GW tracer would benefit from the spatiotemporally denser sampling of GW end members. DSi has the potential to be a GW−SW tracer in the river environment, where stable isotopes can be difficult to use. However, the biological uptake processes (particularly at the low flow river sections, Conley et al. 2000) will affect the DSi concentrations during spring and summer, and should be acknowledged in interpretations (Hurley et al. 1984, Neal et al. 2005). In this work, the results of stable isotope compositions were mainly consistent with the DSi concentrations, as higher DSi concentrations appeared coincident with a stable isotope composition typical of the GW.

6.3. Vulnerability of the water supply

Water quality (NO_3-NO_2-N, dissolved organic carbon (DOC), turbidity) was monitored in order to identify risk of transport of contaminants into drinking water production wells through RW infiltration to investigate the potential RW infiltration into the production wells (S::can sensors) at four study sites at one hour intervals during the springtime maximum river flow period in 2012 (Paper IV).

There were two peaks in the River Vantaa (Hyvinkäänkylä study site) water level during monitoring period when RW rise and slight increase in DOC levels was detected in a production well within 2–5 days after RW level rise above the GW level (Paper IV, Fig. 8). Results of water quality monitoring revealed that in the GW–RW interaction areas transport of pathogens or recalcitrant contaminants pose a risk to safe drinking water production during the maximum river flow periods. Based on the results of this research potential GW quality deterioration during peak-flow periods has been acknowledged at several water plants and the intensified monitoring of GW quality and hydraulic heads have been considered.

In the River Vantaa catchment, there are 12 municipal water intake plants in close proximity to the studied main river channels and close to the GW discharge sites identified in this study (Fig. 4 in Paper IV). These municipal water intake plants have a potential risk of water quality deterioration both via overland flows entering the wells and by RW bank infiltration into the aquifer during floods and heavy rain. The high pumping rates of the abstraction wells close to the SW bodies can also introduce possible contamination via SW infiltration during low-flow conditions. The GW−SW exchange is an essential factor affecting the water quality in municipal water intake wells in shallow aquifers, where a hydraulic connection between the SW body and the aquifer exists, as shown in previous studies (e.g. Boyd 2000, Borchardt et al. 2004). In the River Vantaa catchment, a summer flood in 2004 resulted in water quality problems at two major GW intake plants (Suhonen & Rantakokko, 2006), as well as the contamination of several GW wells (Silander et al. 2006). Nutrients (nitrate and phosphate) and faecal contamination (human sewage or animal sources) are the main causes of lowered water quality in the River Vantaa and its tributaries (Vahtera et al. 2014).

This research demonstrated that DGW could have locally effects on LW quality in the shore water of Lake Pyhäjärvi connected to esker deposits, as the proportion of the GW component in the lake-shore water varied between 4% and 99%. Moreover, the GW input could also be seen in RW quality at the observed discharge sites in the River Vantaa catchment. Therefore, these GW discharge sites could be more important for water quality and quantity than has thus far been acknowledged. Hayashi and Rosenberry (2002) reported that a relatively small net GW component might have a significant role locally.

Climate change is predicted to result in an increasing frequency of floods (Veijalainen et al. 2009, Veijalainen et al. 2010), which could increase the vulnerability of water intake plants located in proximity to main stream channels to contamination. The climate change will affect water quality and quantity issues in municipal waterworks in the future via extreme precipitation events and floods, waterborne epidemics, droughts, temperature changes, storms and thunderstorms and land use changes (Vienonen et al. 2012). The identification and localization of GW−SW interaction sites (as potential risks sites) would enable precautionary water management activities (e.g. reducing the water volume pumped from production wells nearest the river channel/lake shore in the most critical period when the RW/LW level is high/SW quality is poor) and prevent a deterioration in GW quality at pumping wells.

Land use practices and changes in them will also affect the flooding sensitivity of the catchment among the other variables (percentage cover of lakes, soil type, vegetation, artificial surfaces).

7. Conclusions

This study revealed that GW−SW interactions are far more common in the Lake Pyhäjärvi and River Vantaa catchments than has thus far been acknowledged, and these two resources should be integrated as one entity in hydrological studies.

AIR was found to be an applicable method to identify thermal anomalies and possible areas of GW discharge across the river basin and to collect spatially continuous patterns of RW temperatures in entire river sections over a short period of time. Furthermore, AIR can also direct water sampling and further investigations to the relevant GW–RW interaction locations.

Thermal stratification can bias interpretation of AIR results, leading to an underestimation of the extent and magnitude of GW–RW interaction. The longitudinal temperature profiles displayed considerable spatial variability both within and among the rivers.

The most comprehensive and reliable research results were achieved with the multi-method approach applied at multiple scales.

The baseline data on isotopic patterns and hydrogeochemistry in the hydrological cycle were provided by a one-year monitoring survey in the Lake Pyhäjärvi catchment and narrower baseline data on the effect of strong seasonality on stable isotopes and DSi concentrations was provided from the River Vantaa catchment. This research revealed considerable variation in stable isotope and DSi concentrations of the studied rivers.

In snow-type catchment, the evaluation of GW–SW interaction needs temporally frequent sampling in order to estimate the magnitude of seasonal systematics in tracer patterns. Samples taken during the spring thaw and high-precipitation events could be problematic in terms of both sampling and interpretation of the results. The identified interaction locations in the proximity of 13 municipal water intake plants in the studied catchments during the low-flow seasons should be considered as potential risk areas for water supply during flood periods and/or with high pumping rates and taken under consideration in water resources management under changing climatic situations. Climate change is predicted to result in an increase in flood frequency and SW temperatures, which could increase the vulnerability to contamination of water intake plants located in proximity to main stream channels due to the RW. More integrated water resource management practices are needed to secure the water supply and sustain the biodiversity of GDEs in the future.

References

Anderson, M. 2005. Heat as a ground water tracer. Ground Water 43, 951–968.

Artimo, A. 2002. Application of flow and transport models to the polluted Honkala aquifer, Säkylä, Finland. Boreal Env. Res. 7, 161–172.

Asano, Y., Uchida, T. & Ohte, N. 2003. Hydrologic and geochemical influences on the dissolved silica concentration in natural water in a steep headwater catchment. Geochim. et cosmochim. Ac. 67, 1973–1989.

Avery, C. 1994. Interaction of ground water with the Rock River near Byron, Illinois. U.S. Geol. Surv. Water Resour. Investigations Rep. 94–4034.

Ayenew, T. & Gebreegziabher, Y. 2006. Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Awassa, Ethiopia. Hydrolog. Sci. J. 51, 418–431.

Belanger, T.V., Mikutel D.F. & Churchill P.A. 1985. Groundwater seepage nutrient loading in a Florida lake. Water Res. 19, 773–781.

Blume, T., Krause, S., Meinikmann, K. & Lewandowski, J. 2013. Upscaling lacustrine groundwater discharge rates by fiber–optic distributed temperature sensing. Water Resour. Res. 49, 7929–7944.

Borchardt, M.A., Haas, N.I. & Hunt, R.J. 2004. Vulnerability of drinking-water wells in La Crosse, Wisconsin, to enteric-virus contamination from surface water contributions. Appl. Environ. Microbiol. 70, 5937–5946.

Boulton, A.J., Findlay, S., Marmonier, P., Stanley, E.H. & Valet, H.M. 1998. The functional significance of the hyporheic zone in streams and rivers. Annu. Rev. Ecol. Syst. 29, 59–81.

Boussinesq, J.V. 1877 Essai sur la théories des eaux courantes. (Essay on the theory of water flow) Mémoires présentés par divers savants à l'Académie des Sciences. Paris, France, 23, 1–680.

Bovolo, I.C., Parkin, G. & Sophocleous, M. 2009. Groundwater resources, climate and vulnerability. Environ. Res. Lett. 4, 035001.

Boyd, R.A. 2000.Herbicides and herbicide degradates in shallow groundwater and the Cedar River near a municipal well field, Cedar Rapids, Iowa. Sci. Total Environ. 248, 241–253.Brander, M. 2013. Virtaamamittaukset tutkimusmenetelmänä pohjaveden purkautumismäärien sekä jokiveden ja pohjaveden sekoittumissuhteiden arvioinnissa Vantaanjoen valuma-alueen jokiuomissa, MSc thesis, University of Helsinki, Finland.

Britschgi, R., Antikainen, M., Ekholm-Peltonen, M., Hyvärinen, V., Nylander, E., Siiro, P. & Suomela, T. 2009. Mapping and classification of groundwater areas (in Finnish). Environment Institute, Finland.

Brock, T.D., Lee, D.R., Janes, D. & Winek, D. 1982. Ground water seepage as a nutrient source to a drainage lake; Lake Mendota, Wisconsin. Water Resour. 16, 1255–1263.

Brooks, J.R., Wigington, P.J., Phillips, D.L., Comeleo, R. & Coulombe, R. 2012. Willamette River Basin surface water isoscape (δ^{18}O, δ^{2}H), temporal changes of source water within the river. Ecosphere 3, 39.

Brunke, M. & Gonser, T. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biol. 37, 1–33.

Carr, M.R. & Winter, T.C. 1980. An annotated bibliography of devices developed for direct measurement of seepage: U.S. Geol. Surv. Open-File Report 80–344, 38 p.

Clark, I.D. & Fritz, P. 1997. Environmental Isotopes in Hydrogeology. Lewis Publishers, Boca Raton, FL, 328 pp.

Conant, B. 2004. Delineating and quantifying ground water discharge zones using streambed temperatures. Ground Water 42, 243–257.

Conant, B. & Mochnacz, N. J. 2009. Low-altitude and land-based infrared thermography to identify types of groundwater discharge in NWT streams, in: American Geophysical Union, Spring Meeting.

Conant, B., Cygan, G.L. & Ohl, T.T. 2012. Rapid Multi-Scale Methodology for Characterizing Groundwater/Surface Water Interactions and Contaminated Groundwater Discharge. USEPA National Association of Remedial Project Managers (NARPM) 22nd Annual Training Conference, Henderson, Nevada, November 26–30, 2012.

Conley, D.J., Schelske, C.L. & Stoermer, E.F. 1993. Modification of silica biogeochemistry with eutrophication in aquatic systems. Mar. Ecol. Prog. Ser. 101, 179–192.

Conley, D.J., Stalnacke, P., Pitkänen, H. & Wilander, A. 2000. The transport and retention of dissolved silicate by rivers in Sweden and Finland. Limnol. Oceanogr. 45,1850–1853.

Connor, J.N. & Belanger, T.V. 1981. Groundwater seepage in Lake Washington and the Upper St. Johns River Basin, Florida. Water Resourc. Bull. 17, 799–805

Craig, H. 1961. Isotopic variations in meteoric water. Science 133, 1702–1703.

Cristea, N.C. & Burges, S.J.2009. Use of thermal infrared imagery to complement monitoring and modeling of spatial stream temperature. J. Hydraul. Eng. 14, 1080–1090.

Danielescu, S., MacQuarrie, K.T.B. & Faux, R.N. 2009. The integration of thermal infrared imaging, discharge measurements and numerical simulation to quantify the relative contributions of freshwater inflows to small estuaries in AtlanticCanada. Hydrol. Process. 23, 2847–2859.

Danielopol, D.L., Gibert, J., Griebler, C., Gunatilaka, A., Hahn, H.J., Messana, G., Notenboom, J. & Sket, B. 2004. Incorporatin ecological perspectives in European groundwater management policy. Environ. Conserv. 31, 1–5.

Dincer, T. 1968. The use of oxygen 18 and deuterium concentration in the water balance of lakes. Water Resour. Res. 4, 1289–1306.

Downing, J.A. & Peterka J.J. 1978. Relationship of rainfall and lake groundwater seepage. Limnol. Oceanogr. 23, 821–825

Duff, J.H., Toner, B., Jackman, A.P., Avanzino, R.J. & Triska, F.J. 1999. Determination of groundwater discharge into a sand and gravel bottom river—A comparison of chloride dilution and seepage meter techniques: Vernhandlungen Internationale Verieinigung Limnologie 7, 406–411.

Dugdale, S., Bergeron, N. & St-Hilaire, A. 2015. Temporal variability of thermal refuges and water temperature patterns in an Atlantic salmon river. Remote Sens. Environ.136, 358–373.

EC, 2006. Directive 2006/118/EC of the European Parliament and of the Council on the protection of groundwater against pollution and deterioration. OJ L372, 27.12.2006. 19 pp.

Ekholm, M. 1993. Suomen vesistöalueet, National Board of Waters and the Environment, Helsinki, Publ. Serie A 126, 166 pp.

Faux, R.N., Lachowski, H., Maus, P., Torgersen, C.E. & Boyd, M.S. 2001. New approaches for monitoring stream temperature: Airborne thermal infrared remote sensing. Remote Sensing Applications Laboratory, USDA Forest Service, Salt Lake City, Utah, Project Rep., 32 pp.

Finnish Meteorological Institute. 1991. Climatological Statistics in Finland 1961–1990. Supplement to the Meteorological Yearbook of Finland. Helsinki.

Frapporti, G. 1994. Geochemical and Statistical Interpretation of the Dutch National Ground Water Quality Monitoring Network. PhD Thesis, Geologica Ultraiectina 115, University of Utrecht, 119 pp.

Fritz, P., Drimmie, R. J., Frape, S. K. & O'Shea, K. 1987. The isotopic composition of precipitation and groundwater in Canada. In: Isotope techniques in water resources development. IAEA-SM-299/17, 539–550.

Gao, X., Wang, Y., Wu, P. & Guo, Q. 2010. Trace elements and environmental isotopes as tracer of surface water-groundwater interaction: a case study at Xian'an karst water system, Shanxi Province, Northern China. Environ. Earth Sci. 59, 1223−1234.

Gibson, J.J., Edwards, T.W., Birks, S.J., St Amour, N.A., Buhay, W.M., McEachern, P., Wolfe, B.B., & Peters, D.L. 2005. Progress in isotope tracer hydrology in Canada. Hydrol. Process. 19, 303–327.

Graham, C.T. & Harrod, C. 2009. Implications of climate change for the fishes of the British Isles. J. Fish Biol. 74, 1143–1205.

Green, T.R., Taniguchi, M., Kooi, H., Gurdak, J.J., Allen, D.M., Hiscock, K.M., Treidel, H. & Aureli, A. 2011. Beneath the surface of global change: Impacts of climate change on groundwater. J. Hydrol. 405, 532–560.

,Guyonnet, D. A. 1991. Numerical modeling of effects of small-scale sedimentary variations on groundwater discharge into lakes. Limnol. Oceanogr. 36, 787–796.

Hancock, P.J., Boulton, A.J. & Humphreys, W.F. 2005. Aquifers and hyporheic zones: Towards an ecological understanding. Hydrogeol. J. 13, 98–111.

Hansen, A. 1975. Some effects of groundwater on brown trout redds. Trans. Am. Fish. Soc. 1, 100–110.

Harvey, F.E., Lee, D.R., Rudolph, D.L. & Frape, S.K. 1997. Locating groundwater discharge in large lakes using bottom sediment electrical conductivity mapping. Water Resour. Res. 33, 2609–2615.

Hayashi, M. & Rosenberry, D.O. 2002. Effects of Ground Water Exchange on the Hydrology and Ecology of Surface Water. Ground Water 40, 309–316.

Helsinki-Uusimaa Region, 1997. Vantaanjoen kehittämisohjelma, Helsinki, Publ. B18. (in Finnish)

Hinton, M.J., Schiff, S.L. & English, M.C. 1994. Examining the contributions of glacial till water to storm runoff using two- and three-component hydrograph separations. Water Resour. Res. 30, 983–993.

Hunt, R.J., Cpolen, T.B., Haas, N.L., Saad, D.A. & Borchardt, M.A. 2005. Investigating surface water–well interaction using stable isotope ratios of water. J. Hydrol. 302, 157–172.

Hurley, J.P., Armstrong, D.E., Kenoyer, G.J. & Bowser, C.J. 1985. Ground-water as a silica source for diatom production in a precipitation-dominated lake. Science 227, 1576–1578.

Ingraham, N.L. & Taylor, B.E. 1991. Light stable isotope systematics of large-scale hydrologic regimes in California and Nevada. Water Resour. Res. 27, 77–90.

Ito M., Mitchell M.J., Driscoll C.T., Newton R.M., Johnson C.E. & Roy K.M. 2007. Controls on surface water chemistry in two lake-watersheds in the Adirondac region nitrogen solute of New York: differences in sources and sinks. Hydrol. Process. 21, 1249–1264.

Jayakumar, R. & Siraz L. 1997. Factor analysis in hydrogeochemistry of coastal aquifers – a preliminary study. Environ. Geol. 31, 174–177.

Kalbus, E., Reinstorf, F. & Schirmer, M. 2006. Measuring methods for groundwater–surface water interactions: a review. Hydrol. Earth. Syst. Sci. 10, 873–887.

Karlsson, K.-P. (ed.). 1986. Atlas of Finland, folio 132, Water. National Board of Survey and Geographical Society of Finland, Helsinki, 31 pp.

Kendall, C. & Coplen T. B. 2001. Distribution of Oxygen-18 and deuterium in river waters across the United States. Hydrol. Process. 15, 1363–1393.

Kenoyer, G.J. & Anderson, M.P. 1989. Groundwater's dynamic role in regulating acidity and chemistry in a precipitation-dominated lake. J. Hydrol. 109, 287–306.

Kidmose, J., Engesgaard, P., Nilsson, B., Laier, T. & Looms, M.C. 2011. Spatial distribution of seepage at a flow through lake: Lake Hampen, Western Denmark, Vadose Zone J., HOBE Special Issue 10, 110–124.

Kidmose, J., Nilsson, B., Engesgaard, P., Frandsen, M., Karan, S., Landkildehus, F., Søndergaard, M. & Jeppesen, E. 2013. Focused groundwater discharge of phosphorus to a eutrophic seepage lake (Lake Væng, Denmark): implications for lake ecological state and restoration. Hydrogeol. J. 21, 1787–1802.

Kirkkala, T. 2014. Long-term nutrient load management and lake restoration: Case of Säkylän Pyhäjärvi (SW Finland). Annales Universitatis Turkuensis A II 286.

Kløve, B., Allan, A., Bertrand, G., Druzynska, E., Ertürk, A, Goldscheider, N., Henry, S., Karakaya, N., Karjalainen, T., Koundouri, P., Kupfersberger, H., Kvoerner, J., Lundberg A, Muotka, T., Preda, E., Pulido-Velazquez, M. & Schipper, P. 2011. Groundwater dependent ecosystems. Part II: Ecosystem services and management in Europe under risk of climate change and land use intensification. Environ. Sci. & Policy. 14, 770–781.

Koeniger, P., Leibendgut, C., Laink, T. & Marshall, J.D. 2009. Stable isotopes applied as water tracers in column and field studies. Org. Geochem. 41, 32–40.

Korhonen, J. & Haavanlammi, E. 2012. Hydrological Yearbook 2006–2010, Finnish Environmental Institute, Helsinki, The Finnish Environment 8/2012. Finland.

Korkka-Niemi, K. 2001. Cumulative geological, regional and site-specific factors affecting groundwater quality in domestic wells in Finland. Monogr. Boreal Env. Res. 20, 98 pp.

Kortelainen, N.M. 2007. Isotopic fingerprints in surficial waters: Stable isotope methods applied in hydrogeological studies. PhD dissertation, Department of Geology, University of Helsinki.

Kortelainen, N.M. & Karhu, J.A. 2004. Regional and seasonal trends in the oxygen and hydrogen isotope ratios of Finnish groundwaters: a key for mean annual precipitation. J. Hydrol. 285, 143–157.

Kortelainen, N.M. & Karhu, J.A. 2006. Tracing the decomposition of dissolved organic carbon in artificial groundwater recharge using carbon isotope ratios. Appl. Geochem. 21, 547–562.

Krabbenhoft, D.P. & Anderson, M.P. 1986. Use of a numerical ground water flow model for hypothesis. Ground Water 24, 49–55.

Krabbenhoft, D.P., Anderson, M.P., Bowser, C.J. & Valley, J. 1990. Estimating groundwater exchange with Sparkling Lake, Wisconsin, 1: Use of the stable isotope mass-balance method. Water Resour. Res. 26, 2445–2453.

Kuusisto, E. 2015. Suomen tulvat ovat jo muuttuneet (Floods in Finland have already changed), Vesitalous 1, 126–28.

Lahermo, P., Väänänen, P., Tarvainen, T. & Salminen, R. 1996. Geochemical atlas of Finland, Part 3: Environmental geochemistry - stream waters and sediments, Geol. Surv. of Finland, Espoo, Finland.

Lahermo, P., Tarvainen, T., Hatakka, T., Backman, B., Juntunen, R., Kortelainen, N., Lakomaa, T., Nikkarinen, M., Vesterbacka, P., Väisänen, U. & Suomela, P. 2002. Tuhat kaivoa − Suomen kaivovesien fysikaalis- kemiallinen laatu vuonna 1999 (One thousand wells − the physical-chemical quality of Finnish well waters in 1999), Geol. Surv. of Finland, Espoo, Rep. of Investigation 155. (In Finnish with English abstract)

Lee, D.R. 1977. A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22, 140–147.

Lee, D.R. 1985. Method for locating sediment anomalies in lakebeds that can be caused by groundwater flow. J. Hydrol. 79, 187–193.

Lee, D.R. & Cherry, J.A. 1978. A field exercise on groundwater flow using seepage meters and minipiezometers. J. Geological Education 27, 6–20.

Lenters, J.D. 2004 Trends in the Lake Superior water budget since 1948: A weakening seasonal cycle. J. Gr. Lakes Res. 30, 20–40.

Loheide, S.P. & Gorelick, S.M.2006. Quantifying Stream−aquifer Interactions through the Analysis of Remotely Sensed Thermographic Profiles and In Situ Temperature Histories. Environ. Sci. Technol. 40, 3336–3341.

Loheide, S.P. & Deitchman, R.S. 2009. A thermal remote sensing tool for mapping spring and diffuse groundwater discharge to streams, Water Resources Institute, University of Wisconsin, Final Rep. WR07R005.

Matthews, K.R., Berg, N.H., Azuma, D.L. & Lambert, T.R. 1994. Cool water formation and trout habitat use in a deep pool in the Sierra Nevada, California. Trans. Am. Fish. Soc. 123, 549–564.

McBride, M.S. & Plannkuch, H.O. 1975. The distribution of seepage within lakebeds: U.S. Geol. Surv. J. Res. 3, 505–512.

Merlivat, L. & Jouzel, J.1979. Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. J. Geophys. Res. 84, 5029–5033.

Mäntylä, K. & Saarelainen, S. 2008. Rakennetun ympäristön sopeutuminen ilmastonmuutoksen aiheuttamille tulvavaikutuksille, Tutkimuskohteena Vantaanjoki, VTT Technical Research Centre of Finland, Res. Rep. VVT-R-04429-08, 180 pp. (in Finnish)

Neal, C., Neal, M., Reynolds, B., Maberly, S. C., May, L., Ferrier, R. C. Smith, J. & Parker, J. E. 2005. Silicon concentrations in UK surface waters. J. Hydrol. 304, 75–93.

Négrel, Ph. & Petelet-Giraud, E. 2005. Strontium isotopes as tracers of groundwater-induced floods: the Somme case study (France). J. Hydrol. 305, 99–119.

Nielsen, J.L., Lisle, T.E. & Ozaki V. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Trans. Am. Fish. Soc. 123, 613–626.

Nõges, P., Nõges, T., Adrian, R. & Weyhenmeyer, G. A. 2008. Silicon load and the development of diatoms in three river-lake systems in countries surrounding the Baltic Sea. Hydrobiologia 599, 67–76.

Ommen, D.A.O., Kidmose, J., Karan, S., Flindt, M., Engesgaard, P., Nilsson, B. & Andersen, F.Ø. 2012. Groundwater interactions with oligotrophic Lake Hampen, Denmark. Ecohydrology 5, 286–296.

Poole, G.C. & Berman. C.H.2001. An ecological perspective on in-stream temperature: Natural heat dynamics and mechanisms of human-caused thermal degradation. Environ. Manage. 27, 787–802.

Ranta, E., Rita, H. & Kouki, J. 1991. Biometria, tilastotiedettä ekologeille, Yliopistopaino. Helsinki, 569 pp. (in Finnish)

Rautio, A., Korkka-Niemi, K. & Kivimäki, A.-L. 2014. lähdekartoitusta lintuperspektiivistä. Vesitalous 4, 19–22.

Reimann, C. & Filzmoser, P. 2000. Normal and log-normal data distribution in geochemistry; death of the myth. Concequences for the statistical treatment of geochemical and environmental data. Environ. Geol. 39, 1001–1014.

Rock, N.M.S. 1988. Numerical Geology: A Source Guide, Glossary and Selective Bibliography to Geological Uses of Computers and Statistics Numerical Geology. Lecture Notes in Earth Sciences, Vol 18, Springer-Verlag, Berlin, 427 pp.

Rosenberry, D.O. 2005. Integrating seepage heterogeneity with the use of ganged seepage meters. Limnol. Oceanogra., Methods, 3, 131–142.

Rosenberry, D.O. 2008. A seepage meter designed fouse in flowing water. J. Hydrol. 359, 118–130.

Rosenberry, D.O. & Morin, R.G. 2004. Use of an electromagnetic seepage meter to investigate temporal variability in lake seepage. Ground Water 42, 68–77.

Rosenberry, D.O. & LaBaugh, J.W. 2008. Field techniques for estimating water fluxes between surface water and ground water: U.S. Geol. Surv. Techniques and Methods 4-D2, 128 p.

Rosenberry, D.O., Striegl, R.G. & Hudson, D.C. 2000. Plants as indicators of focused ground water discharge to a northern Minnesota lake. Ground Water 38, 296–303.

Rosenberry, D.O., Dean, W.E., Duff, J.H., LaBaugh, J.W., Reddy. M.M., Schuster, P.S., Striegl, R.G., Triska, F.J. & Winter, T.C. 2003. Exchange of Water, Solutes, and Nutrients at the Sediment-Water Interface Affects a Northern Minnesota Watershed at Multiple Scales. In: Proceedings of The First Interagency Conference on Research in the Watersheds, U.S. Department of Agriculture, Agricultural Research Service, Benson, Arizona, October, 2003, p. 468–473.

Rozanski, K., Froehlich, K. & Mook, W. G. 2001. Surface water, Vol. III, in: Environmental isotopes in the hydrological cycle: principles and applications, (Ed.): W.G. Mook, IHP-V, Technical Documents in Hydrology No. 39, UNESCO, Paris.

Räsänen, M., Salonen, V.-P., Salo, J., Walls, M. & Sarvala, J. 1992. Recent history of sedimentation and biotic communities in Lake Pyhäjärvi, SW Finland. J. Paleolimnol. 7, 107–126.

Salonen, V.-P., Korkka-Niemi, K., Moreau, J. & Rautio, A. 2014. Kaivokset ja vesi- esimerkkinä Hannukaisen hanke. Geologi 66, 8–19.

Sams, J. & Veloski, G. 2003. Evaluation of airborne thermal infrared imagery for locating mine drainage sites in the Lower Kettle Creek and Cooks Run Basin, Pennsylvinia, USA. Mine Water and Environment 22, 85–93.

Sandborg, M.1993. Soranoton vaikutus pohjaveteen. Tutkimusraportti I: Pohjaveden laatuun vaikuttavien aineiden geokemiallisia ominaisuuksia (Effect of gravel extraction on groundwater Report 1: Geochemical properties of substances affecting groundwater quality), National Board of Waters and the Environment, Helsinki, Serie 328. (in Finnish)

Scanlon, T. Scanlon, T.M., Raffensperger, J.P. & Hornberger, G.M.2001. Modeling transport of dissolved silica in a forested headwater catchment: Implications for defining the hydrochemical response of observed flowpathways. Water Resour. Res. 37, 1071–1082.

Schafran, G.C. & Driscoll, C.T. 1990. Porewater acid/base chemistry in near-shore regions of an acidic lake: the influence of groundwater inputs. Biogeochemistry 11, 131–150.

Schneider, R.L., Negley, T.L. & Wafer, C. 2005. Factors influencing groundwater seepage in a large, mesotrophic lake in New York. J. Hydrol. 310, 1–16.

Schwalb, A., Burns, S.J. & Kelts, K. 1999. Holocene environments from stable isotope stratigraphy of ostracods and authigenic carbonate in Chilean Altiplano Lakes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 153−168.

Sebestyen, S.D. & Schneider, R.L. 2001. Dynamic temporal patterns of nearshore seepage flux in a headwater Adirondack lake. J. Hydrol. 247, 137–150.

Sebestyen, S.D. & Schneider, R.L. 2004. Seepage patterns, pore water, amd aquantic plants: hydrological and biogeochemical relationships in lakes. Biogeochemistry 68, 383–409.

Seuna, P.1971. Suomen vesistöalueet: Ehdotus vesistöalueiden yleisjaoksi ja vesistötunnukseksi, National Board of Waters, Helsinki, Report 10.

Shaw, R.D. & Prepas, E.E. 1990a. Groundwater –-lake interactions: I- Accuracy of seepage meter estimates of lake seepage. J. Hydrol. 199, 105–120.

Shaw, R.D. & Prepas, E.E. 1990b. Groundwater lake interactions: II. Nearshore seepage patterns and the contribution of ground-water to lakes in Central Alberta. J. Hydrol. 119, 121–136.

Shaw, R.D., Shaw, J.F.H., Fricker, H. & Prepas, E.E. 1990. An integrated approach to quantify groundwater transport of phosphorus to Narrow Lake, Alberta. Limnol. Oceanogr. 35, 870–886.

Silander, J., Vehviläinen, B., Niemi, J., Arosilta, A., Dubrovin, T., Jormola, J., Keskisarja, V., Keto, A., Lepistö, A., Mäkinen, R., Ollila, M., Pajula, H., Pitkänen, H., Sammalkorpi, I., Suomalainen, M. & Veijalainen, N. 2006. Climate change adaptation for hydrology and water resources, Finnish Environment Institute, Helsinki, FINADAPT WorkingPaper 6, Finnish Environment Institute Mimeographs 335.

Silliman, S.E. & Booth, D.F. 1993. Analysis of time-series measurements of sediment temperature for identification of gaining versus losing portions of Judy Creek, Indiana. J. Hydrol. 146, 131–148.

Sinokrot, B.A., Stefan, H.G., McCormick, J.H. & Eaton, J.G. 1995. Modeling of climate change effects on stream temperatures and fish habitats below dams and near groundwater inputs. Climate Change 30, 181–200.

Soveri, J., Mäkinen, R. & Peltonen, K.2001. Pohjaveden korkeuden ja laadun vaihtelusta Suomessa 1975–1999 (Changes in groundwater levels and quality in Finland in 1975–1999), The Finnish Environment 420, Finnish Environmental Institute, Helsinki, 350 pp. (English summary)

Stanford, J.A. & Ward, J. V.1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. J. North Am. Benthol. Soc. 12, 48−60.

Stonestrom, D.A. & Constantz, J.E. eds. 2003. Heat as a tool for studying the movement of ground water near streams: U.S. Geol. Surv. Circular 1260, 96 pp.

Suhonen, V. & Rantakokko, K. 2006. Vantaanjoen tulvatorjunnan toimintasuunnitelma, Centre for Economic Development, Transport and the Environment for Uusimaa, Helsinki, Rep.1/2006. (In Finnish)

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F. & Stein R. 2004. Late Quaternary ice sheet history of northern Eurasia. Quat. Sci. Rev. 23, 1229–1271.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Longuevergne, L., Leblanc, M., Famiglietti, J.S., Edmunds, M., Konikow, L., Green, T.R., Chen, J., Taniguchi, M., Bierkens, M.F.P., MacDonald, A., Fan, Y., Maxwell, R.M. Yechieli, Y., Gurdak, J.J., Allen, D., Shamsudduha, M., Hiscock, K., Yeh, P.J.F., Holman, I. & Treidel, H. 2013. Ground water and climate change. Nat. Clim. Change 3, 322–329.

Tikkanen, M.1989. Geomorphology of the Vantaanjoki drainage basin southern Finland, Fennia, 167, 19–72.

Torgersen, C.E., Faux, R.N., McIntosh, B.A., Poage, N.J. & Norton, D.J. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sens. Environ. 76, 386–398.

Tóth, J. 1963. A Theoretical Analysis of Groundwater Flow in Small Drainage Basins. J. Geophys. Res. 68, 4795–4812.

Triska, F.J, Kennedy, V.C, Avanzino, R.J, Zellweger, G.W. & Bencala, K.E. 1989a. Retention and transport of nutrients in a 3rd–orderstream—channel processes. Ecology 70, 1877–1892.

Triska, F.J., Kennedy, V.C., Avanzino, R.J., Zellweger, G.W. & Bencala, K.E. 1989b. Retention and transport of nutrients in a third-order stream in northwestern California: hyporheic processes. Ecology 70, 1893–1905.

Vahtera, H., Männynsalo, J. & Lahti, K. 2012. Vantaanjoen yhteistarkkailu - Vedenlaatu vuonna 2011, The Water Protection Association of the River Vantaa and Helsinki Region, Helsinki, Publ. of 67/2012, 94 pp.

Vahtera, H., Männynsalo, J. & Lahti. K.2014. Vantaanjoen yhteistarkkailu - Vedenlaatu vuosina 2011 – 2013, The Water Protection Association of the River Vantaa and Helsinki Region, Helsinki, Publ. of 72/2014, 93 pp.

Vanek, V. & Lee, D.R. 1991. Mapping submarine groundwater discharge areas—An example from Laholm Bay, southwest Sweden. Limnol. Oceanogr. 36, 1250–1262.

Veijalainen, N., Sippel, K. & Vehviläinen, B. 2009. Tulvien muuttuminen Vantaanjoella ja Espoonjoella. In, Climate is Changing in The Helsinki Metropolitan Area Background Studies for the Adaptation Strategy, Helsinki Region Environmental Services Authority, Helsinki, Publ. 3/2010, 37–53. (abstract in English)

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B. & Käyhkö, J. 2010. National scale assessment of climate change impacts on flooding in Finland, J. Hydrol. 391, 333–50.

Ventelä, A.-M., Tarvainen, M., Helminen, H. & Sarvala, J. 2007. Long-term management of Pyhäjärvi (southwest Finland): eutrophication, restoration - recovery?. Lake Reserv. Manage. 23, 428–438.

Ventelä, A.-M., Kirkkala, T., Lendasse, A., Tarvainen, M., Helminen, H. & Sarvala, J. 2011. Climate-related challenges in long-term management of Säkylän Pyhäjärvi (SW Finland). Hydrobiologia 660, 49–58.

Vienonen, S., Rintala, J., Orvomaa, M., Santala, E., Maunula, M. 2012. Ilmastonmuutoksen vaikutukset ja sopeutumistarpeet vesihuollossa. Suomen ympäristökeskus (SYKE). Suomen ympäristö 24/2012. 86 pp. ISBN 978-952-11-4046-4.

Wassen, M.J. & Grootjans, A.P. 1996. Ecohydrology: An interdisciplinary approach for wetland management and restoration. Vegatatio. 126, 1–4.

Wawrzyniak, V., Piégay, H. & Poirel, A. 2012 Longitudinal and temporal thermal patterns of the French Rhône River using Landsat ETM+ thermal infrared images. Aquat. Sci. 74, 405–414.

Winter, T.C. 1995. Recent advances in understanding the interaction of groundwater and surface-water. Rev. Geophys. 33, 985–994.

Winter, T.C. & Rosenberry, D.O. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979–1990. Wetlands 15, 193–211.

Winter, T.C., Rosenberry, D.O. & LaBaugh, J.W. Where does the ground water in small watersheds come from? Ground Water 41, 989–1000.

Winter, T.C., Harvey, J.W, Franke, O.L. & Alley, W.M. 1998. Ground Water and Surface Water A Single Resource, U.S Geol. Surv. circular 1139. Denver, Colorado, U. S. Geol. Surv., 87 pp.

White, D.S. 1993. Perspectives on defining and delineating hyporheic zones. J. North Am. Benthol. Soc. 12, 61–69.

Woessner, W.W. 1998. Changing views of stream-ground-water interaction. Proceedings of American Institute of Hydrology/International Association of Hydrologists XXVIII Congress, Gambling with Groundwater, Physical, Chemical and Biological Aspects of Aquifer-Stream Relationships St. Paul, MN, September 1998, 1−6.

Woessner, W. W.2000. Stream and Fluvial Plain Ground Water Interactions: Rescaling Hydrogeologic Thought. Ground Water 38, 423–429.

Woessner, W.W. & Sullivan, K.E. 1984. Results of seepage meter and mini-piezometer study, Lake Mead, Nevada Ground Water 22, 561–568.

Zacharias, I., Dimitriou, E. & Koussouris, T. 2003. Estimating groundwater discharge into a lake through underwater springs by using GIS technologies. Environ. Geol. 44, 843–851.